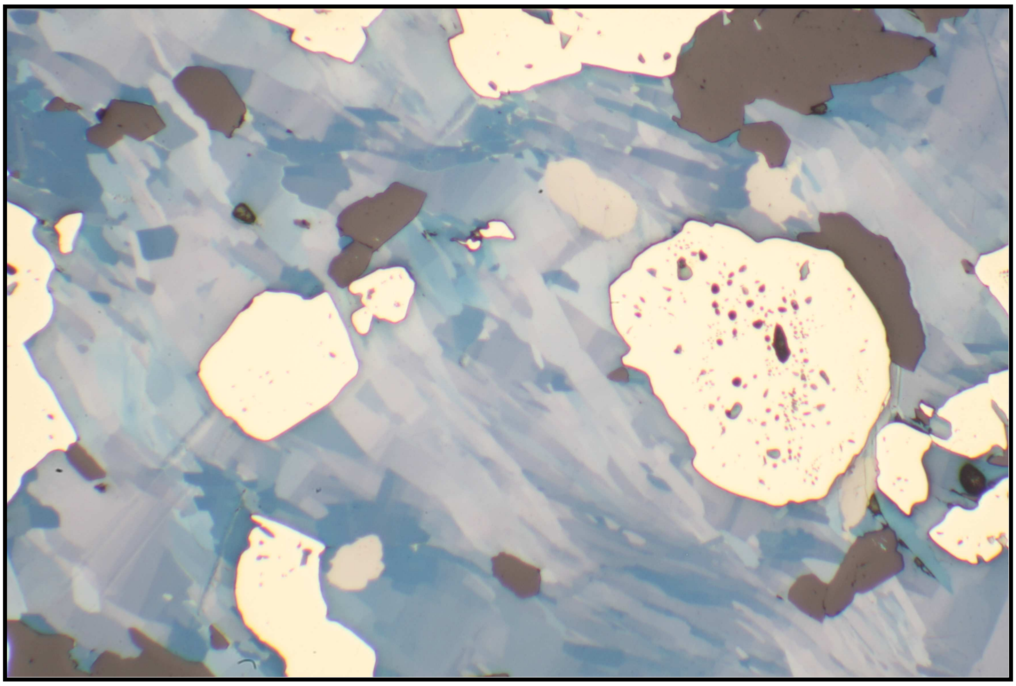
TA3196 Ore Mineralogy and Ore Microscopy



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Preface

This syllabus for *TA3196* is a revised version of the previously used texts for *TA3196*, but now translated into English. Also there are far more illustrations than in previous versions.

This syllabus consists of two parts: the first part is a short repetition of the material from the lecture *Economic Minerals and Rocks TA3140*, but here with direct reference to samples from the training collection, which are examples of specific ore associations. The student thus may, when studying an ore, refer directly to the description of the specific ore association, without looking things up in another syllabus.

The second part is the actual microscopy practical, which consists of a description of the microscope used, and a series of Appendices, which contain the description of the samples to be studied, and necessary tables and figures.

Appendix 6, "*Interaction of Light with Opaque Minerals (Reflected Light Optics)*" is an elucidation on the optics of reflection polarization microscopy. This appendix serves as an explanation for the observable optical effects, analogous to the optics of transmitted light polarization microscopy such as treated in *TA1900*.

Delft,
November 2011

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Ore Mineralogy and Ore Microscopy TA3196

Part I

Ore Mineral Associations, Petrografical Relationships

1. INTRODUCTION

Ore minerals are the valuable minerals in a rock which can be considered an ore. In general these minerals are *opaque minerals*, contrary to the rock forming minerals, which in general are *transparent* or *translucent*. Besides the ore minerals, ores also contain common rock forming minerals, which have been encountered already in the course Mineralen en Gesteenten - TA1900. Only very rarely does an ore consist completely of valuable minerals. In the course TA1900 you have learned to designate the opaque minerals as “ore”.

Ore minerals contain the valuable materials which are the reason for mining en the following mineral processing. Ore minerals are often sulfides (for instance chalcopyrite ($CuFeS_2$), a copper ore minerals, or pentlandite, $(Ni,Fe)_9S_8$, a Ni-ore mineral, but also oxides. Examples of oxidic ore minerals are: hematite, Fe_2O_3, magnetite Fe_3O_4, pyrolusite MnO_2, goethite, FeOOH, cassiterite, SnO_2. Also native metals (Au, Ag) do occur. .

The genesis or ores is discussed in the lecture Economic Minerals and Rocks (TA3140), but several aspects will be repeated here in brief. This will give insight into some important minerals associations. The classification of ores from TA3140 is given again, but with reference to the specific polished sections of the relevant ores in the specimen collection. For aspects of determination of ores, but also or mineral processing it is useful to have insight into the texture of ores. The textures tell a lot about the genesis of the ores, with often important information with respect to the determination of minerals, but textures certainly are not unimportant in the processing of ores. Inclusions, zoning, reactions rims, demixing lamellae, occurrence of crystals in small veinlets, grain size, etc. all are of important in the study of an ore.

This syllabus has the function of practical manual (see appendices), but also as a short reference work with respect to the geochemical associations, and the structure of the minerals, as well as petrographic relationships. For instance, every specimen is described in the practical manual (Appendix 2), but also in the summary of the geochemical associations. The practical manual (Appendix 2) gives the minerals occurring in a specimen, and the specimen index (part 1, section 5) indicates where a specific ore is discussed, which facilitates the study of the manner of occurrence.

2. SHORT SUMMARY OF THE GENESIS OF ORES AND THE DIFFERENT TYPES OF ORES.

In this section is discussed in brief how the different ores are formed, and which mineral associations belong to it. More extensively this is discussed in the course TA3140 – Economic Minerals and Rocks.

Where such a type of ore occurs in the practical sample set, a more detailed description of the specific ore is given. In the margin of the text this is indicated with the word MICROSCOPY

You will find that the subdivision of the ores not always can be applied in a strict sense. Also, some ore types over a larger distance will grade into other ores types, or are in between two classifications. Also there are ores about which there are different theories about the genesis, and it is not uncommon that different theories place the same ore into another category. A very well-known example are the iron ores of Kiruna, which according to one theory must be seen as volcanic exhalative ores, according to another as representatives of the class of segregation ores.

Well known characteristic minerals associations and textures can offer valuable information for the identification of the minerals in an ore. For example, galena, sfalerite and pyrite are common in ores in carbonate rocks, but Sn-minerals, such as cassiterite are unknown in such rocks. chalcopyrite, pyrrhotite, pentlandite, magnetite and pyrite occur often together, but for instance sfalerite or galena are seldom (but that is not “never”) found in this association.

Finally, the classification of ores in types and the mineral associations that are connected to them give an overview of the most important parageneses of ore minerals. The specimens in the practical collection contain typical parageneses.

One may classify the ores into the following main groups (TA3140):

A) MAGMATIC ORES

This is ores which are directly related to igneous rocks. Ore formation due to secondary processes, related to magmatic processes, is not part of this category.

1) Ores related to “Mantle Degassing”

Examples are: Diamond ores, ores related to carbonatites. The latter are of interest for the winning of calcium, phosphate, magnetite, chalcopyrite, Rare Earth Elements (Ce, La, Nd, etc.).
There are NO examples of this class in the practical collection.

2) Segregation deposits

An example is chromite ore. Chromite ($FeCr_2O_4$) is formed in certain mafic or ultramafic magmas, and accumulates in the magma chamber. Such layer like accumulations of chromite are sometimes called Chromitites. Associated minerals are often olivine, plagioclase and (ortho)pyroxene. As results of later low grade weathering, olivine may be changed into serpentinite.

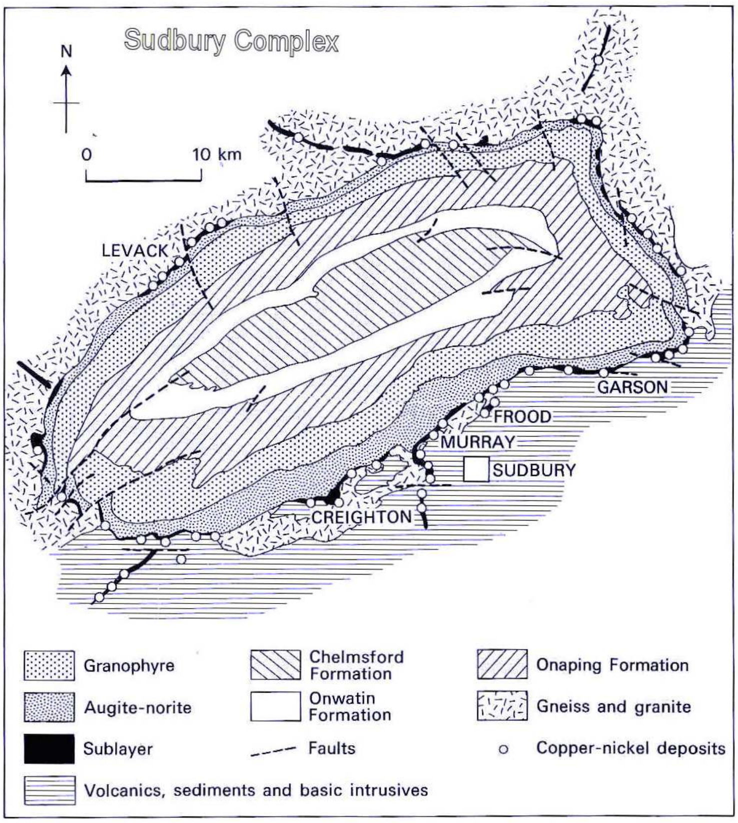
MICROSCOPY ***An example is the specimen T-11. This is a chromite ore from the Philippines. In this sample the olivine is completely altered to serpentine.***

3) Deposits related to the demixing of melts

This is often the case with mafic or ultramafic silicate magmas which contain appreciable amounts of sulfur. The sulfur forms a sulfide melt, which cannot mix with silicate melt, en which separates as a result of its larger density. Examples of such ores are:

a) The Ni-Cu-Fe ores of Sudbury, Canada. Important minerals associations are pyrrhotite ($Fe_{1-x}S$), with pentlandite ($(Ni,Fe)_9S_8$), and chalcopyrite $CuFeS_2$. Oxide may also occur in these sulfidic rocks. Spinel ($MgAl_2O_4$) and magnetite ($FeFe_2O_4$) are not uncommon.

MICROSCOPY ***Specimen T-4 is a typical massive sulfidic ore from Sudbury, with pyrrhotite, pentlandite, chalcopyrite and magnetite.***



The Sudbury Complex, Ontario Canada.

MICROSCOPY ***Specimen T-8 (from the Frood-Stobie mine) shows chalcopyrite, intergrown with the (as such rather rare) mineral cubanite ($CuFe_2S_3$). In T-8 sometimes accessory Bi-Te minerals can be found.***

The Frood-Stobie Mine, Sudbury Area.

b) The Platinum Group Elements (PGE: Pt, Ru, Rh, Ir, Os, Pd). Well-known deposits are the Bushveld Complex (S-Africa), Stillwater Complex (Montana, U.S.A.). Important minerals are for instance braggite (Pt,Pd,Ni)S, laurite (RuS_2) and sperrylite ($PtAs_2$).
There are NO examples of this class in the training collection.

c) Ti- and V-ores, like in Bushveld (vanadium-containing magnetite), and Tellnes, Norway (Ilmenite, $FeTiO_3$).
There are NO examples of this class in the training collection.

4) Granitic Magmas and Pegmatites.

Granitic melts contain H_2O, because they have their origin in the Earth's Crusts. Part of the water is stored in for instance biotite (as OH-groups). Remaining water stays in the melt. At a temperature low enough during the cooling of the magma, the water-rich fluid separates. Metals accumulate in these fluids. In some cases the last silicates crystallize in a very watery fluid. Because diffusion is very rapid in such hot watery fluids, very large crystals can form. A granitic rock with large crystals is called a pegmatite. Many pegmatites crystallize in fracture zones in and around granitic rocks. Pegmatites thus look like veins. The fluid is in this last phase enriched in metals or other economically valuable elements (for instance Be, or Li, or B). There may be crystallization of minerals of economic value (e.g. beryl, $Be_3Al_2Si_6O_{18}$).
There are NO examples of this class in the training collection.

Many metals cannot be incorporated into silicates and form, after separation of the fluid phase, their "own" minerals, like cassiterite (SnO_2). Deposits of the separated fluids form the class of the hydrothermal ores.

B) HYDROTHERMAL ORES

This is a very important class of ores. The ores are formed by hot aqueous solutions. The origin of the solutions may be diverse: magmatic, metamorphous, diagenetic, meteoric, seawater. The metals in these solutions are generally transported as chemical complexes. Cl, but also F are very important in this. The representants of this group are:

1) Magmatic

a) *Greisen Tin Deposits* (related to granite)

In a late stage of the evolution of granite, a fluid separation takes place. The segregated late magmatic hydrothermal solution will react with the country rocks of the granite, but also with crystallized granite itself. By metasomatic changes a rock called *Greisen* is formed. Also veins and stockworks may be associated with this. Mineralizations of Sn (cassiterite – SnO_2), but also veins with mineralizations of W (wolframite – $(Fe,Mn)WO_4$) are often found in Greisens and associated veins. Examples are the many Sn-deposits in Cornwall, England, and N-Portugal. At Panasqeira, N-Portugal (where tungsten is the main product), cassiterite is found in greisens and in associated veins with quartz.

MICROSCOPY ***An example of an ore from Panasqeira can be found in T-5 from the practical collection. This is a complicated ore with many subsequent phases of mineralization. The general model is: the first mineral in the veins was cassiterite, followed by quartz, muscovite and wolframite (by the way: wolframite is extremely rare in T-5). After this, there was a sulfide rich phase, which led to the crystallization of pyrite, pyrrhotite, Fe-rich sfalerite and chalcopyrite. In a later phase, carbonate with secondary pyrite and marcasite was deposited, in which the pyrrhotite was altered. Not all pyrrhotite was altered, so it is still a prominent mineral in the polished sections. Pyrite can also be found as "melnicovite-pyrite" or "gel-pyrite", a cryptocrystalline or amorphous form of pyrite, which is deposited in concentric layers***

In T-18 you will find an ore from Indonesia, which fits in this setting. No clear veins can be recognized.

b) Ag-Ni-Co-Bi arsenide ores

A special paragraph must be added for a peculiar, but with respect to ore minerals spectacular association: *Ag-Ni-Co-Bi arsenide ores*. Silver is often found as a native metal in these ores.

MICROSCOPY ***Specimen T-6 is a sample of the ores from the Cobalt region, near Sudbury, Canada, which are considered to be typical. T-6 contains no native silver and Bi, but for the rest is a beautiful example of these ores. Minerals are among others: skutterudite ($(Co,Ni,Fe)As_{3-x}$), nickeline (NiAs), cobaltite ((Co,Fe)AsS) and loellingite/rammelsbergite[1]. It can be observed that skutterudite and nickeline crystallized early, followed by cobaltite and loellingite/rammelsbergite.***

The Ag-Ni-Co arsenide ores occur during the whole history of the Earth, and they are found in a whole range of rocks. They occur in veins, and closely related diabase veins are found (as in the Cobalt region). The ore bodies in the veins often show growth phenomena, and sometimes "colloform textures" (later we will learn more about this). The mineralogy is determined, besides the common ore minerals pyrite, chalcopyrite, arsenopyrite and galena, by minerals such as native silver (Ag), bismuth (Bi), nickeline and skutterudite. The paragenetical sequence of these ores is often very complicated. With respect to the origin, there are two theories: one implies a genetic relationship with the often associated diabase veins, but a more widely accepted theory lays the origin of the ore forming solutions with felsic magmatism. In the Cobalt region such an igneous rock is not exposed. Mining ion the Cobalt region has stopped in the 1960's.

2) Magmatic/Groundwater

a) Skarn Tungsten Deposits

In contact with limestone, a reaction zone between granite and country rocks will form. Decomposition of calcite forms CO_2, and possible W in the hydrothermal solution can be deposited as scheelite ($CaWO_4$). Later meteoric water may cause retrograde reactions in the rock.
There are NO examples of this class in the training collection.

b) Porphyry Copper and molybdenum Deposits

These ores are related to granitic intrusions which have penetrated high in the Earth's Crust. They are found on the continental side of subduction zones. Aqueous solutions segregate in a late stage of the crystallization of the granitic magma. The fluids are enriched in some main and trace elements. By segregations of the aqueous solutions the melting point of the granite is raised, and enhanced crystallization takes place. The segregated fluids accumulate in the apex of the intrusion. They cause brecciation of the country

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[1] *Loellingite ($FeAs_2$) is also spelled* ***löllingite****. Rammelsbergite is $(Ni,Fe)As_2$*

rock and escape. These fluids cause metasomatism of the surrounding rocks in particular of the elements K, Cu, and Mo, dissolved in the solutions, are deposited as chalcopyrite, ($CuFeS_2$), chalcocite (Cu_2S), and molybdenite (MoS_2).

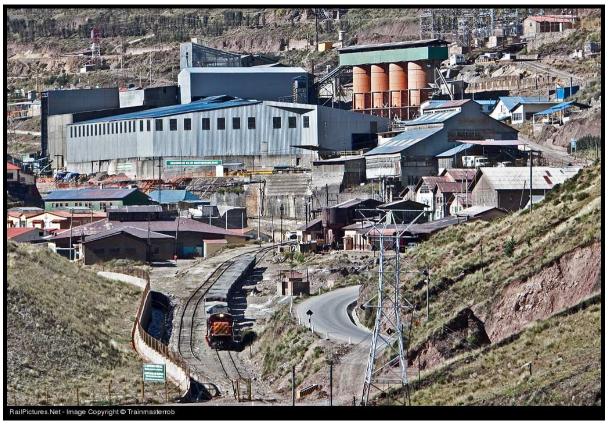
Crystallization of the minerals causes again pressure increase, with a second round of brecciation of the country rocks. In this way a new cycle of vein formation with ore minerals is formed. A so-called ***stockwork*** is formed. When the intrusion cools, percolating groundwater comes into contact with the intrusion, and a hydrothermal alteration zone is formed, which overlaps the previous. Also Cu-sulfides are again mobilized and newly distributed. This class deals with low grade ores of very large proportions. Famous examples are Climax Colorado (Mo), and Chuquicamata Chili (Co, Mo). ***There are NO examples of this class in the training collection.***

d) Mesothermal deposits

These deposits are found in the country rocks around a granitic intrusion. Aqueous solutions flow through fractures, cracks, or the bedding of sedimentary country rocks. The solutions may be magmatic, meteoric, or a mixture of both. The further away from the granite, the lower the temperature. Close to the granite minerals which crystallize at a relatively high temperature are found (cassiterite). Further away Cu-minerals like chalcopyrite and bornite (Cu_5FeS_4), are formed. Also covellite (CuS) may be found, which forms together with pyrite from alteration of chalcopyrite. In the lowest temperature zone sfalerite (ZnS) and galena (PbS) are deposited. Also Ag-minerals may crystallize. Veins may vary in diameter from centimeters to meters, and often can be followed over large distances. The veins are very rich in ore.

An important example of such a Cu-ore is found at Butte, Montana, USA.

MICROSCOPY ***In the training collection you find in T-1 a specimen from such a mesothermal Pb-Zn from*** **Casapalca, Peru*****. Minerals in the ore are galena, sfalerite, pyrite, and tennantite (*** $Cu_3(As,Sb)S_{3.25}$ ***(or*** $Cu_{12}(As,Sb)_4S_{13}$***)***



Casapalca Peru

MICROSCOPY ***In the training collection you find in T-3 a Cu-ore from*** **Bor, Serbia**. ***The copper ores from Bor are found in a hydrothermally altered andesite. The volcanic rocks are associated with intrusive rocks varying from diorite gabbro to granodiorite. Apparently associated to the intrusives in hydrothermally altered andesite one may find massive Cu-ore as lenses, and stockwork deposits. The massive ores (typical minerals: pyrite, bornite, enargite/luzonite, chalcopyrite, chalcocite, covellite) are considered to be hydrothermal replacement ores. Porphyry copper ore is also found at Bor, in an underground mine which displays lower lying ores under the massive ores (mined in an open pit mine).***

Bor, Serbia

MICROSCOPY ***The deposits of*** **Pribram, Czechia**, ***are mesothermal to epithermal Pb-Zn-Ag vein ores. The ores, related to the felsic magmatism of the so-called Bohemian Pluton, are of a Hercynian age. The ores have a complicated mineralogy, and are thought to have formed in multiple phases. Ore minerals are predominantly galena and sfalerite. The further away one moves from the granodiorite (exposed in a mine close to Pribram, at the***

deepest levels), the more one finds Ag-sulfosalts (proustite, pyrargyrite), arsenopyrite, and complex Pb-sulfosalts (e.g. jamesonite). Galena is often silver bearing. These ores are demonstrated in T-9A and T9-B. In T-9B the reaction of original galena to jamesonite is sometimes beautifully demonstrated.

Pribram Mining Museum.

c) Epithermal deposits

These deposits occur several km's above granitic intrusions, or in the vicinity of volcanic activity. The hydrothermal solutions can be partly magmatic, but in general the fluids are of meteoric origin. The magma body is important as a heat source. Maximum temperatures are in the order of magnitude of 300°C. The gold in solution can be of magmatic origin, or it was dissolved from volcanic and sedimentary rocks. The gold is present in solution as a bisulfide or arsenic complex.

There may be several causes for the deposition of native gold. Besides gold, often arsenic or antimony bearing minerals occur. Like for instance orpiment (As_2S_3), realgar (AsS), stibnite (=antimonite) (Sb_2S_3). If there is a lot of tellurium (Te), even gold tellurides or silver tellurides may be found, (for instance calaverite, $AuTe_2$). If there is a lot of pyrite and arsenic, the gold may also occur in solid solution in arsenopyrite or arsenic containing pyrite. This gold can only be demonstrated by chemical analysis (so-called ***"invisible gold")***

MICROSCOPY ***In specimen T-2, you find an example of native gold, deposited in veins with galena, sfalerite, pyrite, and chalcopyrite. The ore is from Sumatra, Indonesia. Sumatra was already known in ancient times for its gold deposits. Evidence are the Sanskrit names of Swarnadwīpa ("Island of Gold") and Swarnabhūmi ("Land of Gold"), due to the gold deposits of the island's highland. Even today gold is mined on Sumatra.***

The modern Way Linggo mine on Sumatra (2010)

MICROSCOPY *Specimen T-13 shows an Au-Bi-ore from* ***Tennant Creek, Australia****. According to the most current theories this ore of Proterozoic age should be placed also in an epithermal setting. Volcanic activity, related to the intrusion of the Tennant Creek granite, and concurrent with folding of the sediments and ironstones in which the veins are found, was the heat source. The hydrothermal solutions, which caused the mineralizations, may be related to granitic intrusives or volcanic activity, or they may have their origin in the dewatering of Proterozoic sediments. The possibly acid solutions leached perhaps the metals and sulfur from the sediments, and transported them to the axial zones of anticlines, which served as channels. Contact of the hydrothermal solutions with more alkali pore fluid from overlying carbonate bearing iron-rich shales resulted in the precipitation of first magnetite, and later sulfides (pyrite, chalcopyrite). Bi-sulfosalts (e.g. bismuthinite) and gold (with a high Se-content), followed as lasts minerals. Sometimes colloform textures are visible (but not very clearly), which indicates local crystallization from a gel stages. Overall temperatures were low.*

Mine shaft Museum, Tennant Creek

Tennant Creek, Location

3) Metamorphic Type

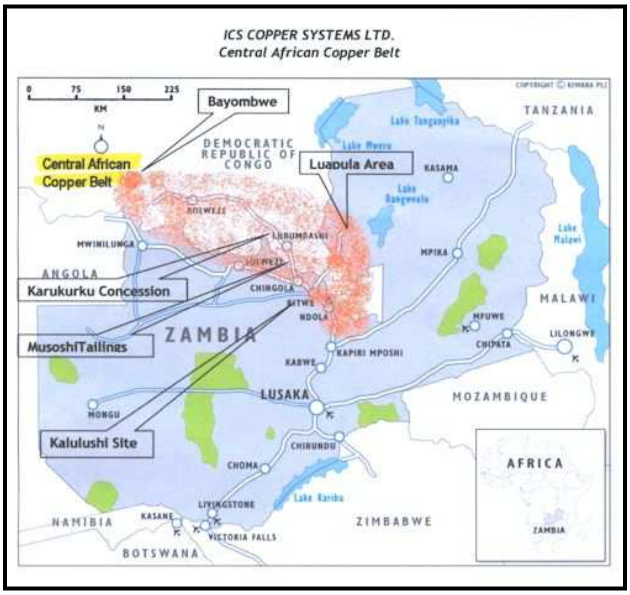
Important representatives of this group of ores are the gold bearing vein-deposits of Archaic age. During metamorphosis lower parts of volcano-sedimentary complexes were dewatered. The resulting solutions leached metals from the volcano-sedimentary complex, The solutions percolated through shear zones and rose, but did not reach the surface. The solutions came no further then regions with greenschist facies metamorphosis. Gold was present as a bisulfide complex. By reaction with iron containing country rocks, the bisulfide complexes broke down and gold and pyrite precipitated. Gold was precipitated at temperatures around 300 en 400°C. Such deposits are found in Archaean Greenstone belts: Golden Mile, Australia, and Porcupine, Ontario, Canada.
There are NO examples of this class in the training collection.

4) Seawater Type

1) ***Volcanogenic Massive Sulfide Deposits*** are formed on the seafloor, where as a result of the heat of submarine volcanism hydrothermal convective systems arise. The solutions originate mainly from seawater, and therefore contain chlorine. Temperatures can be as high as 350°C. The solutions are mainly enriched in Cu, Fe and Zn. Solutions reach the surface (seafloor) via fractures in the seafloor. By rapid cooling sulfides like chalcopyrite ($CuFeS_2$), pyrite (FeS_2) and sfalerite (ZnS) are deposited.
There are NO examples of this class in the training collection.

2) ***Stratiform deposits*** occur in sedimentary basins associated with rifting. The hydrothermal solutions are formed from the dewatering of basin sediments, or can originate from rift related magmatism. The heat of the magmatic activity is the source for hydrothermal flow. Metals are leached from the sediments through which these fluids percolate. Metals are transported as chloride complexes. Brines from shallow convection are often enriched in copper (and cobalt) Because of deposition in specific clastic sediments or marine clays, clearly stratiform deposits are formed. Ore minerals are chalcopyrite, bornite (Cu_5FeS_4), carrolite ($CuCo_2S_4$), but also tennantite, chalcocite. Examples of such deposits are found in the ***Central African Copperbelt.***

MICROSCOPY ***A sample of such an ore is found in specimen T-7 from the training collection. Here you find bornite and chalcopyrite, together with tennantite, sfalerite, and renierite*** **$(Cu,Ge)_3FeS_4$*****. The matrix contains quartz silicates and sometimes graphite. Carrolite can be found in just a few specimens.***



Central African Copper Belt

Zambian Copper Mining in the 1970's

3) With ***Sedimentary Exhalative (SEDEX)*** ores, the origin of the hydrothermal solutions is seawater which intruded basin sediments. With depth, chloride concentration and temperature increase. Convection cells are being formed, , and metals are leached from the basin sediments. When these solutions reach the sea flow, they flow out, and can gather in depressions in the seafloor. Here sfalerite and galena are deposited. Mount Isa, Australia, is an example of this class of ore deposits.
There are NO examples of this class in the training collection.

4) Another class in this group of ores is the ores of the so-called **Mississippi Valley Type**. Formation water leaches metals form sediments during dewatering, as a result of increased pressure, when the sediments reach larger depths. The metal bearing solution migrates as a result of heat of nearby magmatic intrusions. In sediments which are formed in shallow water, by reduction of gypsum and anhydrite in evaporites H_2S may be released, which leads to the precipitation of lead and zinc as galena (PbS) and sfalerite (ZnS). The deposits are stratiform. They are named after deposits in the valley of the Mississippi.
There are NO examples of this class in the training collection.

C) URANIUM ORES

Such ores occur where 6-valent uranium is reduced of a 4-valent state. In a natural environment this occurs by pyrite, organic material or graphite. Uranium precipitates as uraninite. ***There are NO examples of this class in the training collection.*** (Not allowed, because of radiation safety measures).

D) AUTOCHTONOUS ORES

This is about ores which are formed by selective precipitation in specific sedimentary or weathering conditions. The processes take place under atmospheric temperatures and pressures. Separation of the metals takes place as a result of differing solubilities in aqueous environments. These solubilities are caused by eH and pH conditions.

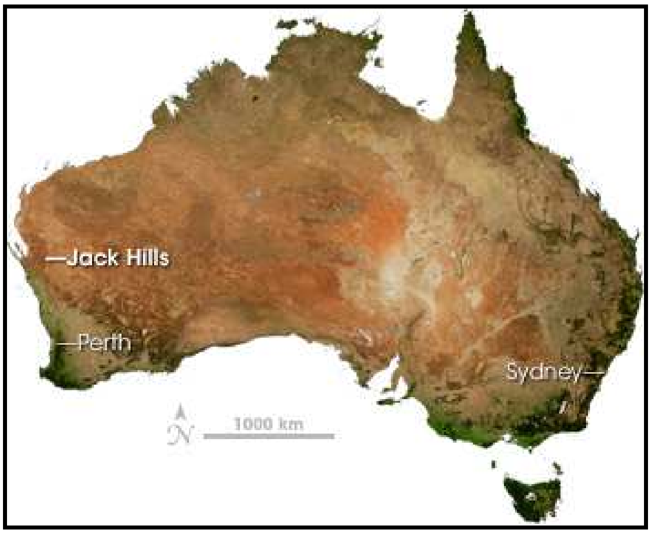
1) Seawater Deposits

a) Iron Ore Deposits

Well-known are deposits from shallow seas from the Proterozoic, called

"Banded Iron Formation" (BIF). Specific for seawater deposits is the so-called Oxide Facies of the BIF. Precipitation took place over large areas along continental margins along shifting shorelines. This oxide facies consists of a variation of Fe-oxide (magnetite, hematite) layers and chert. In the deposits seasonal variations are present. Iron and silica were supplied by nearby landmasses. Iron and silica were also supplied by exhalation of seawater which was forced through basin sediments as a result of convection processes. Iron was leached from the sediments. Later supergene enrichment was possible by oxidation of magnetite to hematite. Remobilization of iron could take place flowed by precipitation as goethite. Later the deposits reached again a certain depth..

MICROSCOPY ***A microscope sample of Precambrian iron ore, originally deposited in seawater can be found in specimen T-19. The iron ore of T-19 is a high grade detritic iron ore. The original ore was eroded, and re-deposited. This ore, from the*** **Jack Hills** ***in*** **Australia** ***comes from a region that belongs to the oldest parts of the Earth's Crust. Age determinations on zircons from rocks in the Jack Hills gave an age of 4½ billion year (!)They are the tough remnants of ancient rocks that have long since disappeared.***

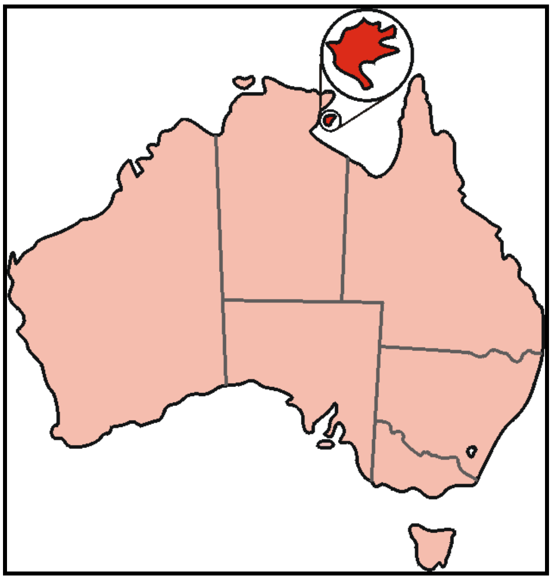


Jack Hills, Location

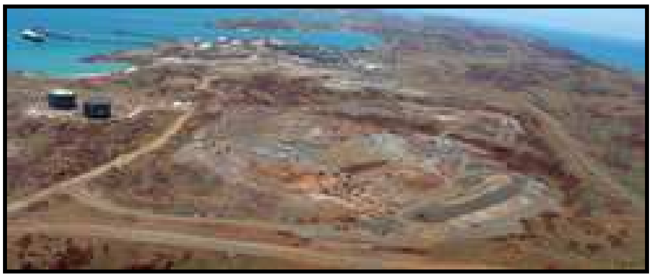
Jack Hills mine , Australia

b) Manganese ore deposits

This concerns shallow deposits in marine sediments and estuary sediments. They are deposited during periods of marine transgression are high sea levels . Mn often originates from Precambrian rocks with low Mn-contents. This Mn is liberated by weathering processes, and transported to the sea. This happened also for Fe. Certain chemical conditions (low eH) lead to different behavior for Mn (soluble) and Fe(insoluble). Fe and Mn were separated. Seawater in partially closed basins can be stratified, leading to parts with relatively high eH, and parts with relatively low eH. These waters mix not or almost not. (Cf. the Black Sea). Where these waters reach the shoreline, manganese deposits form, with Mn predominantly in the form of pyrolusite (MnO_2). When these ores reach higher eH-conditions, pyrolusite is insoluble. This gives rise to Mn-deposits with primarily pyrolusite. Examples Nikopol, Ukraine, Groote Eylandt, N-Australia.



Groote Eylandt, Australia.



Manganese mine, GEMCO, Groote Eylandt, Australia.

MICROSCOPY ***An example can be found in T-12, where an oölitic Mn-ore from India is shown. Mn is mainly present as pyrolusite, but also as psilomelane[2]. You will also find later formed goethite, precipitated under higher eH conditions.***

Pyrolusite

MICROSCOPY ***Also, you find in T-12 an example of a piece of material of a manganese nodule. Manganese nodules are well known from the* Pacific Ocean*, where they have been often found during dredging. As there is few land surface that can serve as a source for manganese, the metal must be almost entirely originated from volcanic activity. The manganese is generally present in the form of Mn-oxides or Mn-hydroxides. The size of the nodules is 1- 30 cm, with an average of 3cm. In size, they are generally comparable to potatoes.***

Manganese nodule and potatoes.

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[2] *Discredited Mineral, 1982. Now a general term for hard, black Mn-oxides. Romanechite,* $(Ba,H_2O)_2(Mn^{4+,}Mn3^{+})O_{10}$*, is one of the most common species.*

Manganese nodules, contain, in contrast to the ores discussed above, appreciable amounts of iron.

2) Evaporites

Evaporites are precipitates of salts which under normal conditions are soluble in sea water or lake water. The most common form is rock salt or NaCl. Evaporites form there where

- A water mass is not completely open to the sea
- The climate is such that natural evaporation exceeds rainfall.

In marine environments deposits are formed of for instance rock salt (NaCl), sylvite (KCl), gypsum/anhydrite, calcium carbonate etc. In continental environments one may find minerals like borax ($Na_2O.2B_2O_3.10H_2O$) and colemanite ($2CaO.3B_2O_3.5H_2O$).
There are NO examples of this class in the training collection.

3) Supergene Deposits

a) Bauxites

Bauxites are the residues of weathering of aluminum rich volcanic or intrusive rocks. Conditions for bauxite formation are:

1) Warm tropical climate
2) Alternating dry and wet season
3) Softly undulating relief
4) Good downward drainage

Decaying vegetation supplies the percolating groundwater of organic acids. Feldspars are decomposed and altered into clay minerals. Residual clay gradually is altered into amorphous aluminum hydroxides, generally gibbsite. During the dry season the metastable amorphous gibbsite recrystallizes into stable crystalline gibbsite.
There are NO examples of this class in the training collection.

b) Lateritic Ni-ores

This concerns weathering products of Ni-bearing olivine. Olivine is easily hydrolyzed by hydrothermal or meteoric waters. An early weathering product is serpentine. Parent rocks are peridotites and related ultramafic rocks. Olivine from ultramafic rocks contains generally some nickel. Soluble Fe and Mg are transported by rainwater. Iron soon precipitates as goethite (FeOOH) or limonite (FeOOH .nH_2O). Some Ni^{2+} adsorbs onto goethite, but the most of the Ni reacts with serpentine, forming garnierite[3] ($Ni_3Si_2O_5(OH)_4$).

Laterite Nickel Mining

c) *Gossan*

The weathered leached oxidic residues of (often, but not always) sulfidic ore deposits are called gossans. Gossan is usually a hard ferricrete horizon. Also they can be weathering products of oxidic iron ores. ***Gossans themselves are NOT considered ore, but are important indicators for ore deeper under the surface.***

MICROSCOPY ***In the training collection, you can find in T-10 an example of a*** **gossan** ***from Zambia, in which the original minerals (magnetite, hematite) but also the weathering products (goethite & limonite) are visible. Goethite and limonite*** **cannot** ***readily be distinguished under the microscope.***

E) ALLOCHTONOUS ORES

Due to erosion, the land surface is slowly worn down. During transport mineral particles undergo sorting, and often also a size reduction. The sorting is a result of the working of gravity. When the mineral is less resistant against mechanical weathering, the grain size will also slowly decrease. Zones of weakness, such as cleavage planes may be very important in size reduction. Minerals without cleavage and great hardness often are not much reduced in

---

[3] *Garnierite (formerly $Ni_3Si_2O_5(OH)_4$) is a discredited mineral. It is now a generic name for green nickel ore, which has formed as a result of lateritic weathering of ultramafic rocks.*

size during the transport process. During sorting, density and grain shape are important. Sorting may lead to formation of economically interesting mineral deposits. The minerals almost always share the following properties: high density, no or almost no cleavage, and chemical stability under weathering conditions. Minerals with these properties are oxides, ore oxidic minerals (e.g., phosphates), native metals and some silicates.
Examples are for instance ilmenite, zircon, chromite, diamond, and rutile. Also quartz is sometimes concentrated in this way. The deposits are formed as a result of the action of sea currents or of rivers. Such deposits are called alluvial deposits or placer deposits.

F) INDUSTRIAL MINERALS.

The definition of industrial minerals (and industrial rocks): mineral resources which are used because of their chemical or physical properties, and not to extract metals from them. In this category we find for instance clay, limestone, dolomite, ilmenite, rutile, and zircon.

Ilmenite and zircon occur usually in igneous rocks but are in general only available in economically interesting amounts in placers or in beach sands. Quartz, a common rock forming mineral, may in a barrier beach become thus concentrated, that the deposit is fit for economic winning of quartz for the production of silicon or of sand for glass manufacture.

Quartz-sand quarry of Sigrano, Heerlen, The Netherlands.


Zircon grains.

Below you will find a list of minerals that are found in placers and minerals that are considered industrial minerals.

Some placer minerals and industrial minerals.

Mineral	**Formula**	**Application**	**Occurrence**
Ilmenite	$FeTiO_3$	TiO_2 (white pigment), also for production of Ti.	As segregation in basic igneous rocks, or as accessory mineral Winning in general from fossil beach sands.
Zircon	$ZrSiO_4$	Used as such, but also ore mineral for the extraction of Zr. Also a semiprecious stone.	Accessory mineral in granite. Mined from placers.
Rutile	TiO_2	Used as such (white pigment, Ultraviolet absorber). Also ore mineral for the winning of Ti.	Accessory mineral in felsic rocks. Mined from placers and fossil beach sands.
Monazite	$(LREE,Th)(PO_4)$	winning of REE, sometimes Th.	Accessory mineral in felsic rocks., or in relation to carbonatites. Mined from placers and fossil beach sands
Xenotime	$(Y, REE, U)PO_4$ REE = Sm, Gd, Eu, Er, Dy	winning of Y, REE.	Accessory mineral in felsic rocks. Mined from placers and fossil beach sands.
Quartz	SiO_2	Glass production, production van Si.	Mined from placers and fossil beach sands.

Dolomite	$CaMg(CO_3)_2$	Glass manufacture, Chemical industry.	Dolomitic limestone, dolostone.
Apatite	$Ca_5(PO_4)_3(OH,Cl,F)$	Production of phosphorus or phosphorus-compounds.	Sediments (Phosphorites).
Calcite	$Ca(CO_3)$	Lime, cement.	Limestone.

MICROSCOPY ***Several placer minerals can be studied in specimen T-14. Many of the above mentioned industrial minerals, however, are better studied with a transmitted light polarization microscope, as they are not opaque.***

3. TEXTURES IN ORES AND ORE MINERALS

The study of minerals and rocks requires more than just the identification of the minerals present. Also the interpretation of the textures, which are the special relationships between mineral grains, is important. The interpretation of textures is not only one of the most important aspects of the study of ores and rocks, but also one of the most difficult. The textures in rocks give a lot of information about the nature of processes, such as initial ore formation, but also re-equilibration after deposition or metamorphosis, deformation, annealing, or weathering as a result of meteoric influences.

However, the extent to which minerals retain their original composition and texture varies to a great deal. The nature of the mineral, temperature, and reaction kinetics are of course important parameters. It appears from research that oxides bisulfides, sfalerite and arsenides are the most refractory with respect to re-equilibration. At the other end of the scale we find minerals like argentite (Ag_2S) and sulfosalts[4]. Pyrrhotite ($Fe_{1-x}S$) and the Cu-Fe-sulfides (chalcopyrite $CuFeS_2$, and bornite Cu_5FeS_4) are approximately halfway this scale. However, crystals formed from a melt, may with changing melt composition during cooling become partly resorbed. This can be observed in the training collection in T-4 in somewhat rounded crystals of primary magnetite.

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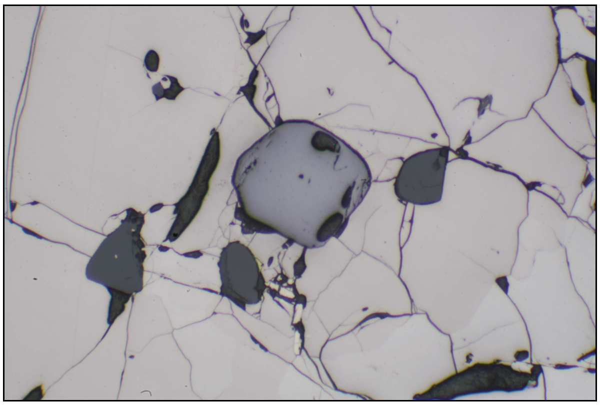
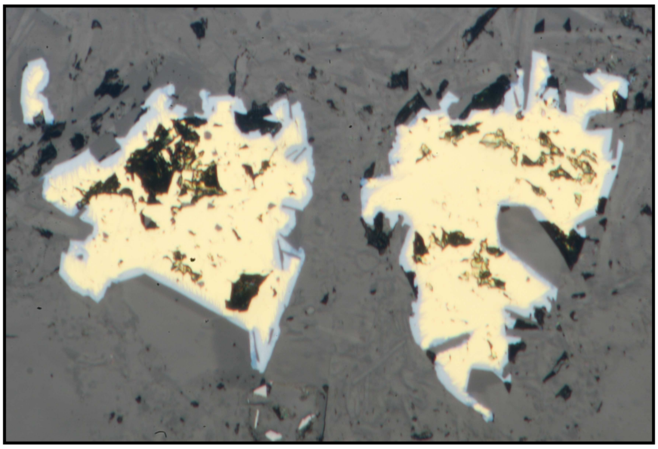
[4] *A sulfosalt is a compound containing sulfur (S) and As, and/or Sb, or Bi. Examples are orpiment,* As_2S_3*, realgar, AsS, bismuthinite,* Bi_2S_3*, tennantite,* $Cu_{12}As_4S_{13}$*, tetrahedrite,* $Cu_{12}Sb_4S_{13}$.



Rounded crystal of magnetite as a result of resorption. Specimen T-4.

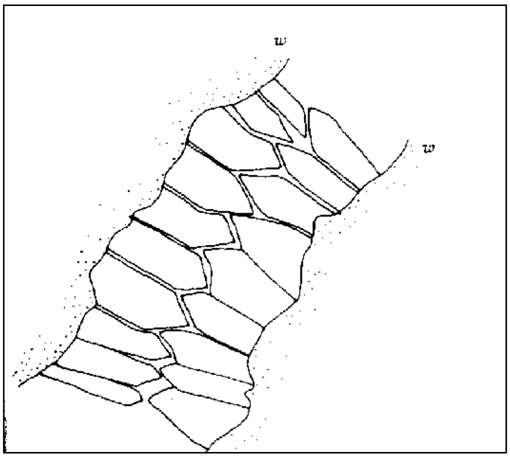
Textures, mineralogy and composition of minerals or solid solutions mirror often several stadia in the history of the ore or rock. For instance, in a polymetallic ore pyrite, pyrrhotite, sulfosalts and native metals may occur. The morphology and inclusion patterns of the refractory pyrite may reflect initial HT-conditions, whereas the coexisting pyrrhotite has equilibrated at medium temperatures during a cooling phase. Sulfosalts may have equilibrated until the lowest temperatures. Finally, weathering processes may have superimposed textures on top of these. An example of a very complicated texture, which shows different stages of formation, is shown in specimen T-5. Also T-9b shows sometimes beautiful examples of reactions textures. Here the original galena, has reacted (sometimes not completely) to jamesonite. Original features of the galena are visible.

Interpretation and recognition of textures may also provide information with respect to the recognition of certain minerals. Chalcopyrite ($CuFeS_2$) often is altered to covellite (CuS) or digenite (Cu_9S_5). The blue covellite and digenite in minuscule grains may be difficult to identify, if one is restricted to measurement of reflection. Knowledge of the alteration reactions offers the possibility for identification with only minimal optical inspection (anisotropy, interference colors with crossed polars). Digenite is isotropic, and covellite is extremely anisotropic and has vibrant interference colors (red/orange). The difference is easily seen. Another example is pentlandite ($(Ni,Fe)_9S_8$), which often alters to violarite $(Ni, Fe)_3S_4$. This is certainly a reason to look in pentlandite crystals, which show some sign of alteration, for violarite.

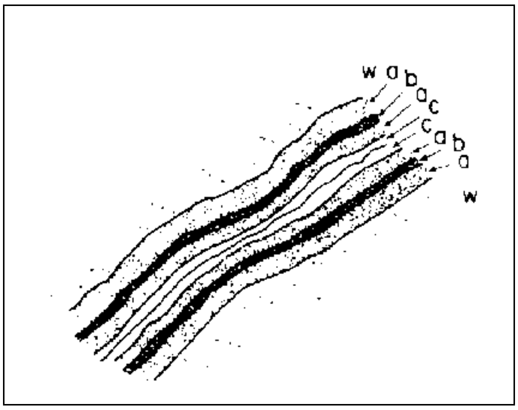


Blue (isotropic) digenite replacing chalcopyrite (yellow) at the rims, Los Bronces Mine, Chile.
Width of field 0.37 mm.

The figure below shows the growth of crystals from the walls of the crack into the fluid, leading to euhedral crystals. Crystallization as a result of changing fluid composition may lead to rhythmic banding.



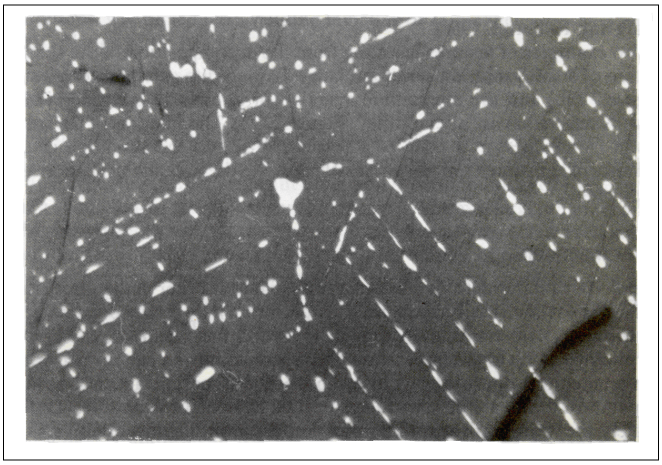
Crystals grow from the wall of a fissure
into the fluid. After Craig and Vaughan (1994).



Rhythmic banding in a vein. After Craig and Vaughan (1994).

In the training collection specimen T-12 shows growth of crystals of lithiophorite from the rims of cavities into the once open voids, which are now filled with resin.

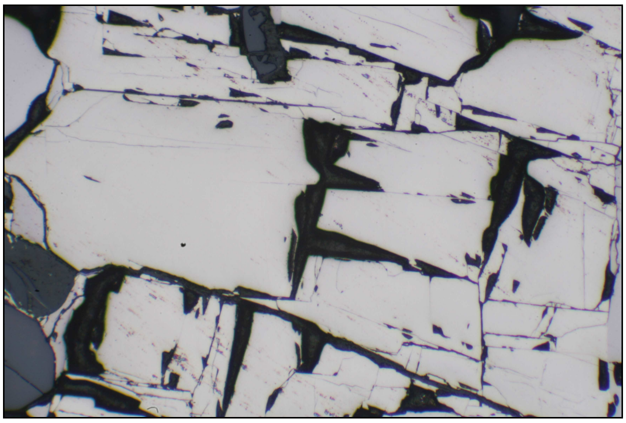
Sometimes textures may be misleading. A well-known example is the occurrence of oriented blebs of chalcopyrite. This seems to indicate demixing of chalcopyrite from sfalerite., but research indicated that the possibility of HT-solid solution of chalcopyrite in sfalerite is rather limited. Possibly the texture is the result of epitaxial growth of chalcopyrite nuclei on sfalerite surfaces, or it may be a replacement texture. .



Oriented blebs of chalcopyrite in sfalerite. The oriented blebs are NOT the result of demixing. (After Craig and Vaughan, 1994).

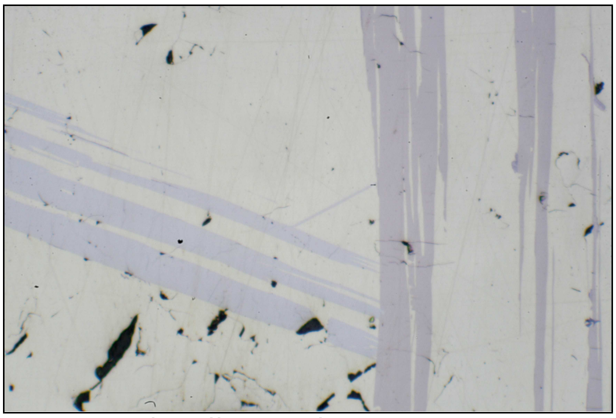
Although demixing is well known from metallurgical systems, it is a rather rare phenomenon in mineralogy. An example of demixing is the occurrence of magnetite lamellae in ilmenite. This is however more complicated than it seems, as it appeared from research that the amount of magnetite-ilmenite solid solution at high temperatures is rather limited. But is not ilmenite that is the original phase, but ulvöspinel. On cooling the ulvöspinel may exsolve magnetite, while the ulvöspinel itself later oxidizes to ilmenite.

Most minerals have approximately the same thermal expansion coefficient, but this is not always the case. Pentlandite is an exception. On cooling pentlandite shrinks more than pyrrhotite and pyrite, with which is usually occurs together. Pentlandite upon cooling acquires opening fractures along its cleavage planes, leading to a somewhat crumbling appearance. See for instance the specimens T-4 and T-8 in the training collection.



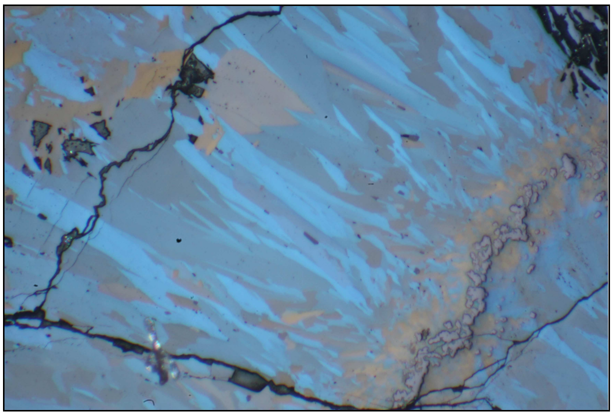
Opened cleavage planes of pentlandite. Specimen T-4

Some minerals may exhibit twinning. Twinning may be enhanced in such minerals by deformation. In the training collection this is apparent in specimen T-8, where ubiquitous twinning of cubanite may be observed.



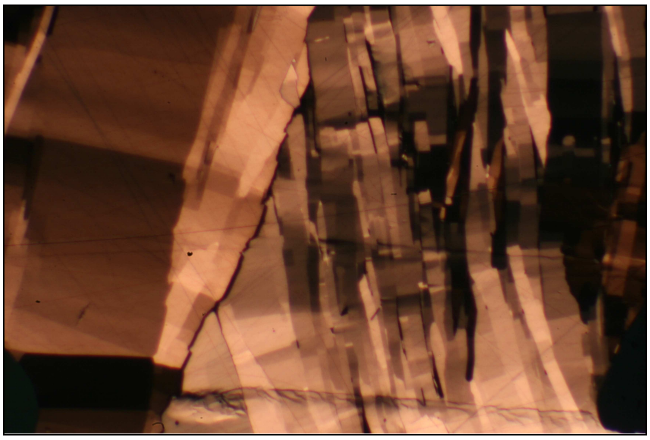
Twinning lamellae in cubanite. Specimen T-8.

A clear example of deformation twinning is given in the image below, which shows deformation twinning lamellae in loellingite (Training collection T-6). The lamellae in deformation twinning are often irregular, but this is not necessarily the case.



Deformation twinning in loellingite. Specimen T-6.

Deformation of minerals may lead to unduleus extinction or unequal distribution of interference colors. This can clearly be observed in the covellite crystals of specimen T-3.



Unequal extinction and interference colors in covellite. The alternating, zonal change of the interference colors is due to deformation. Specimen T-3.

4. REFERENCE

Craig, J.W. and Vaughan, D.J. (1994) *Ore Microscopy and Ore Petrography. 2nd edition, John Wiley and Sons, New York. 434 pp.*

5. OVERVIEW OF THE ORES OF THE TRAINING COLLECTION

Sample	Type of Ore/Association	Description / Information
T-1	Mesothermal Pb-Zn vein ore. Casapalca, Peru.	page 11
T-2	Epithermal Au-ore, Sumatra, Indonesia.	page 13
T-3	Meso / Epithermal Cu-ore Bor, Serbia.	page 12
T-4	Magmatic Cu-Ni ore, Sudbury, Canada.	page 7
T-5	Hydrothermal Sn-ore, greisen association, Panasqueira, Portugal.	page 9
T-6	Hydrothermal Ni-Co-As vein ore Cobalt, Canada.	page 9, 10
T-7	Stratiform Cu-Co-(Ge) ore, Congo	page 15, 16
T-8	Magmatic Cu-Ni ore, Sudbury, Canada.	page 8
T-9A/B	Hydrothermal Ag-Pb-Zn ore, Pribram Czechia.	page 12
T-10	Supergene Fe-ore, Zambia	page 22
T-11	Magmatic Cr-ore, Philippines	page 7
T-12	Sedimentary Mn-ore, India en Mn-nodule, Pacific	page 18 - 20
T-13	Hydrothermal Au-Bi ore, Tennant Creek, Australia	page 13, 14
T-14	Placer minerals	page 24
T-15	Industrial material.	page 67
T-16	Industrial material: Iron ore pellet and sinter Tata Steel, IJmuiden.	page 66, 67
T-17	Polished sections of a milled Pb-Zn-ore, Meggen, Germany.	page 65, 66
T-18	Hydrothermal Sn-ore, greisen association, Indonesia.	page 9
T-19	Iron ore, Jack Hills, W-Australia	page 17
T-20	Chrome-ore, Rustenburg, South Africa	page 17

6. THE CHEMICAL FORMULAS OF SOME COMMON OPAQUE MINERALS

The formula given below is an ideal formula.

Mineral	**Chemical formula**	**Remarks**
Anatase	TiO_2	Polymorph of rutile
Arsenopyrite	$FeAsS$	
Bornite	Cu_5FeS_4	
Cassiterite	SnO_2	
Chalcopyrite	$CuFeS_2$	
Chalcocite	Cu_2S	
Chromite	$FeCr_2O_4$	
Covellite	CuS	
Digenite	Cu_9S_5	
Galena	PbS	Name originates from Latin. The Latin word is possibly derived from Etruscan
Goethite	$FeOOH$	
Hematite	Fe_2O_3	
Ilmenite	$FeTiO_3$	
Loellingite	$FeAs_2$	Name also spelled as löllingite
Magnetite	Fe_3O_4	Formula also written as $FeFe_2O_4$. Most known magnetic mineral
Marcasite	FeS_2	Polymorph of pyrite
Molybdenite	MoS_2	
Nickeline	$NiAs$	In the past known as niccolite
Pentlandite	$(Fe, Ni)_9S_8$	
Pyrite	FeS_2	Polymorph of marcasite
Pyrrhotite	$Fe_{1-x}S$	May exhibit magnetic properties, depending on the exact composition
Pyrolusite	MnO_2	
Rammelsbergite	$(Co, Ni, Fe)As_2$	
Rutile	TiO_2	Polymorph of anatase
Scheelite	$CaWO_4$	
Sfalerite	ZnS	Polymorph of wurtzite
Tennantite	$Cu_{12}As_4S_{13}$	Complete solid solution with tetrahedrite
Tetrahedrite	$Cu_{12}Sb_4S_{13}$	Complete solid solution with Tennantite
Ulvöspinel	Fe_2TiO_4	
Wurtzite	ZnS	Polymorph of sfalerite
Wuestite	$Fe_{1-x}O$	Name also spelled as wüstite

Ore Mineralogy and Ore Microscopy TA3196

Part II

Microscopy practical

1. INTRODUCTION

To determine the composition of an ore or raw material, a simple chemical analysis is not enough. To make a scheme for the technological processing of an ore, one must study the material using different approaches. One of them is microscopical study. Many ores and intermediate products consist of opaque phases, which make transmitted light microscopy impossible. In this course Ore Mineralogy and Ore Microscopy we shall learn how to work with a reflected light polarization microscope ("ore microscope"), and how this microscopy technique can be applied.

In the study of ores, a number of questions can be answered by microscopic study>

1) Which phases are present ?
2) How much valuable material is present and in which phases is it present ?
3) What is the grain size, and what is the shape of the grains ?
4) How is the intergrowth of coexisting phases ?
5) What are the shape, size and distribution of pores (if present) ?
6) What is the spatial distribution of important phases, with respect to later liberation ?
7) In case of liberation: are the desired particles liberated or not in a specific milling step?

Usually, in combination with microscopy also micro-analysis (electron microprobe) and quantitative image analysis is used. With electron microprobe of very small grains a qualitative or quantitative chemical analysis can be made. With quantitative image analysis microtextures can be analyzed.

2. SAMPLE PREPARATION

The microscopical investigation of opaque minerals is done with polished sections or polished thin sections. There are several steps in the making of a polished section:

- Cut a small part from the original sample. Is this part representative ?
- Immerse in resin
- Grind off the immersed sample
- Polishing of the ground sample

Some materials (soft materials, porous materials must be impregnated before cutting, grinding and polishing. In Appendix I it is described in detail how a polished sample is made. During the practical you will make a polished section yourself.

The surface of a finished polished section that has not been used for a longer time must be cleaned before use. Usually, short repolishing is sufficient to remove dirt, traces of oxidation, etc. Before microscopic inspection the surface should be cleaned with alcohol.

Only clean, well-polished section will lead to good results. The polished section must be pressed into modeling paste with a straightening press. Perfect vertical reflection of the incident light beam is only achievable with a perfectly horizontal specimen
.

3. THE REFLECTION POLARIZING MICROSCOPE

A. GENERAL

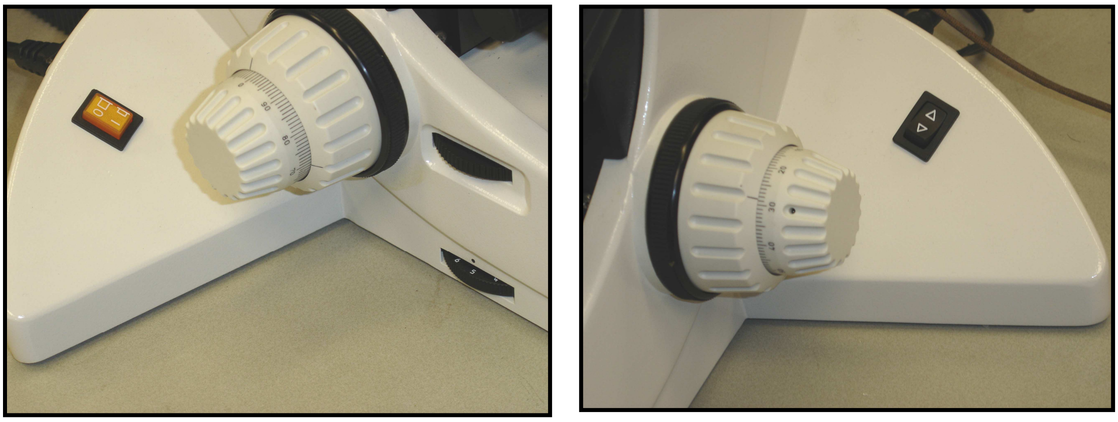
Polarization microscopy in reflected light microscopy differs in a number of things with polarization microscopy in transmitted light, but there are also similarities. This will be treated in another section.

Nowadays, microscope objectives are the same for transmitted and reflected light microscopy. With reflective microscopes used for determination of ore minerals a photo-electric ceil is placed on top, which can be inserted into the light beam when desired. The cell is connected to a millivolt meter. This is necessary to distinguish the different minerals In principle, reflection should be measured at one specific wavelength, (e.g. 540 nm or 650 nm), because for most minerals the reflection is dependent on the wavelength (dispersion). For identification of the most relevant ore minerals, it is sufficient to measure the reflection of the microscope lamp without any filter (meaning without daylight filter). The reflection value so measured matches the one of 540 nm.

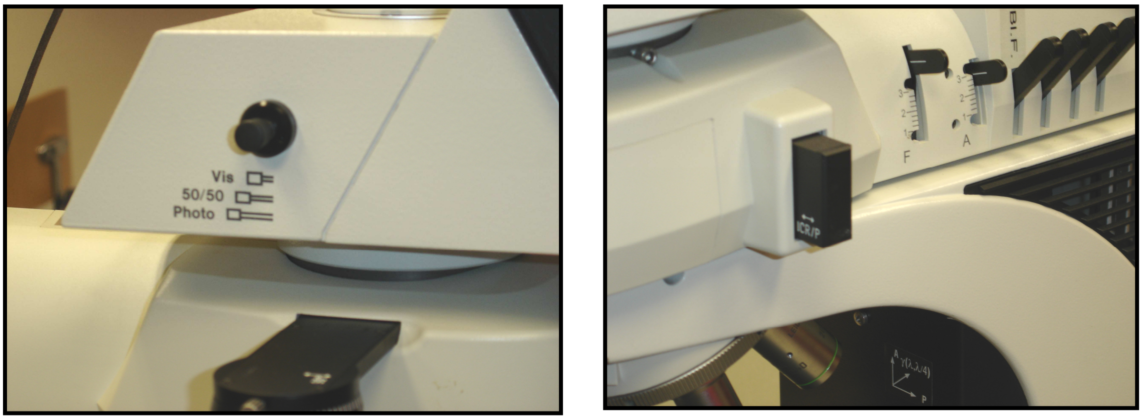
B. SHORT INTRODUCTION OF THE DM-LP MICROSCOPES

Below the operational items of the microscope will be described in brief.

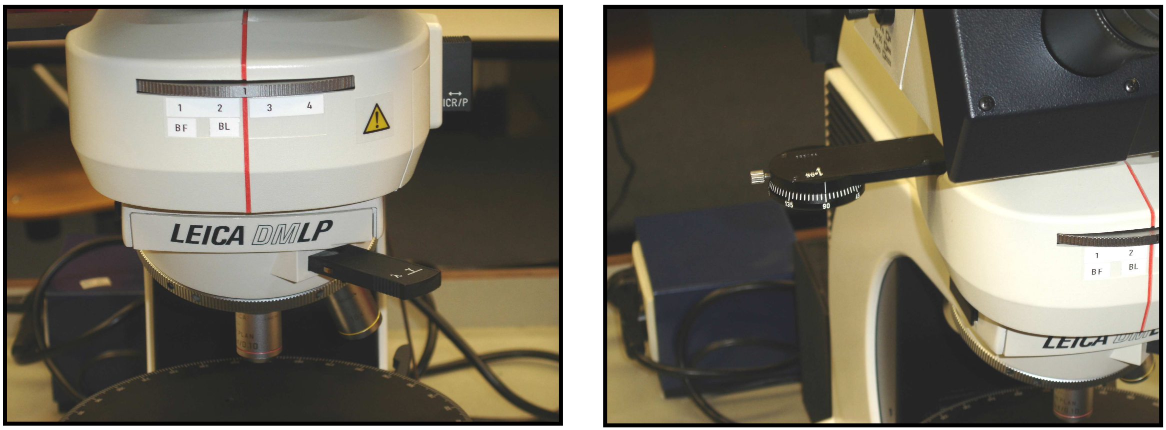
Overview of the microscopes.



Left photograph: the on-off switch of the transformer (orange) the control of the transformer (lower rotary knob). Right photograph: the switch for transmitted light and reflected light. Up = reflected, down = transmitted light. On both photographs: the focusing rings (coarse is outer one, fine is inner one), and the black rings for interlock of the microscope table, and the skid resistance of the focusing controls. **The black rings must not be turned.**



Left photograph: the sliding switch for optical image (position VIS) or measurement of the reflection (position Photo) Right photograph: the polarizer. This should always be switched ON. The photograph to the right shows the field diaphragm (sliding switch F) and aperture diaphragm (sliding switch A), and Daylight filter or Blue filter (switch BF). The diaphragms are completely open when the switch is in the top position. The blue filter is in if the switch is in de top position. The other switches have no function.



Left photograph: the selector ring for Bright Field (BF) or Bertrand Lens (BL). The ring should always be on BF. The quartz plate selector below left should not be inserted. Right photograph: the adjustable analyzer.

To start with the microscope, proceed as follows:

- Position the adjustor ring of the transformer in the lowest position.
- Switch the microscope on (orange button).
- Put all diaphragms in the open position (sliding switches to top position).
- Put the front selector ring in position BF.
- Put the analyzer in the 90° position.
- Turn the table that far to the down position that a specimen on a glass plate can be positioned under the objective lenses.
- Put the 10x objective lens in position (turn with the revolving objective-holder, NEVER touch the objective lens !!)

The adjustment of the binocular part will be discussed on the first practical session. In principle this needs to be adjusted only once.

To make an image through the microscope put the adjustor ring of the transformer at position 5 – 6.

For normal microscopy you will use the objectives with magnification 10x, 20x en 50x. In order to get a quick overview of the specimen, or to find again a certain location in the specimen, you may use the 4x objective lens. For measurement of the reflection the adjustor ring of the transformer should be put in the maximum position.

ATTENTION: If you have measured the reflection, first put the transformer in the normal position.

C. OBJECTIVE LENSES

In a reflection microscope the objective lens also functions as a condenser. Objectives differ not only by their magnification but also by their immersion medium. The maximum size of the light cone determines the resolution, the smallest distance between two points that can be focused. The size of the light cone is not only determined by the objective lens, but also by the refractive index of the immersion medium. This is expressed by the definition of the Numerical Aperture (NA). This quantity is a measure for the resolution and determines the depth of focus. The formula is:

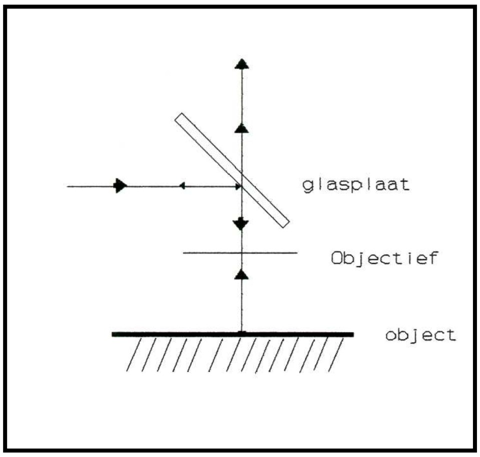
$$\boxed{NA = n \sin \alpha}$$

Here NA is numerical aperture, n is the refractive index of the immersion medium, and α is the half of the top angle of the light cone. The numerical aperture is always marked on the objective lens, usually combined with the magnification: for instance 10/0.20 for a 10x objective lens.
Objective lenses are made for use in air or immersion oil The refractive index of air is 1.0, the refractive index of the commonly used oil is 1.5180. In the past, sometimes also water was used: n=1.33.
Most observations with a reflective polarizing microscope are carried out in air, but sometime oil is used, especially at very high magnifications. Oil-immersion objective can be recognized by a black ring and the word “Oil”.

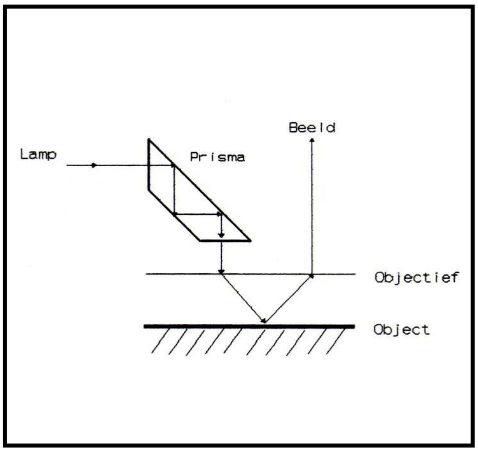
The microscopes in the practical classes have 4 objective lenses: 4x/0.10, 10x/0.20, 20x/0.40, 50x/0.85. They are all for use in air.

D. OPAQUE ILLUMINATOR

The opaque illuminator (see figures) is probably the most typical part of the reflection microscope. This device directs the light beam downward onto the specimen, and leads the reflected light beam upward into the optical system, where ultimately it arrives in the ocular lenses.

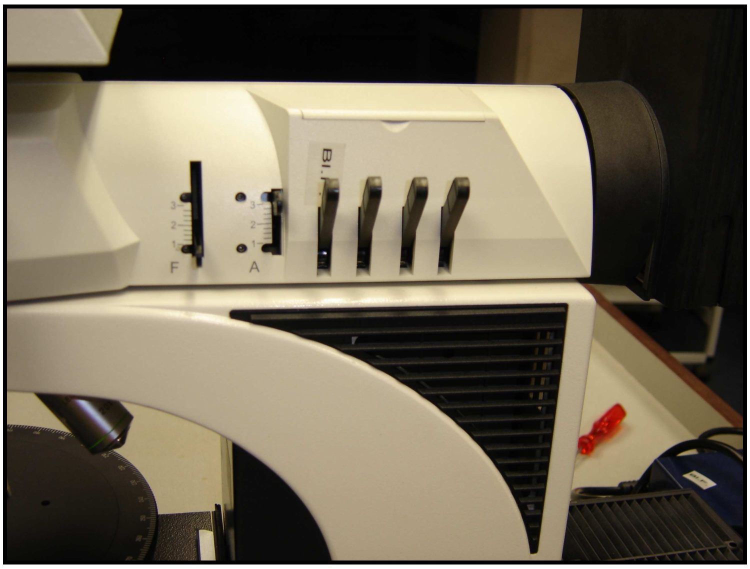


Schematic drawing of the opaque illuminator, consisting of a two-way glass



Schematic drawing of an opaque illuminator consisting of a Berek prism.

The opaque illuminator may consist of a two way mirror, or consist of a special prism (Berek prism) Many research microscopes have both possibilities. The microscopes used at the practical only have a two way mirror.



From left to right: Field diaphragm (F), Aperture diaphragm (A), and Blue filter (BL.F.) The other three switches have no function.

A diaphragm is open if the switch is in the upper position. The Blue Filter is in if the switch is in the upper position.

E. DIAPHRAGMS

The aperture diaphragm (A) controls the parallelism of the ray beam that illuminates the specimen. The ray beam actually is a light cone of which the top angle is determined by the aperture diaphragm,

The aperture diaphragm is imaged onto the innermost focal plane of the objective lens. When the diaphragm is open, the top angle of the light cone is at its maximum for the objective lens in use. When closed, the top angle is at its minimum. The smaller the top angle, the larger the contrast, but the smaller the resolution.

The field diaphragm (F) is imaged in the outer focal plane of the objective lens. With the field diaphragm, a part of the field of view, which is not of interest, can be covered. Stray light is eliminated. This is especially important when measuring the reflection. Also it may be used to judge if a mineral grain exhibits, or if the grain is isotropic.

F. FILTER(S)

To filter the light of the lamp, so that the spectrum resembles that of daylight, a filter is used. This is the blue filter or daylight filter. For measurements at specific wavelengths, a monochromator can be used, but also interference filters can be applied (e.g., 546 nm, or 485 nm). For the latter filters, a strong illumination (halogen lamp) is necessary, in order to get a sufficient clear image.

G. POLARIZER/ANALYZER

The polarizer and analyzer have of course the same function as in transmitted light microscopy, but there is a difference in the construction. The analyzer of the reflection microscope by default can be turned over 90°, in contrast with the analyzer of a transmitted light microscope. Rotating the analyzer is important in determining weak anisotropy. In the table below the different settings of the microscope for different observations is summarized.

Adjustment of the microscope for different applications and observations. LM = low magnification, MM = middle magnification, HM = high magnification, P= polarizer, A = analyzer, AD = aperture diaphragm, FD = field diaphragm, "+" = switched on, "-" = switched off.

	P	**A**	**Objective lens**	**Filter**	**AD**	**FD**	**Remarks**
Color/ pleochroism	+	-	*LM*	+	*open*	*open*	*Turn the table.*
Anisotropy (interference colors)	+	+	*LM, MM*	-	*open*	*open*	*Check a lot of grains.*
Internal Reflections	+	+	*LM, MM*	-	*open*	*Open or closed*	*Check a lot of grains. Maximum illumination.*
Polishing Harness	+	-	*MM, HM*	+	*closed*	*open*	
Reflection/bi-reflection	+	-	*LM, MM (HM)*	-	*open*	*closed*	*Check a lot of grains.*
Texture, structure	+	+/-	*LM, MM, HM*	+	*open*	*open*	*If necessary, use a micrometer. Oil immersion for small intergrowths.*
Twinning	+	+	*LV, MV*	-	*open*	*open*	*Turn the table.*

4. MICROSCOPICAL DESCRIPTION OF OPAQUE MINERALS

In this chapter we will pay attention to a series of parameters, which can be determined with the polarization microscope. Also an overview is given which optical properties are important for the determination of opaque minerals. An elaborate treatise of the optics of reflected light microscopy is beyond the scope of this manual. In Appendix 6 a short overview is given. If more information is needed, this can be found in the works cited in the literature. Considering the work in practice, one can subdivide the microscopical determinable features in 2 groups, based on the use or not use of the analyzer.

Observations with parallel polars

- *Color and reflection pleochroism*
- *Reflection and bireflection*
- *Morphology of crystals, cleavage, zoning, texture.*
- *Polishing hardness.*

Observations with crossed polars

- *(An)isotropy*
- *Internal reflections.*

A. OBSERVATIONS WITH PARALLEL POLARS

1. Color and reflection pleochroism

The explanation why a mineral has a color under the reflection microscope is related to reflection. The intensity of reflected light from a polished surface not necessarily is the same for every wavelength. When white light is used, some wavelengths may be more strongly reflected than others. This may result in a noticeable color. Sometimes the color is very strong. The colors of ore minerals in general are weak to very weak.

The human eye functions better with respect to the registration of contrast (comparative situations) then with respect to absolute color values. This results in the phenomenon that the color perception of a mineral may be influenced by the surrounding minerals. Perception of color is, however, strongly depending on the person, and there may be differences between the color as perceived by different people. Also the description of the color may be expressed different by different people (for instance yellowish white, beige, vivid white, brownish white, etc. may all be a description of the same shade of white). Color sensation is also dependent on the illumination used. Illumination and light optics also change with microscopes (make, alignment, etc.).

However, a large number of colors may be identified by many people unambiguously, so color may be used as a selection criterion.

Examples of strongly colored ore minerals: chalcopyrite (greenish yellow), covellite (bluish colors) nickeline (pinkish orange), bornite (orange, brown or pink), renierite (orange), digenite (light blue).

Examples of weakly colored ore minerals: chalcocite (bluish grey), sfalerite (grey), pyrite (yellowish white), magnetite (brownish grey, grey, brown).

For anisotropic minerals the reflection of light of a specific wave length may be depending on the orientation of the crystal. Color differences may be observed depending on the orientation: ***reflection pleochroism.*** Reflection pleochroism occurs always together with bireflection. Where in the following reflection is mentioned, always reflection pleochroism is meant.

Some examples of pleochroitic minerals are: covellite, molybdenite, pyrrhotite, cubanite, proustite.

2. Reflection

The intensity of the *reflection (R)* may be measured with a photo-electric cell and a millivolt meter. The intensity of the reflection may vary with the orientation of the mineral grain. This change of reflection with orientation may be used for identification. The maximum difference in reflection that can be measured on a mineral is called the *bireflection (ΔR).* ***Minerals with a noticeable bireflection are anisotropic.*** By the way, the bireflection not necessarily results in a noticeable pleochroism: the color difference may be too faint to be observable.

$$\boxed{\Delta R = R_{\max} - R_{\min}}$$

Reflection and bireflection are measured with a photo-electric cell and a millivolt meter. It is necessary to calibrate the millivolt meter with a reflection standard. As seen from the text above, reflection actually should be measured in monochromatic light. Much used wave lengths are: ***470 nm, 546 nm, 589 nm, 650 nm.*** Reflection values of minerals at these wave lengths are listed in tables in reference works (e.g. Criddle and Stanley, 1993). For simple identification procedures, it is sufficient to measure in polychromatic light. In practice this light is the uncorrected light of the microscope lamp. Reflection values determined in this way may be compared with those at 546 nm. ***The match is not perfect, but sufficient for determination.*** It is therefore ***useless*** to determine values ***behind the decimal point.*** The relationship between reflection and millivolt is linear. Therefore only one standard is measured.

Procedure

- The used standard is SiC (silicon carbide), with a reflection at 546 nm of 21.5 % (also valid for uncorrected lamp light).
- Sample and standard require a neat, clean, and well-polished surface.
- The surface of sample and standard should be ***aligned perfectly horizontal.*** The object to be measured must have its surface at right angles with the axis of the microscope. When this is not the case, a part of the light will reflect in an oblique direction. Consequently, the measured value will be too low. ***To get a well oriented sample, the specimen is placed in plasticine/modeling paste on a small glass plate. It is then pressed with a straightening press.***
- Reflection should preferentially be measured on one grain only. An aggregate will give scattering at the edges of the grains, and in an aggregate different grains may have different optical orientations. Sometimes it is not possible to measure a single grain. One should mention in the description that the reflection was measured on an aggregate, so the measured reflection is probably lower than the actual value. Such a measurement can, however, indicate an order of magnitude for the reflection.
- The maximum light intensity is used: ***aperture diaphragm open, blue filter out, analyzer out, transformer put on maximum.***
- The field diaphragm should be used to single out a grain, and shield it from the surrounding grains, which may disturb the measurement.
- The measurement should be carried out on sample and standard with the ***same setting of the microscope. Only the focus may be changed when switching from sample to standard, and vice versa.***
- The values of the millivolt meter are converted to reflection with following formula:

$$\boxed{R = \frac{G_{mineral}}{G_{standard}} \times 21.5\%}$$

With ***R = reflection***, and $G_{mineral}$ and $G_{standard}$ are the readings on the millivolt meter for ***mineral*** and ***standard*** respectively.

- ***Bireflection*** can ***only*** be measured on ***monocrystals*** (so ***not*** on ***aggregates!!).*** During measurement, the table of the microscope should be rotated slowly and fluently, while the reading of the millivolt meter is monitored to observe maximum and minimum indications. One should measure ***more*** than one grain, and use the highest and lowest value for the reflection and thus the highest bireflection. It may be that a grain exhibiting bireflection is not oriented to show the maximum bireflection.

3. Crystal Morphology, Cleavage, Zoning, Texture.

When crystals can grow without or with minimum restrictions, specific morphologies develop. The shape of the crystal depends on the crystal structure. In many cases the form is characteristic for a mineral. Examples are the cubic crystals of pyrite and galena. Such well-formed crystals are called *euhedral (or idiomorphic).* Crystals that do not show a typical morphology are called *anhedric.*

For the crystal shape, the following division is used: isometric crystals, elongated crystals, bladed crystals.

Examples: pyrite (isometric, "cubes"); arsenopyrite (elongated), jamesonite (elongated, needle like); covellite (bladed).

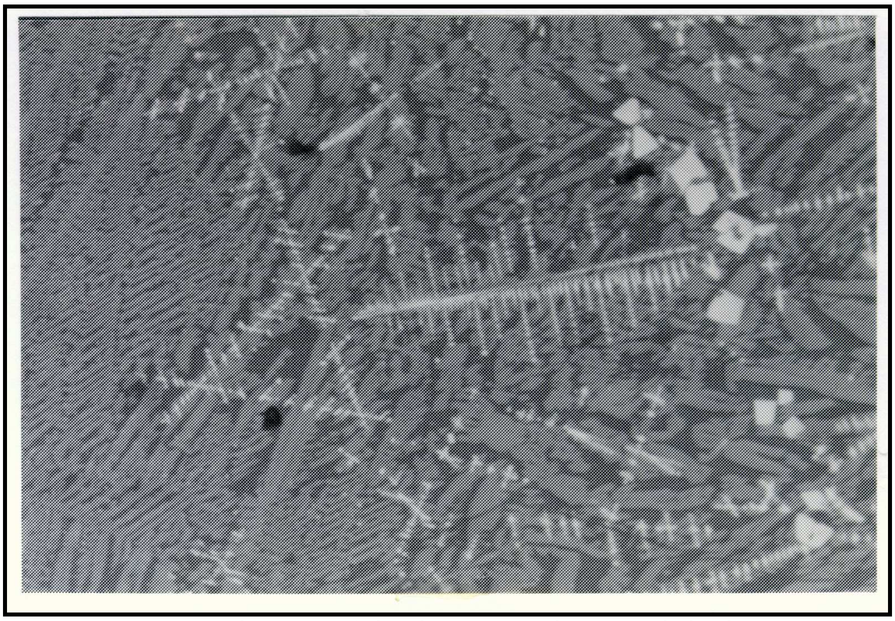
Because in a polished section only a 2-dimensional image is visible, it is not always possible to identify the shape. This may even be impossible.

A special case is dendritic crystals: they are formed under extreme non-equilibrium conditions, often during rapid cooling.

Isometric crystals of pyrite.

Bladed (tabular) crystals of covellite.

Elongated crystals of jamesonite.



A microscopical image of dendritic crystals in a polished section.

Dendritic crystals (of ice) in 3D.

Cleavage is also caused by the crystal structure and thus may serve for determination.
Example: galena, millerite.

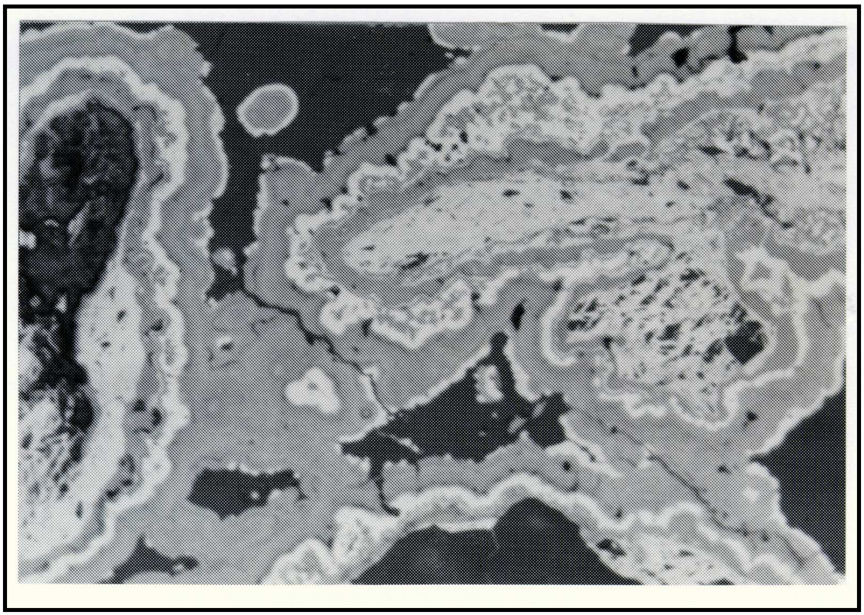
Galena. Three perpendicular cleavage directions are clearly visible.

Zoning: zoning may be chemical (compositional gradient) or physical (zones with inclusions). Zoning is seldom determinative, but may be of use. Zoning is often very important with respect to the formation of rocks. The occurrence of large amounts of inclusions is of course also relevant for ore processing.

Zoning in sfalerite, due to different Fe-contents.

When mentioning texture, this is about issues as intergrowths, grain size, shape of grains, grain size distribution, size of pores, pore size distribution, pore geometry, lineation in the rock. Intergrowths and grain size (distributions) are important for mineral processing . For identification this is in general not of importance.

Colloform Texture: however, there are minerals that occur in a specific texture. An example is a so-called colloform texture. Minerals in a colloform texture often are precipitated from colloidal solutions. The appearance of the aggregates is often spherical or ***botryoidal*** (which means: like a bunch of grapes). In these cases one should be aware of the possibility of dealing with cryptocrystalline aggregates. Cryptocrystalline means: the crystal structure is not visible anymore, crystal sizes are submicroscopic. Often the minerals in such textures can only be determined by other techniques (X-ray diffractions, electron microprobe).



Colloform texture, microscopic image.

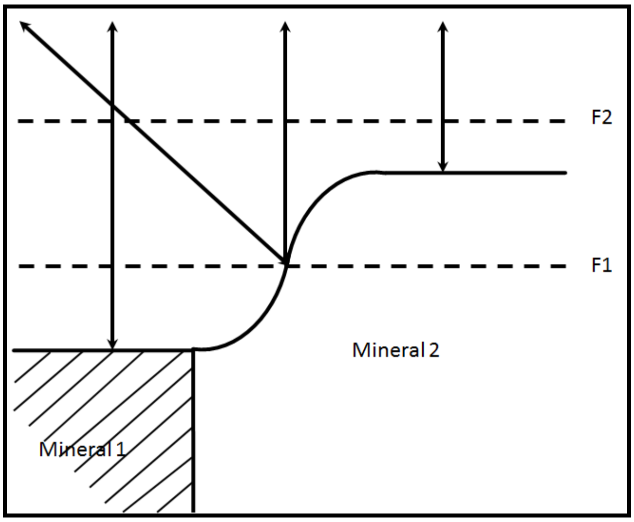
Minerals with a colloform habitus appear ***botryoidal*** (like a bunch of grapes).

Colloform texture in a polished hand specimen.

4. Polishing Hardness

Due to differing hardness of minerals, during polishing a relief is formed. In microscopy, light is scattered on the flanks of the harder grain. This leads to the appearance of a white line, similar to the Becke[5]-line, but different in origin. This light line, called the ***Kalb[6]-line***, can best be observed with a closed aperture diaphragm. This line is not visible if the interface

is in focus, but becomes visible if the microscope is focused above the hardest grain (F2). The white line moves to the ***softer*** one of the two grains if the table of microscope is ***lowered*** (= increasing the free working distance). The Kalb-line is sometimes called the pseudo-Becke line.



The scattering of light on the flank of the hardest grain causes the Kalb-line to appear. This line is

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[5] After Friedrich Johann Karl Becke, Austrian mineralogist (born, Dec. 31, 1855, Prague, Bohemia, Austrian Empire—died June 18, 1931, Vienna, Austria),

[6] After Georg Kalb, German mineralogist, early 20th century.

NOT visible if the microscope is focused on plane F1. Focusing on F2, or near F2 makes the line appear.

B. OBSERVATIONS WITH CROSSED POLARS.

1. Anisotropy

When minerals are studied with crossed polars, anisotropic minerals will show interference colors. So far this is comparable to the situation in transmitted light microscopy. However, the optics of ore mineralogy is far more complicated. The light beings reflected back from the mineral surface is ***not linearly polarized***, but ***elliptically polarized***. It is beyond the scope of this manual to explain all the optical phenomena in detail. (However, see Craig and Vaughan, 1994, Ch. 4, for a clear explanation).

Anisotropy occurs for crystals with non-cubical symmetry. Just like in the optical mineralogy of transparent minerals, they can be subdivided in uni-axial and bi-axial minerals. This subdivision is, however, never used, because in many cases, uni-axial and bi-axial minerals cannot be clearly distinguished. Also konoskopic observations using a Bertrand lens (interference figures, in Dutch called “assenbeelden”) are not applied. If konoskopical observations are to be meaningful, a light path through the crystal must exist. This is not the case for most minerals in ore microcopy. ***Konoscopic procedures are useless in ore microscopy.*** See also Appendix 6. This also means that we cannot distinguish uni-axial and bi-axial crystals in a simple way. Also the determination of the optical sign is almost impossible. As a result the determination of ore minerals is a lot more complicated, and also less accurate than the determination of transparent minerals. A reflection microscope for polarized light (“ore microscope”) only has a Bertrand Lens if the microscope can also be used transmission mode. This is the case with the microscopes we use for the practical.

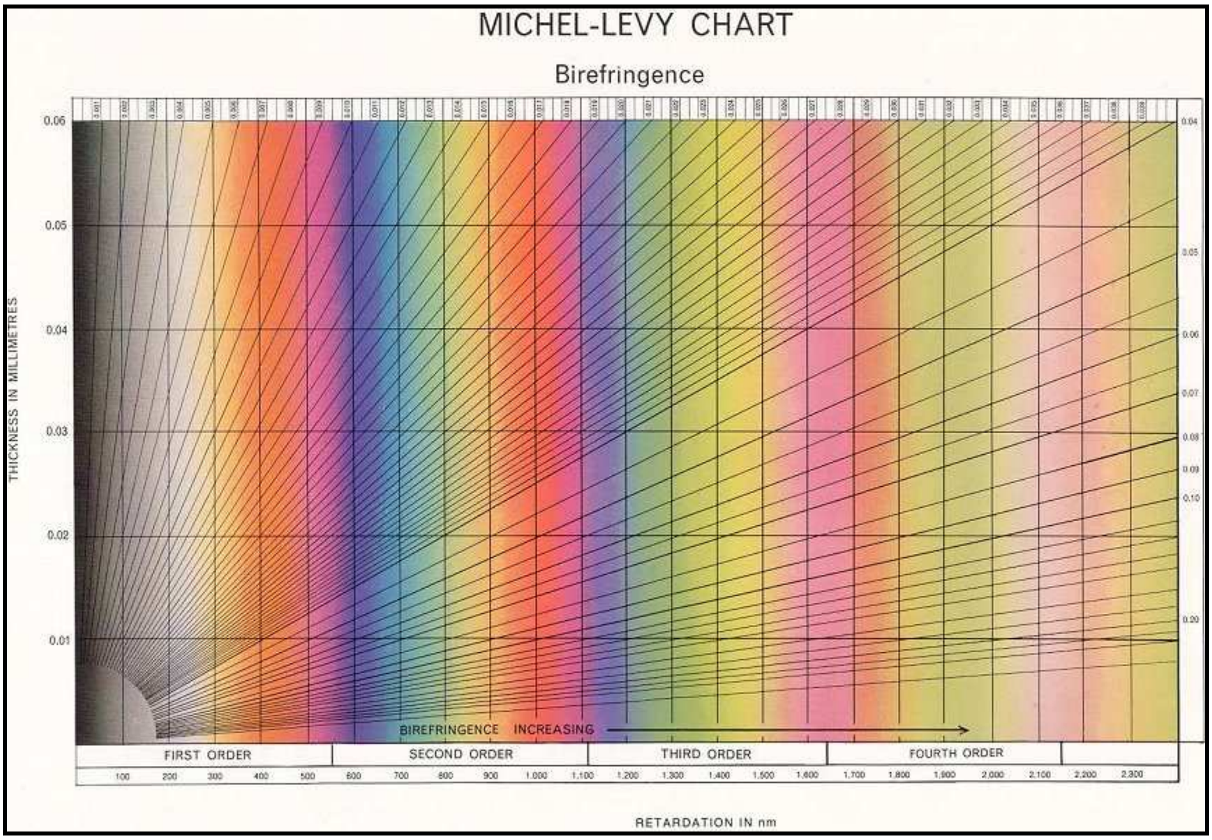
(Because with the microscopes used in the practical the Bertrand lens cannot be inserted in the ray path, konoskopic images are impossible for these microscopes).

Anisotropy in reflection is caused by:

1) Difference in phase
2) Difference in amplitude
3) A combination of both

It appears that interference colors are often more clearly observed when the polarizers are not perfectly crossed (at 90° angle), but turned from that position for 4 or 5°. This is mainly the case for weakly anisotropic minerals, and therefore also for the determination of the anisotropy class

Unlike the birefringence in transmitted light microscopy, the anisotropy does not nod to be quantified precisely. Interference colors are ***NOT*** simply related to each other, as is the case in transmitted light polarization microscopy (*Michel-Levy Chart,* with colors in the 1ste, 2e, 3e order etc.).



The Michel-Levy color chart for birefringence. In ore microscopy this chart is **NOT** applicable.

Because in the case of reflection in general clearly visible dispersion occurs, the interference colors usually are (in terms of the transmitted light polarization microscopy) ***“anomalous”.*** In general a more or less arbitrary subdivision is made in:

- "Extremely anisotropic" (EA)
- "Strongly anisotropic" (SA)
- "Distinctly anisotropic" (DA)
- "Weakly anisotropic" (WA)

Of course, ***bireflection,*** if measurable, is also a measure for the anisotropy, but the measurement of bireflection is in general not accurate enough to quantify the subdivision given above. When measured in monochromatic light, such quantification indeed often ***can*** be made. Nevertheless, bireflection of uncorrected lamplight is an important piece of data. The microscope should be used at a ***medium or low magnification***, and the ***blue filter*** should be ***switched off.***

For practical use, the subdivision given above can be characterized as follows:

- **Extremely anisotropic (EA):** interference colors are very strong. They are visible at

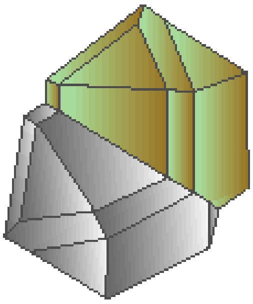
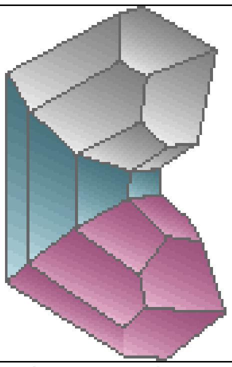
perfectly crossed polars (90°) crossed polars, and at low light intensity (transformer approximately at position 4).
Examples: covellite, lithiophorite, mackinawite.

- **Strongly anisotropic (SA):** the interference colors are vibrant and clear. Perfectly crossed polars (90°), and maximum light intensity.
  Examples: marcasite, pyrrhotite, rammelsbergite, nickeline (niccolite).
- **Distinctly anisotropic (DA):** Greyish and whitish interference colors, sometimes still vibrant. Well visible at 90° crossed polars, and maximum light intensity, and better when the polars are 2° out of the 90°-position. This is approximately half the distance between two scale marks on the analyzer of the DM-LP-microscopes.
  Examples: cassiterite, hematite.
- **Weakly anisotropic (WA):** Interference colors are grey, brown, and bluish. Very difficult, or even not at all visible at maximum light intensity with perfectly crossed polars (90°). Much better visible when the polarizer is 5° out of the 90° position. On the DM-LP microscopes this is 1 mark on the scale of the analyzer
  Examples: chalcocite, bornite.

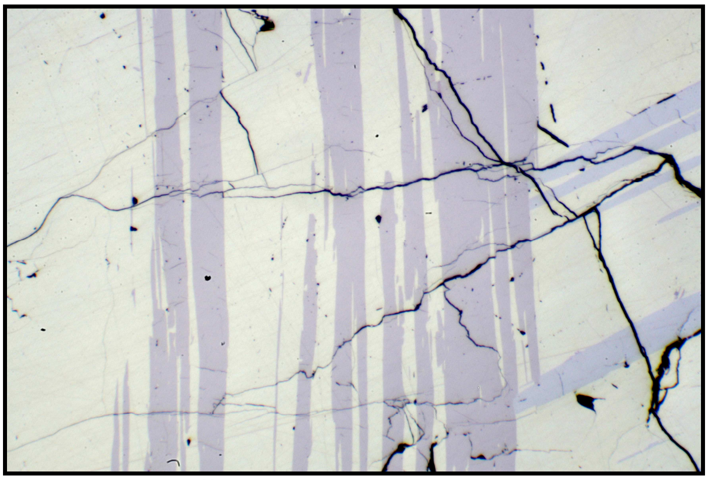
Isotropic minerals (minerals with a cubic symmetry) have ***no*** interference colors.
Examples: pyrite, skutterudite, sfalerite, tennantite.

It is advisable to study more than one grain when determining the anisotropy. The observed anisotropy may be strongly dependent on the direction in the crystal. Compare this with finding the birefringence in studying transparent minerals: one should look in that case for “the highest interference color”, in order to determine the correct value for the birefringence. In studying ore minerals also the maximum effect should be looked for. When there is doubt about the anisotropy class, one may indicate that the anisotropy is in between two classes, e.g. I-WA, Isotropic - Weakly Anisotropic, or SA – EA, Strongly Anisotropic - Extremely Anisotropic.

Twinning is with anisotropic minerals best visible with crossed polars. By the way, cubic minerals can also exhibit twinning (for instance of pyrite twinning is well known). Twinning can appear in many forms. For ore microscopy the type of twinning is important: singular or multiple twinning (lamellar, cyclic). Examples are for instance *chalcopyrite* ($CuFeS_2$) and *cubanite* ($CuFe_2S_3$), both lamellar; *rutile* (TiO_2) and *cassiterite* (SnO_2), both singular. *Stannite* (Cu_2FeSnS_4) may even show raster-like twins, like microcline. Of *arsenopyrite* (FeAsS), besides *twins* also *triplets* are known.

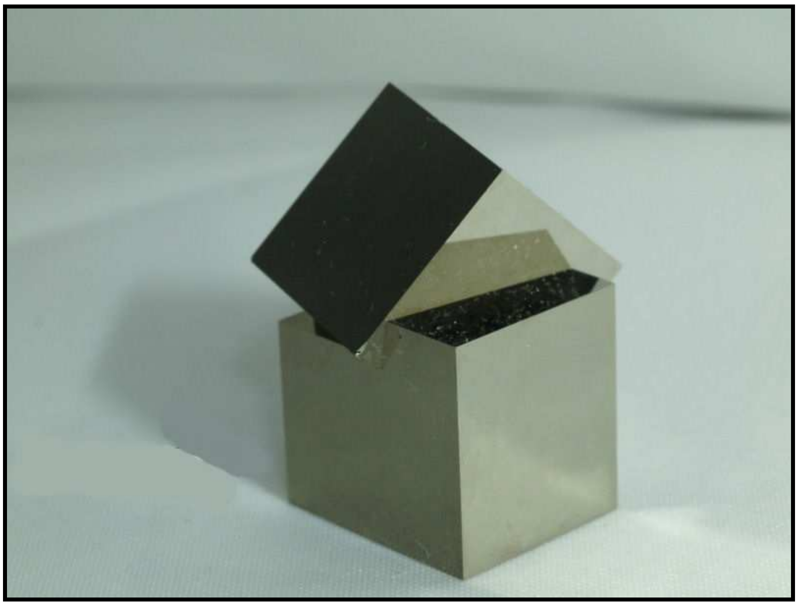
	
Cassiterite twin schematic	Rutile twin, schematic

	
Cassiterite twin.	Rutile twin.

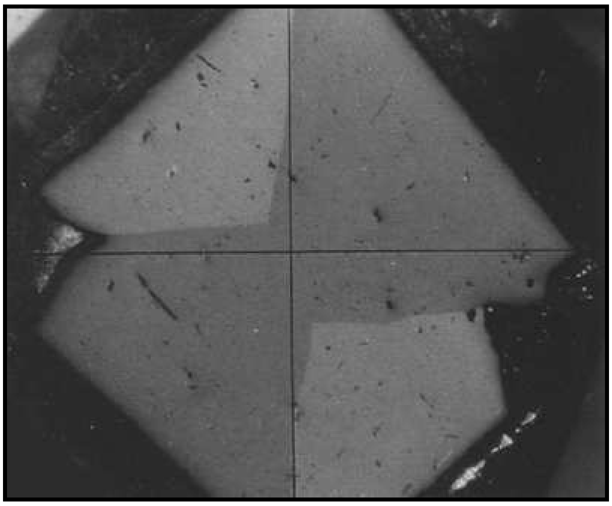


Lamellar twins in cubanite ($CuFe_2S_3$)

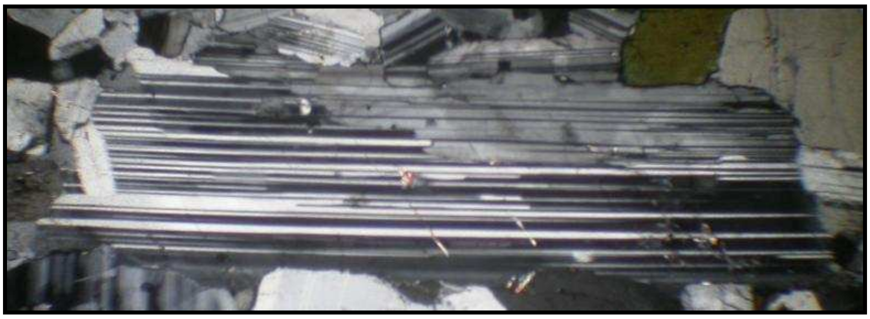
Pyrite twins



Pyrite twins



Pyrite twin in a polished section (a so-called “iron cross”).



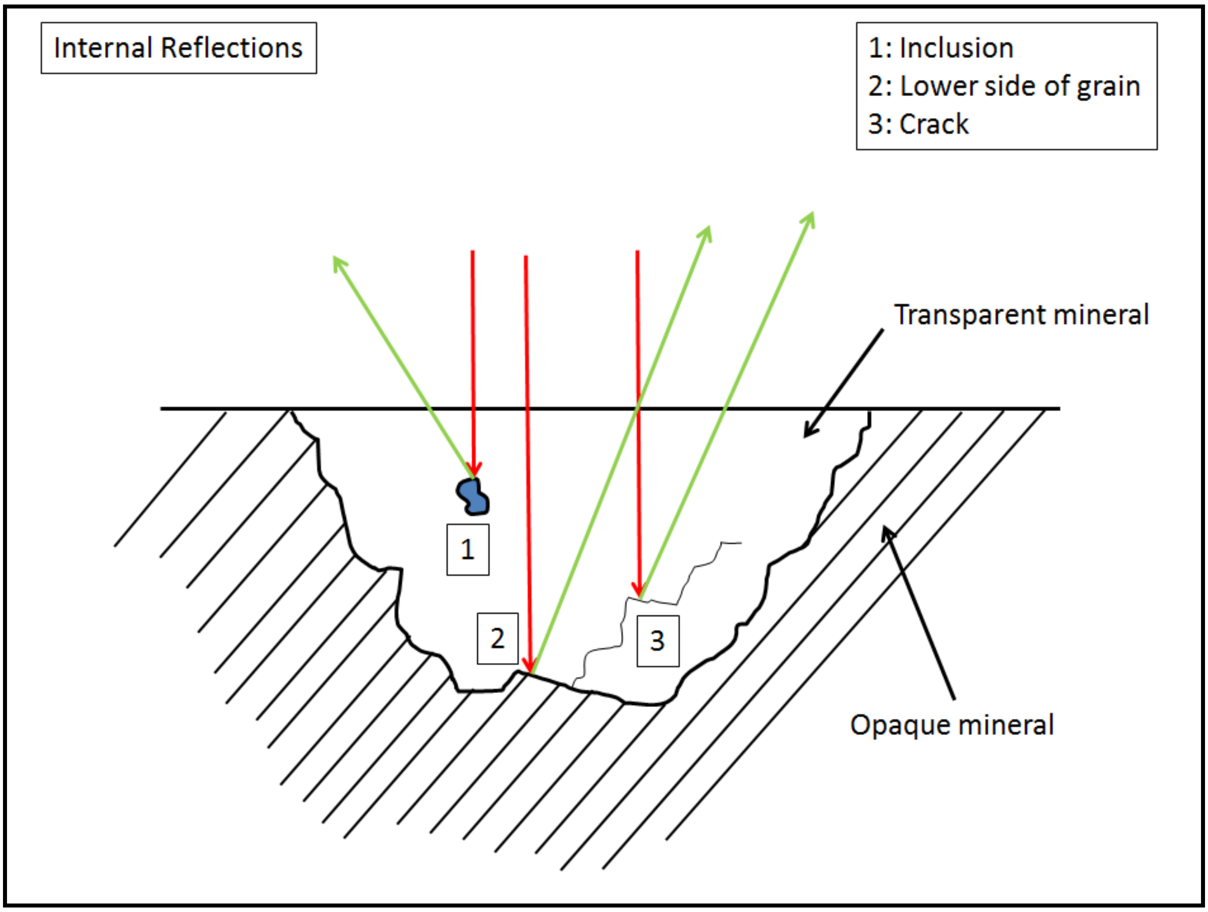
Polysynthetic twinning in plagioclase. The mineral is strongly anisotropic. Although this is a thin section, it may also be visible in a polished section.

N.B.: Also the transparent minerals may be ***anisotropic*** (WA, DA, SA, EA), and **also** may ***show twinning*** under an ore microscope (e.g. feldspars, like plagioclase).

2. Internal Reflections

Internal reflections are formed under the surface of the specimen in transparent minerals at defects (cracks, cleavage planes, inclusions), or at the boundary of the crystal at depth. Not always the whole spectrum of light is reflected, and the mineral is (somewhat) transparent for certain wavelengths (often long wavelengths, e.g. red and yellowish colors. This light can then be reflected at defects or the boundary of the crystal, to emerge again from the surface.

In this way the specific colors of the internal reflections of certain ore minerals may be explained. It seems as if the mineral is lighted up from below. At rotating the table of the microscope, the internal reflections may remain the same, change or disappear. Internal reflections of course are normal for transparent minerals in the specimen (in general silicates). Because they transmit a large part of the visible spectrum, their internal reflections in general are multicolored, but this does not have to be that way. For opaque minerals with a reflection > 40%, internal reflections are extremely rare.

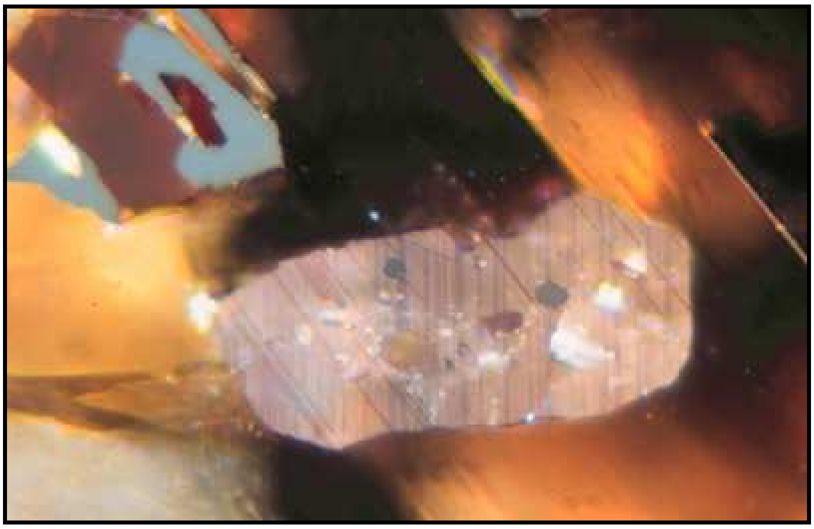


Internal Reflections (schematic)

To make internal reflections visible, usually one must apply a low or medium magnification (10x, 20x). The blue filter must be switched off, and the analyzer should be switched on. The latter blocks the rays reflected from the surface to a great extent. Sometimes the internal reflections are that strong, that they can be seen with the analyzer off.

Examples of minerals with internal reflections:

- *white, milky, cloudy*	*carbonates, quartz*
- *yellow, yellowish brown*	*cassiterite, sfalerite*
- *orange*	*goethite, zinkite*
- *red*	*cuprite, hematite, pyrargyrite, proustite*
- *brown*	*cassiterite, sfalerite, chromite*
- *reddish brown*	*rutile*
- *many colored*	*silicates*



Internal reflections.

3. Determination of the Vickers Hardness

The Vickers Hardness Number (VHN) is a generally accepted method to determine micro hardness. The VHN method is not only used in mineralogy, but also in materials science and metallurgy. The test is based on an indent which a specially cut diamond crystal makes in a (mineral) surface. There are also other micro hardness measurement methods, such as Knoops micro hardness, which is used particularly for very brittle materials or thin sheets. These methods are not treated here.

A diamond is indented into a mineral under a predetermined load (usually 100 g), for a given time (35 seconds) and the cross-sectional area of the indentation is converted into a number, the Vickers hardness number. The cross-sectional area is determined by measuring the diagonals of the indent.

The diamond is pressed into the material during a controlled time, and with a known load (exerted by a weight).

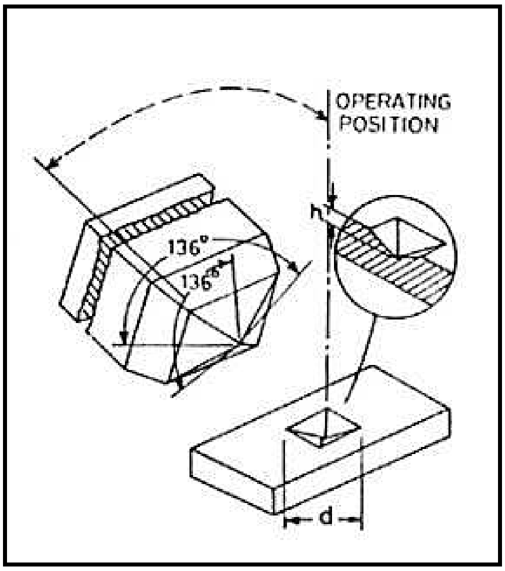
The formula is as follows:

$$\boxed{VHN_p = \frac{1854.4P}{d^2}}$$

P : applied load, for minerals in general 100 grams.
d : length of the diagonal of the indent, in μm.

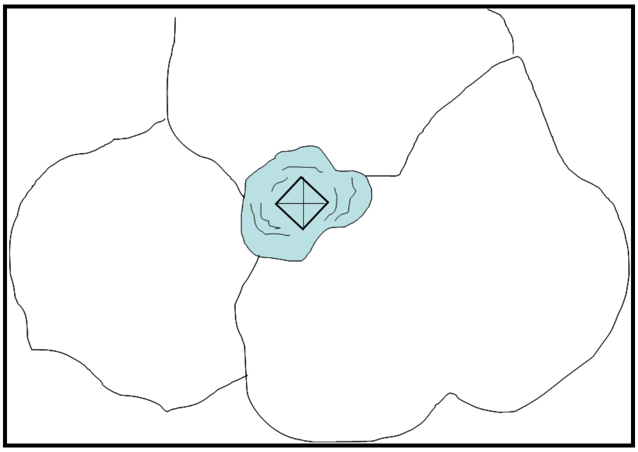
The Vickers indentation may be distorted, leading to two values for d. In principle, $d_1 = d_2$. If this not the case, an average should be taken.

The VHN will differ for different loads. Therefore the load should be mentioned as a subscript. For a load of 100 grams, the subscript is dropped.
Hardness is a directional property, defined according to the crystal structure. Some minerals therefore show a large variation in VHN. Mechanical deformation may lead to a larger hardness (work hardening). Variations in chemical composition may also lead to a difference in hardness. As a result of this, minerals have not an exactly defined hardness, but per mineral a range of possible VHN is found.

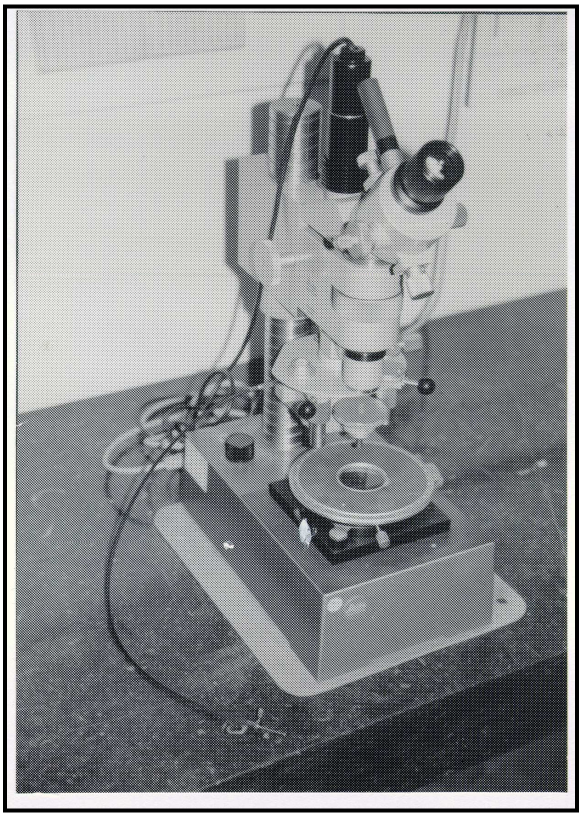


Schematic diagram showing the shape of the Vickers indenter and impression.

However, grains should be sufficiently large for a VHN-test. Hardness changes in general at the borders of a crystal, and of a very small mineral grain it is unclear if the thickness is sufficient for the indent to be completely inserted in that specific mineral. Of very small inclusions, therefore ***NO*** VHN-value can be determined. In that case a relative hardness should be determined.



A VHN indent in a grain that is too small. Effects at the border of the grain will play a significant role, The grain drawn to the right would do.



The Vickers Micro-Indenter

It should also be borne in mind that the VHN-method is ***destructive!*** It should be applied only when needed.

Procedure

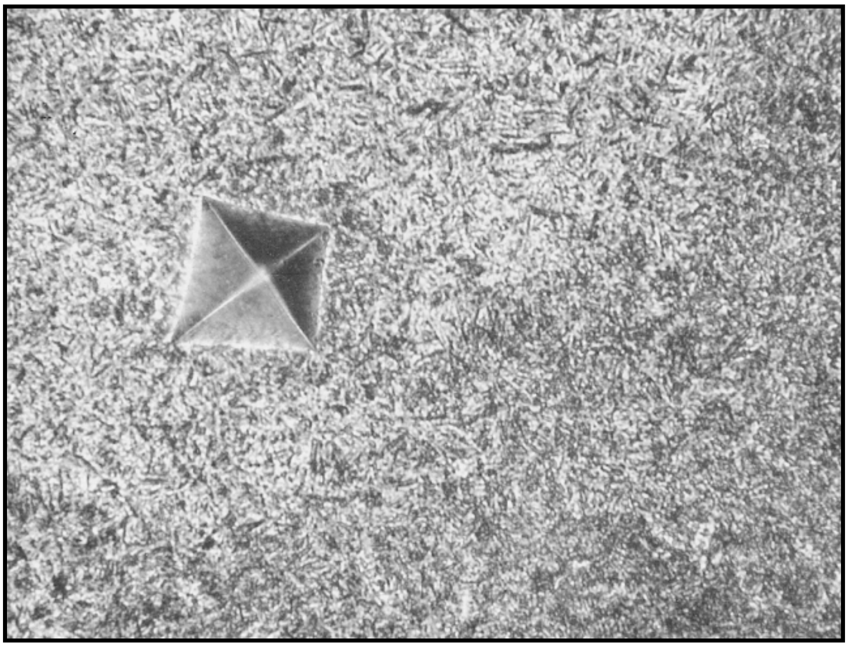
Adjustment of the Micro-Indenter

1. Focus the crosshairs and the scale with the ring on the ocular.
2. Set the lower scale to zero with the adjusting screw.

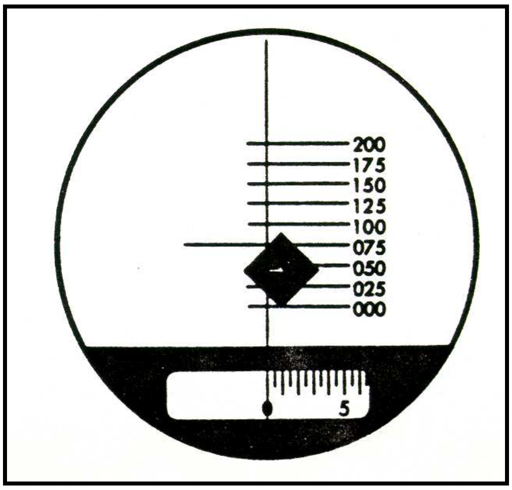
Measurement:

1. Select a grain with the low magnification.
2. Focus on the spot to be tested with the high magnification.
3. Place the diamond over the spot to be tested.
4. Press shortly on the releaser.
5. Wait 35 seconds. This includes the time necessary to have the diamond go down and touch the surface. A longer time than 35 seconds is not important, a shorter time is incorrect.
6. ***Turn the diamond UPWARDS until you hear a CLICK ! (otherwise the tip of the diamond will BREAK OFF at step 7, and diamonds are expensive….)***

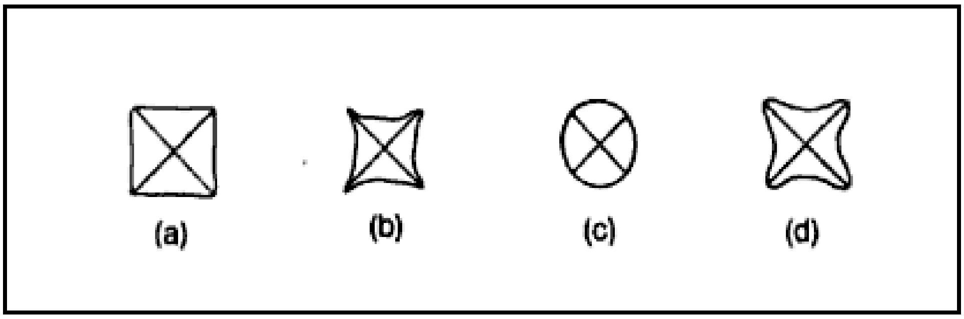
7. Turn the large magnification objective above the tested spot.
8. Place the lower corner of the indent on one of the horizontal lines (e.g. the "0-line" or the "25-line") with the by means of th14e adjusting screws at the table of the indenter..
9. Measure the vertical diameter of the indent. The numbers indicated are in μm's).
   The lower scale indicates values between two black lines. The fine adjustment is operated with adjusting screw to the left of the ocular.
10. The VHN values are given in a table. Values for a load of 100 grams are listed in this manual as Appendix 4. For non-standard weights, tables are available in the microscopy room.



A VHN-indent in case-hardened steel



The image you see through the ocular of the micro-indenter.
The square represents the indent.



Micro-indentations may have: straight edges (a), concave edges (b), convex edges (c), or have a sigmoidal shape (d)

Basic shapes of micro-indentations indentations are given in the figure above. Combinations may occur. Type (a) is most common. Minerals having distinct cleavages or fractures may develop fracturing and deformations around the indentations. These may be classified as *star radial fractures, side radial fractures, cleavage fractures, parting fractures, cleavage shell fractures* and *concentric shell fractures.*

4. Identification Scheme

We will assume that the specimen is ready for microscopical use (that is: clean, and pressed in plasticine/modeling paste with a straightening press). The locations of the mineral under investigation are looked up, and remembered, or noted in a sketch drawing.

If possible, determine the properties for each mineral in the following order.

1. *Color, and pleochroism if applicable*
2. *Reflection, and bireflection if applicable*. Is it not possible to measure a reflection exactly, than try to get the best obtainable value. If necessary, make an estimate.
3. *(An)isotropy*, in case of an anisotropic mineral indicates the interference colors observed.
4. *Internal reflections.* Indicate also the colors observed.
5. *Polishing hardness.*
6. *VHN* (if measurable).

Other properties and manner of occurrence:

7. *Twinning (if applicable)* (lamellar, singular, raster-like).
8. *Cleavage (if applicable)*

9. *Euhedral crystals with a typical morphology ((*isometric, elongated, needle-like, tabular/bladed). It may also be of importance if only anhedral[7] crystals occur of the mineral investigated.
10. *Intergrowths, colloform texture, zoning, demixing, reaction rims, occurrence in veins etc.*

The different measurements and observations must be combined. This can be done with:

- The computer program ***OMI (Opaque Mineral Identification)*** by H.J. Glass & J.H.L. Voncken (2010).

and by using the reference works*:*

- *Tables for Microscopic Identification of Ore Minerals,* by Uytenboogaard and Burke, (1971);
- *The Ore Minerals and their Intergrowths,* by P. Rahmdohr, (1960, 1969, 1980);
- *Quantitative Data File for Ore Minerals (IIIth Edition),* by A.J. Criddle and C. Stanley, (1993);
- *Determination Tables for Ore Microscopy,* by C. Schouten, (1962).

Use of the tables and the computer program will be explained in the practical sessions.

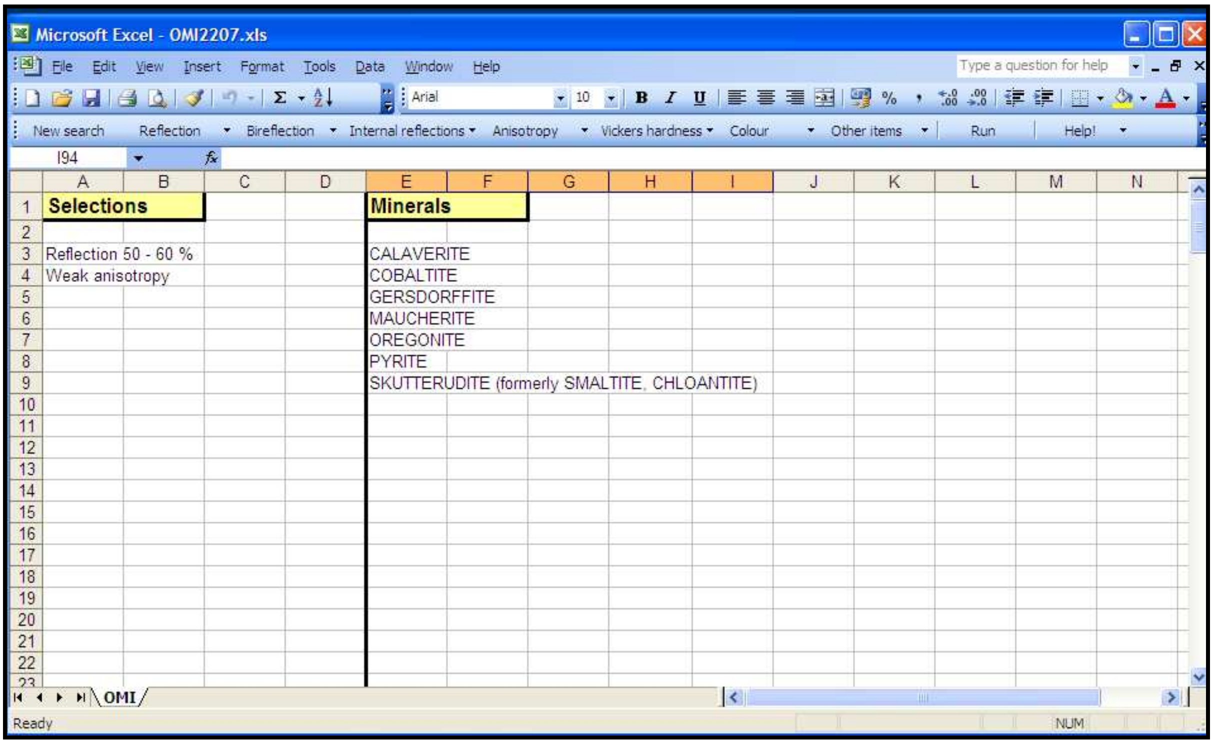
The tables, reference works and the program do not persé give the (only) correct solution, They are only a help for the determination. Use also must use common sense.

Below a couple of images of possible output of the program are given. The database of the program contains some 200 most common ore minerals. Minerals which have been redefined are also mentioned with their former names. See for instance skutterudite in the image below.

In general the program will ***not*** give ***one unique solution,*** but will give a few possible solutions (say, 3 or 4).

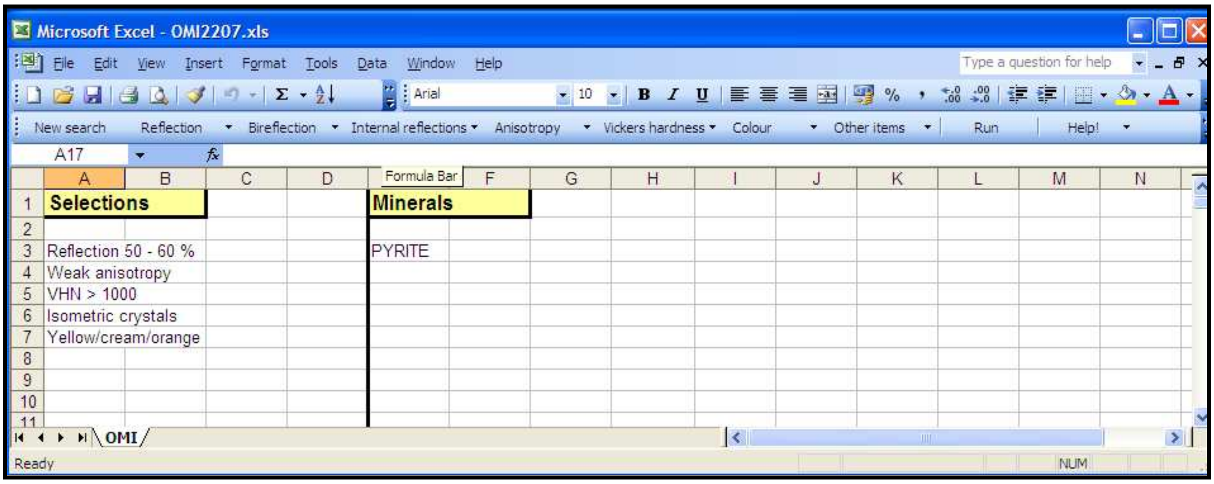
---

[7] ***Anhedral*** is in petrology a term for crystals which do not exhibit their typical shape. Anhedral crystals rarely have straight sides. It is the opposite of ***euhedral*** or ***idiomorphic***. A synonym of anhedral is ***xenomorphic***.



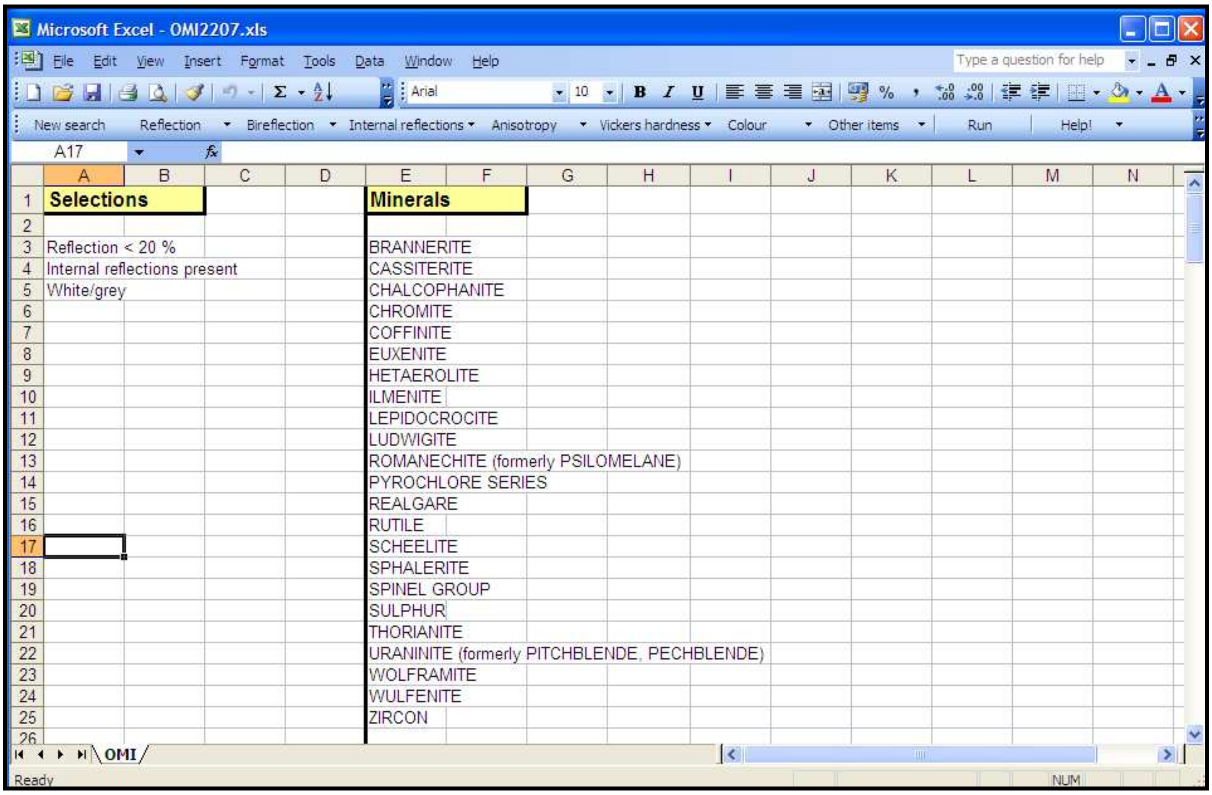
Selections	Minerals
Reflection 50 - 60 %	CALAVERITE
Weak anisotropy	COBALTITE
	GERSDORFFITE
	MAUCHERITE
	OREGONITE
	PYRITE
	SKUTTERUDITE (formerly SMALTITE, CHLOANTITE)

Output of the program. There are 7 solutions. Try to get more data.



Selections	Minerals
Reflection 50 - 60 %	PYRITE
Weak anisotropy	
VHN > 1000	
Isometric crystals	
Yellow/cream/orange	

Output of the program. There is only one solution. Check in the reference works if this solution is likely to be correct.



	A	E
1	**Selections**	**Minerals**
2		
3	Reflection < 20 %	BRANNERITE
4	Internal reflections present	CASSITERITE
5	White/grey	CHALCOPHANITE
6		CHROMITE
7		COFFINITE
8		EUXENITE
9		HETAEROLITE
10		ILMENITE
11		LEPIDOCROCITE
12		LUDWIGITE
13		ROMANECHITE (formerly PSILOMELANE)
14		PYROCHLORE SERIES
15		REALGARE
16		RUTILE
17		SCHEELITE
18		SPHALERITE
19		SPINEL GROUP
20		SULPHUR
21		THORIANITE
22		URANINITE (formerly PITCHBLENDE, PECHBLENDE)
23		WOLFRAMITE
24		WULFENITE
25		ZIRCON

Output of the program. There are too many solutions. You ***must*** get more data. Determination of (an)isotropy might reduce the list considerably

The program does NOT warn for impossible combinations of input data. (e.g. Isotropic and Bireflection > 4%). One merely gets NO matching results in such a case.

The program may also be used in another way: The ***Chemical Data*** option (under ***Other Items***) provides the possibility to enter elements present in the mineral chemistry. When a not yet identified mineral is found in, for instance, a copper ore, in which several other copper containing ore minerals have already been identified, one may, for the yet unknown mineral, use the chemical data option to select the copper containing minerals that match the optical observations (thus assuming the unknown mineral contains copper).

C. APPLICATIONS OF ORE MICROCOPY

In several parts of Resource Engineering, ore microscopy is used. Below 3 examples are described.

1. Liberation analysis

Liberation analysis if the analysis of the grain size fractions in the different stages of a milling process. It is an important never to mill longer than necessary. When the grain size

and the grain size distribution of (an) ore mineral(s) is known in principle a milling process scan be started, which, at a certain grain size liberates the ore minerals from the unusable rest.
In research into the best milling procedure, the different size fraction must be studied with an ore microscope to establish if the valuable minerals have already been liberated. It is also useful to investigate how much energy it costs to liberate the still not liberated particles, and to compare these costs against the increased costs of the milled material. It may well be, that it costs that much energy to liberate the finest grains,, that it is more economical to dispose of it, because the costs of liberation are dwarfed by the costs of further milling.

A well-known theory to get insight in the energy necessary to decrease the grain size is the theory of Bond. This is more in detail treated in Physical Processing TA3390.
In Bond's theory, two important concepts occur:

d_{80}: the sieve size through which 80% of the grains pass, in µm.

W_1: the so-called ***"Work index"***, the theoretical work done (in Kwh/ton) necessary to crush an infinitely large piece of material ($d_{80\text{ - feed}} = \infty$) to $d_{80\text{ - }product} = 100$ µm.

Bond's formula is:

$$\boxed{E = 10 W_i \left[\left(\frac{1}{\sqrt{d_{80}}}\right)_{product} - \left(\frac{1}{\sqrt{d_{80}}}\right)_{voeding}\right]}$$

W_i is known of a large number of minerals, d_{80} follows form the sieve analysis.

In the practical you will study material from different milling steps from the processing of a Pb-Zn-ore. **This is the set polished sections with number T-17.**

2. Processing of iron ore

We will not discuss the processing of iron ore in detail, but some aspect of the feed of the blast furnace will be treated. This will all be treated in detail in the course Extractive Metallurgy TA3380.

Most blast furnaces are not fed anymore with lump ore. Most ores are not rich enough, and pre-concentration must take place at the mine sire. This renders the ore to fine powder. Fine powder cannot be fed into a blast furnace. Here another agglomeration step is applied. Usually this is sintering and pelletizing.

To produce sinter, the ore is mixed with flux (olivine, limestone, and dolomite), circulated material (returned process material) and cokes breeze. The mixture is burned (locally under reducing conditions, because of the cokes, and the particles are bound together. The process takes place in a very short time interval, in which temperatures up 1400°C are reached. The particles are cemented together by molten calcium ferrites (Ca-Fe-O compounds) and silicate rich phases. Magnetite, which may be present, is not always oxidized to hematite, and magnetite may be present in sinter. Also formation of new hematite takes place, as well as recrystallization of original hematite. The final result is an inhomogeneous product.

In the pelletizing process, a binder (bentonite) is added to bind the fine particles in first instance. During sintering, the grains are bound together. Sintering of pellets takes place under oxidizing conditions ate approximately 1300°C. In contrast to the formation of sinters, described above, the particles are ground to a very small particle size. The material is virtually completely Fe-containing material (hematite, magnetite, but also goethite). Magnetite is usually completely oxidized to hematite. The final pellets are very homogenous, and contain mainly hematite.

The sinter is rather compact, and not easily accessible for the reducing gas. Pellets are very porous, and have deliberately a very open structure to allow for access of the reducing blast furnace gas.

In the practical we will study a pellet and a sinter, and we will pay attention to the mineral phases present, recrystallization, neck formation, pore structure etc. **This is the polished section T-16.**

3. Pyrometallurgical processing of Sulfidic Nickel-Copper Ore

Just as with the processing of iron ore, we will not discuss in depth the pyrometallurgical aspects of the process. The process is one of the most important in the processing of sulfidic nickel-copper ores: the process as carried out (and invented) by INCO (International Nickel Corporation). In the practical we will carry out a microscopic investigation of an intermediate product of this process, a solidified copper-nickel matte (a matte is an industrial sulfidic melt). The applied ores are sulfidic, with as most important minerals pentlandite $(Fe,Ni)_9S_8$, pyrrhotite ($Fe_{1-x}S$), chalcopyrite ($CuFeS_2$), and cubanite ($CuFe_2S_3$). Iron is not extracted from the material. Copper is the last metal to be extracted.

During the process, a sulfidic melt (matte) is formed, and a silicate melt (slag), which has a lower density, and floats on top of the matte. The matte is regularly tapped, and then cast into large containers, where it cools. During the slow cooling, copper and nickel crystallize into separate phases. Also a metal phase is formed, because there is not enough sulfur in the matte, due to the extraction as SO_3. The metal phase includes also precious metals. The solidified matte is broken and ground, and mineral separation is applied. The slow cooled matte is very well suited for microscopic examination, **and in T-15 you will find an example from the plant. This time, the minerals present are *not* mentioned, and you should find out yourself whether you can identify them.** At least one sulfide mineral in this polished section you have ***not*** seen before. Of course, the original minerals, mentioned above, are all gone.

D. REFERENCES

Most of these books are available in the practical room, or in the storage room.

General:

- Craig J.R. and Vaughan, D.J. (1994): *Ore Microscopy and Ore Petrography. John Wiley and Sons, New York. 434 pp.*

The Ore microscope / Optical properties of opaque minerals:

- Freund, H. (ed.) (1966): *Applied Ore Microscopy. Macmillan Company, New York.*
- Galopin R. & Henry, N.F.M. (1972): *Microscopic Study of Opaque Minerals.*
- Patzelt, W. (1974): *Polarizationsmicroskopie, Grundlagen, Instrumente, Anwendungen. Edition E. Leitz GmbH, Wetzlar.*
- Piller, H. (1977): *Microscope Photometry. Springer Verlag, Berlin, New York.*

Identification, Reference books:

- Criddle , A.J., and Stanley, C.J. (1993) *Quantitative Data file for Ore Minerals, 3th Edition, Chapman and Hall, London, 635 pp.*
- Kühnel, R.A., Prins, J.J., Roorda, H.J. (1980): *The "Delft' System For Mineral Identification (1980), I. Opaque Minerals, Delft University Press, 204 pp.*
- Picot, P. & Johan, Z. (1977): *Atlas des Mineraux Metalliques, Memoires B.R.G.M.*
- Rahmdohr, P. (1960, 1969, 1980): *The Ore Minerals and their Intergrowths, Pergamon Press, (also in German edition)*
- Schouten, C. (1962): *Determination Tables for Ore Microscopy, Elsevier, 242 pp.*
- Uytenboogaard, W. and Burke, E.A.J. (1971): *Tables for Microscopic Identification of Ore Minerals. Elsevier.*

Computer program:

- H.J. Glass and J.H.L. Voncken (2010*) An Easy-to-Use Program for the Determination of Common Opaque Minerals. Computers and Geosciences, Vol. 36, 12, 1532 – 1534*

Ore Mineralogy and Ore Microscopy TA3196

Appendices

APPENDIX 1. MAKING A POLISHED SECTION

1) PREPARATION OF THE RESIN, AND MAKING THE NON-POLISHED SPECIMEN.

To make a polished section, a piece of rock of sufficient size has to be sawed off from a specimen. The rock fragment can be imbedded in resin. Round molds are used for this. The rock fragment is placed with flat side downward.

- Prepare the araldite fluid as follows: Araldite F (massive rocks) or Araldite D (porous rocks or powder) + Hardener HI951
- Composition of the mixture: 1 part of the hardener versus 8 parts araldite (massive rocks) or 10 parts araldite (porous rocks, or powder)
- Mix the liquid well.
- Pour the liquid carefully into the mold. Take care no air bubbles are formed.
- Let the liquid dry during 24 hours.
- Porous rocks should be dried under a low vacuum (200 torr).
- For making polished sections of powder, the amount of the powder is one leveled off tea spoon.

- For fast production of polished sections a different kind of resin is used: **DEMOTEC**. **You will make a polished section yourself with this resin.**
- **Composition of the mixture: 2 parts powder versus 1 part liquid**.
- **The specimen is ready for polishing in approximately 20 minutes.**

2) Polishing

The polishing process proceeds in different stadia. Several materials are used. How long the polishing process takes place depends on the material to be polished. No indication of time can be given. The materials you will polish are pellets for the blast furnace (origin Tat Steel, IJmuiden). With these materials you can polish to a good surface finish in under an hour.

- Hard material: use a rotating table and the following corundum powders: "150", then "2F", then "3F".
- Soft material: use the diamond polishing table.

With an already leveled specimen, the procedure is different. **This applies to your specimen.** Now the tables with polishing paper are used. Apply the following grain sizes: 320, 500, 1000, 2400, and 4000.

Furthermore for all operations the following should be noted:

- When changing the table, clean the specimen ultrasonically!!! On the new table turn the specimen ¼ with respect to its original position.
- Use felt plates with a diamond powder solution. The following grain sizes of diamond are used: 6 µm, then 3 µm, then 1 µm. When changing the table, clean the specimen ultrasonically!!!

APPENDIX 2. SHORT DESCRIPTION OF THE POLISHED SECTIONS IN THE TRAINING COLLECTION (T-COLLECTION).

The descriptions given here are very short, and are intended to give an overview of the minerals present, so that they may be easier traced. Use always the reference works and the computer program to verify the minerals found, and to verify their characteristics. Answer the questions, and carry out the orders.

Try after a little practice to determine the minerals first by yourself, and look in this appendix afterwards.

NB: The polished sections are NOT treated according to increasing specimen number.

Abbreviations: ***I*** = Isotropic, ***WA*** = Weakly Anisotropic, ***DA*** = Distinctly Anisotropic, ***SA*** = Strong Anisotropic, ***EA*** = Extremely Anisotropic, ***R*** = Reflectance

---

Polished section T-1 — Pb-Zn ore, Casapalca, Peru

Pyrite	- Light yellow, I - WA.
Galena	- Whitish grey, I, with triangular pits. Mark the three cleavage directions of galena.
Sfalerite	- Grey, I, with yellow chalcopyrite inclusions.
Tennantite	- Greenish grey, I.

Polished section T-2 — Au-ore Sumatra, Indonesia

An example of the way to describe a polished section. Conclusions are made using the program and the reference works.

Mineral 1

Color: Light grey; pleochroism by bireflection: no
Reflection: 17 %
Optical Category: I
Internal Reflections: brown
Polishing Hardness: Mineral 1 > Mineral 2
VHN: 128 - 276
Other Properties:
Twins: no
Cleavage: no
Typical crystal morphology: no
Typical texture: no

Conclusion: Sfalerite

Mineral 2

Color: white; pleochroism as a result of bireflection: no

Reflection: 42 %
Optical Category: I
Internal Reflections: no
Polishing Hardness: Mineral 2 < Mineral 3
VHN: 56 - 116
Other Properties:
Twins: no
Cleavage: yes
Typical crystal morphology: no
Typical texture: no

Conclusion: Galena

Mineral 3
Color: yellow; pleochroism by bireflection: no
Reflection: 44 - 46 %
Optical Category: WA - DA Interference colors (recognizable if the analyzer is turned (more than) 5 degrees): yellowish, Bluish
Internal Reflections: no
Polishing Hardness: Mineral 3 > Mineral 5
VHN: 174 - 219
Other Properties:
Twins: lamellar, may sometimes be observed
Cleavage: no
Typical crystal morphology: no
Typical texture: no

Conclusion: Chalcopyrite

Mineral 4
Color: pale yellow; pleochroism by bireflection: no
Reflection: 53.5%
Optical Category: I
Internal Reflections: no
Polishing Hardness: hardest mineral present
VHN: > 1000
Other Properties:
Twins: no
Cleavage: no
Typical crystal morphology: yes, isometric
Typical texture: no

Conclusion: Pyrite

Mineral 5
Color: light yellow; pleochroism by bireflection: no
Reflection: > 60 %
Optical Category: I - WA
Internal Reflections: no
Polishing Hardness: < Mineral 3
VHN: < 100
Other Properties:
Twins: no
Cleavage: no
Typical crystal morphology: no
Typical texture: no

Conclusion: Gold
Remark: accessory

Mineral 6
Color: blue; pleochroism by bireflection: yes, Colors: greyish blue - blue
Reflection: 7 - 23 % (difficult, sometimes not even measurable)
Optical Category: SA - EA; observed interference Colors: orange, orange-brown
Internal Reflections: no
Polishing Hardness: < Mineral 3
VHN: not measurable
Other Properties:
Twins: no
Cleavage: no
Typical crystal morphology: no indication
Typical texture: no

Conclusion: Covellite
Remark: accessory

Other Minerals
Color: dark grey, pleochroism by bireflection: possible
Reflection: < 10 % . Minerals with a reflection < 10 % are usually transparent (silicates etc.). Covellite (R: 7 - 23 %) is an exception.
Optical Category: diverse
Internal Reflections: many colored

Conclusion: Silicate minerals and related (transparent)

Polished section T-3

Cu-ore, Bor, Serbia

Main minerals:

Covellite - blue pleochroitic. (What is the shape of the covellite crystals: isometric, bladed, elongated?)
Pyrite - light yellow, isometric crystal with many inclusions. (Mark the high relief of the pyrite crystals. (Pyrite is one of the hardest minerals in the training collection, VHN > 1000).
Enargite - somewhat pinkish-grey, irregular masses. (Is enargite harder or softer than covellite?)

Silicate minerals/
Transparent minerals - Dark grey or dark brown with many internal reflections. The silicate minerals/transparent minerals from here on are not mentioned anymore in the description.

Minor minerals and accessory minerals:
Digenite - Bluish green, I - WA, often inclusions in enargite.
Chalcocite - white grey, I - WA, in general rims and segregations in digenite.

Bornite - violet or orange, I- WA, inclusions in enargite of digenite, little present
Chalcopyrite - yellow, inclusions in bornite/enargite, very little present

Polished section T-4 Cu-Ni ore, Sudbury, Canada

Main minerals:

Pyrrhotite - beige brown, SA, bireflectant. (Has pyrrhotite twins?)
Pentlandite - cream, I. Pentlandite occurs in two distinct forms:
1) Irregular, usually isometric grains with two sets of cleavage, which intersect in angle of approximately 90°
2) "Flames" related to fissures and cracks. The second pentlandite is younger.
Chalcopyrite - (dark) yellow, WA - DA. (Has chalcopyrite twins?)

Accessory Minerals:

Magnetite - grey, R = 22, I, isometric idiomorphic crystals. Check the magnetism of the polished sections. Are there other minerals which might be magnetic?
Ilmenite - pinkish grey, R = 19, SA, as elongated crystals or demixed laths in magnetite.

Polished section T-5 Sn-ore, Portugal

Main minerals:

Pyrite - Contains some pinkish inclusions of pyrrhotite.
"Melnicovite" - "Colloform Pyrite", as yellow, pockmarked aggregates with clear zoning, or sometimes so-called "birds-eye" structure. Not always very clear. Study this form of pyrite in the book by Rahmdohr.
Pyrrhotite - Brownish/pinkish, SA. This is the original mineral.
Cassiterite - Grey, hard (high positive relief), DA, IR. Shows often singular twins with a straight twinning plane. Cassiterite will in a number of sections actually be a minor mineral with respect to the amount present, but it is counted to the main minerals because it is the important ore minerals in this rock.
Sfalerite - Grey.

Accessory minerals:

Tennantite - Light bluish grey, I - WA.

Chalcopyrite - Yellow.
Wolframite - Grey, WA - DA. Not in all polished sections.
Stannite - Greenish grey, DA. Light blue color, when next to chalcopyrite. Not in all polished sections.

In some polished sections chalcopyrite is a main mineral.
In the gangue siderite may be identified: siderite itself has white internal reflections (which are not are only a little determinative), but it is partly altered to hematite, which results in red internal reflections.

Polished section T-6 Ni-Co ore, Cobalt, Ontario, Canada

Main minerals:

Löllingite/Rammelsbergite - White, SA (- EA), radial aggregates.
Nickeline - Orange, SA (- EA)
Cobaltite - Pinkish grey, hard.
Skutterudite - White, sometimes idiomorphic rectangular crystals, I.

For all these minerals R > 50 %.

Accessory minerals:

Chalcopyrite - Yellow
Sfalerite - Grey

Study the reference works with respect to these strongly reflecting minerals. What is the relationship between rammelsbergite, pararammelsbergite, safflorite en löllingite? Study also the collection of standard minerals ("Ores Composites") with respect to these minerals.

Polished section T-7 Cu-ore, Zambia

Main minerals:

Bornite - Violet/purple, WA, tarnishes easily.
Chalcopyrite - Yellow.
Tennantite - Greenish grey.
Renierite - Orange, SA.
Sfalerite - Grey.

Accessory minerals:

Digenite - Greyish blue, together with chalcocite.
Chalcocite - White-grey, sometimes bluish grey, I- WA, rims.
Carrolite - Pinkish white, veined. Only in a few polished sections.
Enargite - Pinkish grey, DA - SA, rare.
Galena - White, I, not in all polished sections.

Polished section T-8. Cu-Ni ore, Canada.

Main minerals:

Chalcopyrite - Yellow.
Cubanite - Khaki, cream, SA.
Pyrrhotite - Pinkish, SA.
Pentlandite - Cream, I, with 2 sets of cleavage.
Mackinawite - Grey-pinkish, EA, small segregations.

Accessory minerals:

Sfalerite - Grey.
Violarite - Pinkish, I, alteration of pentlandite, in veins and cracks in this mineral.
Magnetite - Grey and hard, I.
Ilmenite - Pinkish grey, SA.

In some polished sections galena (white isotropic) may be found. Greyish white and strongly anisotropic minerals are tellurides (compositions containing the element Tellurium, Te). Tellurides are not treated in this course.
Study the similarities and differences between pyrrhotite and cubanite with the book by P. Rahmdohr.

Polished section T-9 Ag-Sb ore, Pribram, Czechia

There are two types of specimens, Ag-poor and Ag-rich. You must exchange the specimens to be able to study both.

T-9 A) Ag-rich

Main minerals:

Proustite/pyrargyrite - Bluish, SA (-EA), red IR. Proustite and pyrargyrite are very difficult to distinguish optically.
Arsenopyrite - White, SA, R > 50. Are arsenopyrite crystals isometric, elongated

or bladed?
Sfalerite - Grey.
Pyrite - Light yellow

Accessory minerals:

Chalcopyrite - Yellow.
Galena - White.
Not in all sections:
Argentite - Greenish grey, very soft, I, weathered
Argentopyrite - Honey-yellow, small crystals, in proustite.

T-9 B) Ag-poor

Main minerals:

Jamesonite - Bluish white, needles, DA - SA
Galena - White.
Arsenopyrite - White, SA, R > 50.
Sfalerite - Grey
Pyrite - Light yellow.

Accessory minerals:

Chalcopyrite - Yellow, I - WA (Not in all sections).
Ag-rich
Tetrahedrite/freibergite - Greenish grey, I. Not in all sections.

Study the Ag-minerals in the "Ores Composites Collection".

Polished section T-10 Fe-ore (gossan) Zambia

Main minerals:

Magnetite - Pinkish brown, I
Hematite - White (Bluish), SA
Goethite - Bluish grey, DA, yellowish, red-orange IR.

Polished section T-11 Cr-ore, Philippines

Chromite - Grey, I, R = 12 - 13. Brown IR.

Serpentine matrix with white-greenish IR.

Is chromite related to magnetite with respect to its crystal structure?

Polished section T-12 Mn-ore, India/Mn-nodule, Pacific Ocean

Mn-ore, India:

Main minerals:

Pyrolusite - Yellowish white, pleochroitic, elongated
Cryptomelane - Bluish grey, occurs in a ***cryptocrystalline aggregate,*** SA
A cryptocrystalline aggregate may ***appear*** to be ***isotropic***, while the minerals in the aggregate, here cryptomelane, actually are ***not!***

Lithiophorite - Bluish grey, pleochroitic EA (interference color are black or white.), around open cavities, Relative low reflection (10 - 20 %).
Goethite - Bluish grey, with red IR.

Mn-nodule, Pacific Ocean:

Mark the colloform textures! Several Mn-minerals are present in intimate intergrowths. Optical determination of the different ore minerals is impossible!! The resolution of the optical microscope is ***too low*** for this. The technique to solve this is electron microprobe (also: Electron Probe Micro Analysis or EPMA). This technique will be demonstrated during the practical, if there is enough time. The following minerals have been identified in this way: *psilomelane, todorokite, woodruffite, pyrolusite, hollandite, cryptomelane, birnessite.*

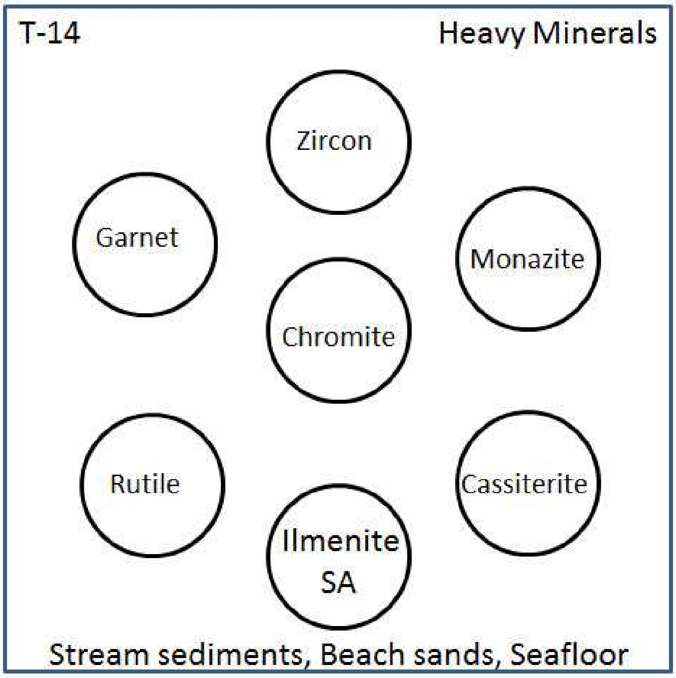
Polished section T-13 Au-Bi ore, Tennant Creek, Australia

Magnetite - Grey
Bismuthinite - White, EA-SA.
Chalcopyrite - Yellow.
Gold - Yellow, R > 70.
Guanajuatite - White with cleavage. *Remark: This mineral does NOT occur in the database of the program OMI !!*
Hematite - Bluish, wormlike inclusions.
Pyrite - Light yellow, not in all sections.

Is there a relationship between guanajuatite and bismuthinite?

Polished section T-14 Heavy Minerals

In this composite polished section you find seven fractions of heavy minerals.



You will notice that you can determine *chromite*, *cassiterite*, *ilmenite* and rutile with an ore microscope. The minerals *zircon*, *monazite* and *garnet*, which are also shown for comparison, are better determined with a transmitted light microscope. However, all these minerals occur in heavy mineral sands.

Polished section T-15 Ni-Cu Matte, INCO Ltd. Sudbury, Ontario, Canada

In this polished section you find a piece of a so-called “slow cooled matte” from the nickel ore processing according to the INCO-process. This process is one of the most important industrial processes with respect to the processing of sulfidic nickel ores. The ore for this process could have been the ore of T-4, or T-8.

Instruction:

- Determine all phases in the polished section.

N.B.: because fort his polished section there are no mineral names or identified phases given, this is a good exercise to check if you have mastered the determination of opaque minerals. By the way: not all polished sections have the same amount of synthetic phases.

Polished section T-16 Iron-ore, pellet and sinter, Tata Steel, IJmuiden

In this composite polished section you find a pellet and a sinter, both from the practice of the iron making process.

Pellet:

Main mineral: hematite.
Sporadic you may find: magnetite, silicate.

Pay attention to the pre structure. Can you find clear signs of sintering (sinter necks)? Has the sintering process proceeded just as far in all parts of the polished section? Are the pores interconnected?

Sinter:

Main minerals:

Hematite	
Magnetite	
Ca-ferrite	(needle-like crystal, rather low reflection, not to be determined by ore-microscopy.
Silicate	(unspecified)

Can you see newly formed hematite? Have there been more phases of formation of magnetite and hematite? Can you find reactions of the silicate material? Compare the pore structure of pellet and sinter.

Polished section series T-17. Steps of a milling process of a Pb-Zn-ore (Bad Grund, Germany)

You will find the following polished sections:

T-17/0	: the "original" broken Pb-Zn-ore, (from the cone crusher)
T-17/01 till T-17/03	: ore from the different milling steps.

Instruction:

1) Determine the two ore minerals and accessory minerals. What is the smallest grain size of the main minerals and accessory minerals?

2) Determine per milling step the amount of energy/ton, according to the Bond-formula.
Data: d_{80} of first feed: 500 μm. W_i : 12 Kwh/ton.
It is intended that you use the measuring eye-piece to determine in each one of the milling steps on average the mean grain size. You may use that as d_{80} of the feed of the following milling step. In practice of course an accurate sieve analysis is necessary. For simplicity that is omitted here.

3) Determine in which milling steps according to you most of the material is liberated (>90%). In practice of course an accurate determination of the amount of liberated material is necessary. This can be achieved by Quantitative Image Analysis.

4) Until what grain size one should continue milling to liberate the smallest of the ore grains? How much energy will this costs in Kwh/ton?
Make a graph of the grain sizes versus the necessary energy.

Polished section T-18 Sn-ore, Pamantoeh, Indonesia

Main mineral:

Cassiterite	- Grey, Reflection between 10 and 14 %. Very hard. Clearly pleochroitic. Anisotropy: DA, but difficult to determine because of the ubiquitous brown red internal reflections. Sometimes twinning is visible. Zoning is sometimes beautifully visible.

Study this section together with T-5.

Polished section T-19 Fe-Ore, Jack Hills Mine, W-Australia

Lump ore concentrate, broken, sieved at 10 – 15 mm, from a detritic iron ore deposit in the Jack Hills, W-Australia.

Minerals:

Hematite - White, SA, complex twinning. Sometimes red IR.
Magnetite - Brown, I, alteration to hematite.
Goethite - Grey, WA, Orange IR, fills spaces between grains, cement.

Polished section T-20 Cr-ore, Rustenburg, South Africa

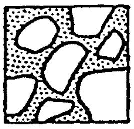
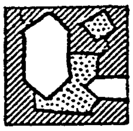
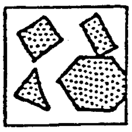
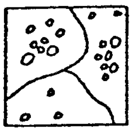
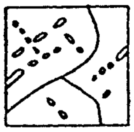
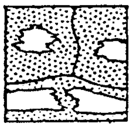
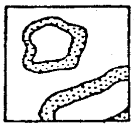
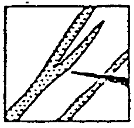
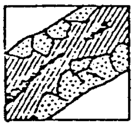
Chromitite from the socalled Upper Group (UG) ", Bushveld Complex. Of the 2 chromitite layers in Bushveld this is the second counted from below. This the socalled "UG-2 chromitite", which is economic the most important. T-20 is a sample of this.

Because of the sporadic occurrence of PGE (Platinum Group Elements) in the processing refining is applied to recover the PGE. However most of the PGE are found in the layer just abobe the UG-2: the socalled Merensdky Reef. This is a coarse grained norite/pyroxenite with minerals like *pyrrhotite* ($Fe_{1-x}S$), *pentlandite* ($(Ni, Fe)_9S_8$) with trace levels PGE, *laurite* (RuS_2), *braggite* (Pt,Pd, Ni)S, native *Pt,* e.d. .

Main mineral: *chromite*

Accessory: *pyrite, chalcopyrite*
Sometimes : *pyrrhotite*, *laurite* (RuS_2) as inclusion in *chromite* (zeldzaam)
Silicates: *plagioclase, orthopyroxene* (both not determinable in reflection).

APPENDIX 3. SOME CRITERIA FOR THE DETERMINATION OF THE RELATIVE AGE OF MINERALS.

	Embedded grains and fragments are older than the cementing matrix.
	Euhedral crystals are older than subhedral which are older than anhedral grains.
	Pseudomorphs (even after euhedral crystals) are younger than the host mineral.
	Inclusions are older than the host mineral.
	Oriented inclusions are often a product of exsolution. In this case they are of the same age or younger than the host mineral.
	Exsolutions indicate the same age of both neoformed phases.
	Replacement. Remnants embedded in neoformed mineral are older. Products of replacement are younger.
	Crusts, overgrowth, reaction rim and coating are younger than the core.
	Host mineral is older than veins. Crossing veins are younger than crossed ones.
	Mineral in central part of a vein is younger than others.

APPENDIX 4. TABLE FOR VHN_{100}

Prüfkraft P = 100 g

d in μ	Vickershärte HV									
	0	1	2	3	4	5	6	7	8	9
13	1097	1081	1064	1048	1033	1018	1003	988	974	960
14	946	933	920	907	894	882	870	858	847	835
15	824	813	803	792	782	772	762	752	743	734
16	724	715	707	698	689	681	673	665	657	649
17	642	634	627	620	612	606	599	592	585	579
18	572	566	560	554	548	542	536	530	525	519
19	514	508	503	498	493	488	483	478	473	468
20	464	459	454	450	446	441	437	433	429	425
21	420	417	413	409	405	401	397	394	390	387
22	383	380	376	373	370	366	363	360	357	354
23	351	348	345	342	339	336	333	330	327	325
24	322	319	317	314	311	309	306	304	302	299
25	297	294	292	290	287	285	283	281	279	276
26	274	272	270	268	266	264	262	260	258	256
27	254	253	251	249	247	245	243	242	240	238
28	237	235	233	232	230	228	227	225	224	222
29	221	219	217	216	215	213	212	210	209	207
30	206	205	203	202	201	199	198	197	195	194
31	193	192	190	189	188	187	186	185	183	182
32	181	180	179	178	177	176	174	173	172	171
33	170	169	168	167	166	165	164	163	162	161
34	160	159	159	158	157	156	155	154	153	152
35	151	151	150	149	148	147	146	146	145	144
36	143	142	142	141	140	139	138	138	137	136
37	135	135	134	133	133	132	131	130	130	129
38	128	128	127	126	126	125	124	124	123	123
39	122	121	121	120	119	119	118	118	117	116
40	116	115	115	114	114	113	112	112	111	111
41	110	110	109	109	108	108	107	107	106	106
42	105	105	104	104	103	103	102	102	101	101
43	100	99,8	99,4	98,9	98,5	98,0	97,6	97,1	96,7	96,2
44	95,8	95,3	94,9	94,5	94,1	93,6	93,2	92,8	92,4	92,0
45	91,6	91,2	90,8	90,4	90,0	89,6	89,2	88,8	88,4	88,0
46	87,6	87,2	86,9	86,5	86,1	85,8	85,4	85,0	84,7	84,3
47	83,9	83,6	83,2	82,9	82,5	82,2	81,8	81,5	81,2	80,8
48	80,5	80,2	79,8	79,5	79,2	78,8	78,5	78,2	77,9	77,6
49	77,2	76,9	76,6	76,3	76,0	75,7	75,4	75,1	74,8	74,5
50	74,2	73,9	73,6	73,3	73,0	72,7	72,4	72,1	71,9	71,6
51	71,3	71,0	70,7	70,5	70,2	69,9	69,6	69,4	69,1	68,8
52	68,6	68,3	68,0	67,8	67,5	67,3	67,0	66,8	66,5	66,3
53	66,0	65,8	65,5	65,3	65,0	64,8	64,5	64,3	64,1	63,8
54	63,6	63,3	63,1	62,9	62,6	62,4	62,2	62,0	61,7	61,5

Prüfkraft P = 100 g

d in μ	Vickershärte HV									
	0	1	2	3	4	5	6	7	8	9
55	61,3	61,1	60,8	60,6	60,4	60,2	60,0	59,8	59,5	59,3
56	59,1	58,9	58,7	58,5	58,3	58,1	57,9	57,7	57,5	57,3
57	57,1	56,9	56,7	56,5	56,3	56,1	55,9	55,7	55,5	55,3
58	55,1	54,9	54,7	54,5	54,4	54,2	54,0	53,8	53,6	53,4
59	53,3	53,1	52,9	52,7	52,5	52,4	52,2	52,0	51,8	51,7
60	51,5	51,3	51,2	51,0	50,8	50,7	50,5	50,3	50,2	50,0
61	49,8	49,7	49,5	49,3	49,2	49,0	48,9	48,7	48,5	48,4
62	48,2	48,1	47,9	47,8	47,6	47,5	47,3	47,2	47,0	46,9
63	46,7	46,6	46,4	46,3	46,1	46,0	45,8	45,7	45,5	45,4
64	45,3	45,1	45,0	44,8	44,7	44,6	44,4	44,3	44,2	44,0
65	43,9	43,7	43,6	43,5	43,3	43,2	43,1	43,0	42,8	42,7
66	42,6	42,4	42,3	42,2	42,1	41,9	41,8	41,7	41,5	41,4
67	41,3	41,2	41,1	40,9	40,8	40,7	40,6	40,5	40,3	40,2
68	40,1	40,0	39,9	39,7	39,6	39,5	39,4	39,3	39,2	39,1
69	38,9	38,8	38,7	38,6	38,5	38,4	38,3	38,2	38,1	37,9
70	37,8	37,7	37,6	37,5	37,4	37,3	37,2	37,1	37,0	36,9
71	36,8	36,7	36,6	36,5	36,4	36,3	36,2	36,1	36,0	35,9
72	35,8	35,7	35,6	35,5	35,4	35,3	35,2	35,1	35,0	34,9
73	34,8	34,7	34,6	34,5	34,4	34,3	34,2	34,1	34,0	33,9
74	33,9	33,8	33,7	33,6	33,5	33,4	33,3	33,2	33,1	33,0
75	33,0	32,9	32,8	32,7	32,6	32,5	32,4	32,4	32,3	32,2
76	32,1	32,0	31,9	31,8	31,8	31,7	31,6	31,5	31,4	31,4
77	31,3	31,2	31,1	31,0	30,9	30,9	30,8	30,7	30,6	30,6
78	30,5	30,4	30,3	30,2	30,2	30,1	30,0	29,9	29,9	29,8
79	29,7	29,6	29,6	29,5	29,4	29,3	29,3	29,2	29,1	29,0
80	29,0	28,9	28,8	28,8	28,7	28,6	28,5	28,5	28,4	28,3
81	28,3	28,2	28,1	28,0	28,0	27,9	27,8	27,8	27,7	27,6
82	27,6	27,5	27,4	27,4	27,3	27,2	27,2	27,1	27,0	27,0
83	26,9	26,8	26,8	26,7	26,7	26,6	26,5	26,5	26,4	26,3
84	26,3	26,2	26,2	26,1	26,0	26,0	25,9	25,8	25,8	25,7
85	25,7	25,6	25,5	25,5	25,4	25,4	25,3	25,2	25,2	25,1
86	25,1	25,0	25,0	24,9	24,8	24,8	24,7	24,7	24,6	24,6
87	24,5	24,4	24,4	24,3	24,3	24,2	24,2	24,1	24,1	24,0
88	23,9	23,9	23,8	23,8	23,7	23,7	23,6	23,6	23,5	23,5
89	23,4	23,4	23,3	23,2	23,2	23,1	23,1	23,0	23,0	22,9
90	22,9	22,8	22,8	22,7	22,7	22,6	22,6	22,5	22,5	22,4
91	22,4	22,3	22,3	22,2	22,2	22,1	22,1	22,0	22,0	22,0
92	21,9	21,9	21,8	21,8	21,7	21,7	21,6	21,6	21,5	21,5
93	21,4	21,4	21,3	21,3	21,3	21,2	21,2	21,1	21,1	21,0
94	21,0	20,9	20,9	20,8	20,8	20,8	20,7	20,7	20,6	20,6
95	20,5	20,5	20,5	20,4	20,4	20,3	20,3	20,2	20,2	20,2
96	20,1	20,1	20,0	20,0	20,0	19,9	19,9	19,8	19,8	19,7

APPENDIX 5. LIST OF COMMON OPAQUE MINERALS AND THEIR PROPERTIES.

(Compiled by dr. R.A. Kühnel)

EXPLANATIONS AND ABBREVIATIONS

Optical categories :	I	isotropic		
	WA	weakly anisotropic		
	DA	distinctly anisotropic		
	SA	strongly anisotropic		
	EA	extremely anisotropic		
Reflectance :	R	(%)		
Vickers hardness no.	VHN			
Colours :	G	green	g	greenish
	B	blue	b	bluish
	Y	yellow	y	yellowish
	CR	cream		
	O	orange		
	R	rose		
	V	violet	v	pinkish
	BR	brown	br	brownish
	GR	grey	gr	greyish
	W	white		
Internal reflections	IR	abundant		
	ir	rare		
Diagnostics	tw	twinning		
	zo	zoning		
cl common	col	colloform		
cl often	i	isometric crystals		
(cl) rare	el	elongated crystals		
	f	flat crystals		
	d	dendritic crystals		
	cl	cleavage		
	ex	exsolutions		
Pleochroism	P			

LIST OF SOME COMMON ORE MINERALS AND THEIR PROPERTIES

	Mineral name Chemical formula	Colour Pleochroism	Optical category	R %	VHN range	IR	Other diagnostics
1.	ANATASE TiO_2	GR	WA-DA	20	576-	IR (b-w)	i,el
2.	ARGENTITE (ACANTHITE) Ag_2S	GR,g	I (WA-DA)	30.1 31.2	20-61		tw
3.	ARSENOPYRITE FeAsS	cr,v,W	DA-SA	49.3- 52.6	715- 1354		i,el,tw,zo
4.	AZURITE $Cu_3(CO_3)_2(OH)_2$	GR,b P	WA-DA	7-9	100-300	IR (blue)	el
5.	BISMUTH Bi	cr,W P	DA-SA	55.1- 69.3	10- 19		tw,cl
6.	BISMUTHINITE Bi_2S_3	W (P)	EA	36.8- 50.6	67- 216		tw,cl,(el)
7.	BORNITE Cu_5FeS_4	V,O	WA	16.6- 25.8	68- 105		tw,cl
8.	BRAVOITE $(Fe,Ni,Co)S_2$+Cu	CR,R,br	I - WA	30.9 53.9	668-1535		zo,i
9.	CARROLITE Co_2CuS_4	cr,W,r	I	42.6	351- 566		i,(zo)
10.	CASSITERITE SnO_2	br,GR P	DA	10.5- 13.1	811- 1532	IR (y,br,r)	tw,cl,zo,col
11.	CHALCOCITE Cu_2S	b,W	WA-DA	30	58- 98		tw, ex
12.	CHALCOPYRITE $CuFeS_2$	Y	WA-DA	34- 51.4	174- 219		tw
13.	CHROMITE $FeCr_2O_4$	GR	I	11.2- 13.8	1036- 2000	IR (br)	i,zo,d
14.	CINNABAR HgS	W,b-gr	DA	24.5 29.3	51-98	IR (red)	i
15.	COBALTITE (Co,Fe)AsS	v,W	WA-DA	56.2	948- 1367		i,cl,tw,zo
16.	COLUMBITE- TANTALITE $(Fe\lessgtr Mn)(Nb\gtrless Ta)_2O_6$	GR,W,br	DA	15.3 17.7	240 1021	ir (y-br) (red)	cl,tw,f,d

Mineral name Chemical formula	Colour Pleochroism	Optical category	R %	VHN range	IR	Other diagnostics
17. COPPER Cu	V	I	38– 79	48– 143		tw, zo
18. COVELLITE CuS	B	EA	5.9– 27.5	59– 129		f, el, cl
19. CRYPTOMELANE $(K,Na,Ba)Mn_8O_{16}$	GR, b	DA SA	26– 27	525 1048		el, evl (radial aggr.)
20. CUBANITE $CuFe_2S_3$	cr, GR P	SA	39.2– 42.2	150– 264		f, ex
21. CUPRITE Cu_2O	b, GR	SA	25– 30	179– 218	IR (red)	cl
22. DIGENITE $Cu_{1.765}S$	gr, B	I	20– 21.3	56–83		reaction rims, ex
23. ENARGITE Cu_3AsS_4	v, GR (P)	SA	25.1–	133–	ir	el, cl, tw, zo
24. GALENA PbS	b, W	I	43.1– 47.9	56– 116		cl, tw, zo
25. GERMANITE Cu_6FeGeS_8	R, V	I	19.7–26.2	372–450		zo
26. GOETHITE FeOOH	GR	DA	15–	525–	IR (Y,O)	col, zo, el
27. GOLD Au	Y	I	>60	41– 94		d, zo, (el)
28. GRAPHITE C	BR P	EA	5– 20	7– 12		f, cl
29. HEMATITE Fe_2O_3	GR P	DA–SA	22.8– 31.5	739– 1114	IR (red)	f, el, cl, tw, col
30. HETEROGENITE $CoOOH.H_2O$	cr, W P	EA	10– 25	517– 572		cl, col
31. ILMENITE $FeTiO_3$	BR P	SA	16.6– 20.2	501– 752	ir (br, red)	tw, ex
32. JAMESONITE $4PbS.FeS.Sb_2S_3$	W, GR (P)	DA-SA	34.7 40.6	67–126	(red)	el, cl, tw
33. LINNAEITE Co_3S_4	CR, W, r	I	45–50	351–566		i, cl

Mineral name Chemical formula	Colour Pleochroism	Optical category	R %	VHN range	IR	Other diagnostics
34. LITHIOPHORITE $(Al,Li)MnO_2(OH)_2$	W, GR	EA	10-20	60-100		f, col, cl
35. LOELLINGITE $FeAs_2$	W, y	SA	55	368-1048		zo, el, d, tw
36. LUZONITE $Cu_3(As,Sb)S_4$	R, O, V	SA	24.8-26.0	205 397		tw
37. MACKINAVITE FeS	R, GR, (br) P	EA	21.8 46.0	52-58		cl veins, ex
38. MAGNETITE $FeFe_2O_4$	GR	I	20.6- 21.1	440- 1100		i, el, tw, zo, (ccl)
39. MALACHITE $Cu_2(CO_3)(OH)_2$	GR, g	DA	6-9.5	100-300	IR (green)	el
40. MARCASITE FeS_2	y, W (P)	SA	44.8- 53.2	762- 1561		col, (el), tw, zo
41. MILLERITE NiS	Y P	SA	51.5 59	192-376		el, cl, zo
42. MOLYBDENITE MoS_2	b, W P	EA	20.1- 47	16- 101		f, col, cl, tw
43. NICCOLITE $NiAs$	y, v, O P	EA	38.5- 62.4	308- 533		tw
44. PENTLANDITE $(Fe,Ni)_9S_8$	CR, g	I	44.1 47.0	202-231		i, cl, ex (flame-like incl.)
45. PROUSTITE $3Ag_2S.Sb_2S_3$	b, GR P	SA	25- 28	50- 156	IR (red)	tw, zo
46. PSILOMELANE $Ba_3Mn_8O_{16}(OH)_6$	b, w, GR P	SA	15- 30	203- 813	ir (br, r)	col, (el)
47. PYRARGYRITE $3Ag_2S.Sb_2S_3$	b, GR	DA	28-31	50-156	ir (red)	tw, zo
48. PYRITE FeS_2	Y	I - WA	46- 55.9	913 2056		i, zo, col
49. PYROLUSITE MnO_2	W P	EA	27.2- 40.8	76- 1500		el, cl, tw, (zo)
50. PYRRHOTITE FeS	v, CR P	SA - EA	30.9- 42.5	230- 390		(cl), tw, (zo)

Mineral name Chemical formula	Colour Pleochroism	Optical category	R %	VHN range	IR	Other diagnostics
51. RAMMELSBERGITE $(Ni,Co,Fe)As_2$	W	SA	60	459-830		tw, zo, f, el, d
52. RENIERITE $Cu_{3-x}Ge_xFeS_4$	O, BR	DA SA	23.4 29.4	295-425		(tw)
53. RUTILE TiO_2	b, GR P	SA	19.4-24.6	933-1280	IR (y-red)	cl, tw, el
54. SCHEELITE $CaWO_4$	W, GR	DA	9.9-10.5	285-464	IR (white)	zo
55. SILVER Ag	cr, W	I	90-95	46-118		tw, zo
56. SKUTTERUDITE $(Co,Ni,Fe)As_3$	cr, br, W	I, (WA)	52.9-53.8	268-974		cl, zo
57. SPHALERITE ZnS	GR	I	16.9-20.0	128-276	IR	(cl), tw, zo
58. SPINEL $(Mg,Fe,Mn,Zn)(Al,Cr)_2O_4$	GR	I	< 10	>1000	IR	i, (tw)
59. STANNITE Cu_2SnFeS_4	br, g, GR	SA	24.4-29.8	140-326		cl, tw, zo
60. STIBNITE Sb_2S_3	gr, W P	EA	30.2-50.4	42-129		tw, zo, el
61. TENNANTITE Cu_3AsS_3	GR	I	23.2-31.4	251-400	ir (red)	(cl)
62. TENORITE CuO	GR, gr, W P	SA	20-25	203-254		tw
63. TETRAHEDRITE Cu_3SbS_3	GR	I	29.0-33.2	251-425	(red)	cl, zo
64. URANINITE UO_2	br, GR	I	17.1	625-929	ir (brown)	(cl), tw, zo, col
65. WOLFRAMITE $(Mn,Fe)WO_4$	GR, W (P)	WA	15.7-18.7	258-657	ir (red)	el, zo, cl, tw
66. ZIRCON $ZrSiO_4$	GR	DA	10.9-11.9	1000	IR (white)	zo, el, i

APPENDIX 6. INTERACTION OF LIGHT WITH OPAQUE MINERALS (REFLECTED LIGHT OPTICS).

A. INTRODUCTION

This text is an attempt to explain some theoretical backgrounds of the optics of opaque minerals, starting from the optical crystallography of transmitted light microscopy. We will treat the following concepts.

- linear, circular and elliptical polarization
- uni-axial and bi-axial minerals, optical axes, indicating surface.
- reflection, bireflection, reflection pleochroism
- symmetrical sections, extinction
- change of polarization by non-perpendicular incidence of light.
- convergent-light figures ("axial images")

The optical crystallography terminology as used in the lecture and practical series TA1900 is supposed to be known. However, you will see that you can apply only little of that in the optics of opaque minerals.

B. GENERAL CONCEPTS

1. Reflection

When light hits a polished surface, a large part of that light is reflected, this reflectance ***R*** is expressed as a percentage of the intensity of the incident light. When this incident light is perpendicular to the surface, the reflectance R is related as follows to the optical constants ***N***, ***n*** and ***k:***

$$\boxed{R = \frac{(n - N)^2 + k^2}{(n + N)^2 + k^2}}$$

Here ***N*** is the refractive index of the immersion medium (often air), ***n*** the refractive index of the material, and ***k*** is the absorption coefficient. This equation is called the *Fresnel*[8] *Equation*. Reflection is thus a real number with a value between 0 and 1. However, usually the reflection is expressed in *percent of the intensity* of the incident light.

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[8] *Augustin-Jean Fresnel* (Broglie, May 10, 1788 – Ville-d'Avray, Juli 14, 1827) was a French engineer and physicists, who has made great contributions to optics (including fundamentals of polarized light optics).

2. Refractive index

The ***refractive index of opaque phases*** can be expressed as an ***imaginary number:***
$n_c = n + ik$

In the case of air, with $N \approx 1$, the Fresnel Equation is then reduced to:

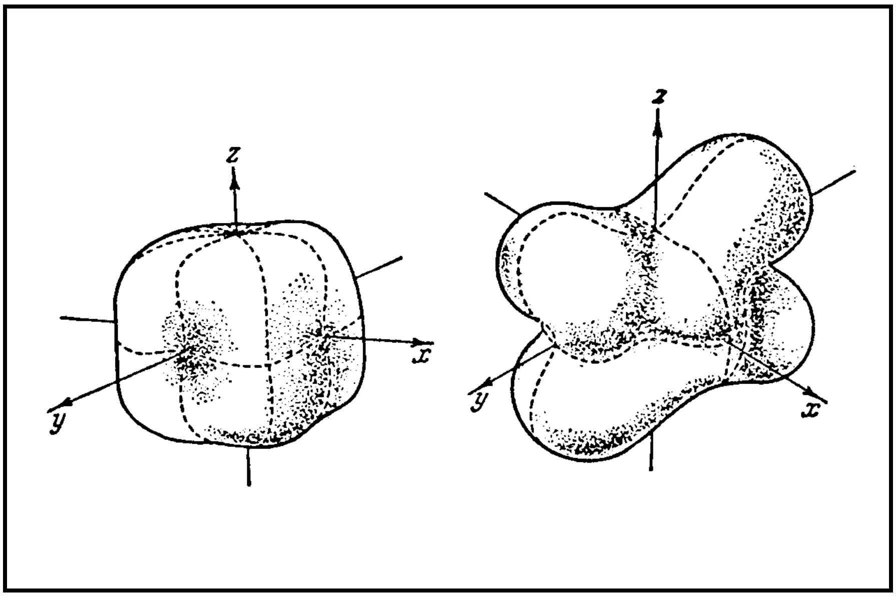
$$\boxed{R_{air} = \frac{(n_c - 1)^2 + k^2}{(n_c + 1)^2 + k^2}}$$

In microscopy, also other immersion media may be applied instead of air, such as water (***N*** = 1.33), or immersion oils (a commonly used oil in ore microscopy has a refractive index of N = 1.5180).

3. Indicating Surfaces

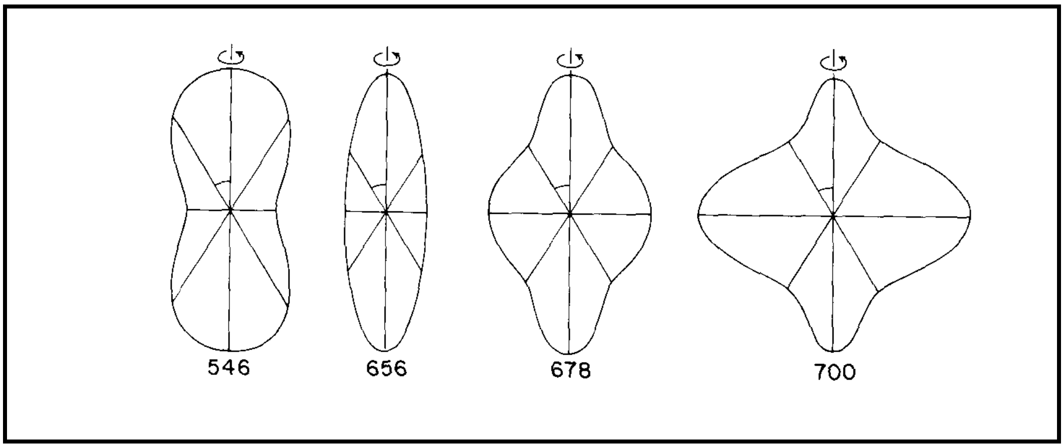
As you have learned in the course TA1900, in transmitted-light polarization microscopy a so-called indicating surface (the indicatrix) is used to show the relations hip between crystal structure and refractive index.

Also in reflected light optics indicating surfaces are used. It stands to reason that here ***not*** an indicating surface for the ***refractive index*** is meant: the refractive index is of course ***an imaginary number.*** Usually the ***indicating surface for the <u>reflection</u> is used,*** as this quantity can be easily determined. If in the following the term indicating surface is used, it will be for reflection.



Three-dimensional representations of indicating surfaces of opaque minerals (after Kühnel, Prins and Roorda (1980).The surfaces constructed are for ***reflection***, not ***refraction*** (which is an imaginary number)

Also in discrepancy with transmitted-light optics, the indicating surfaces are not ellipsoids (of revolution), but have a more complicated form. See for instance the image above, or the image below, of which the latter shows sections through the indicating surfaces of covellite (CuS) for different wavelengths.



Sections through the indicating surface for reflection of covellite (CuS) for different wavelengths in nm (after Craig and Vaughan, 1994).

4. Elliptical polarization

In reflection we have to deal with the phenomenon of elliptical polarization. A linearly polarized light ray that is reflected from a non-isotropic surface will be split in two rays, each with a different velocity, analogous to the splitting of a linearly polarized light beam which travels through a transparent material. In reflection, interference of the partial rays occurs, which leads to elliptical polarization. The nature of this wave motion will depend on the difference in *amplitude* and *phase* of the two original waves.

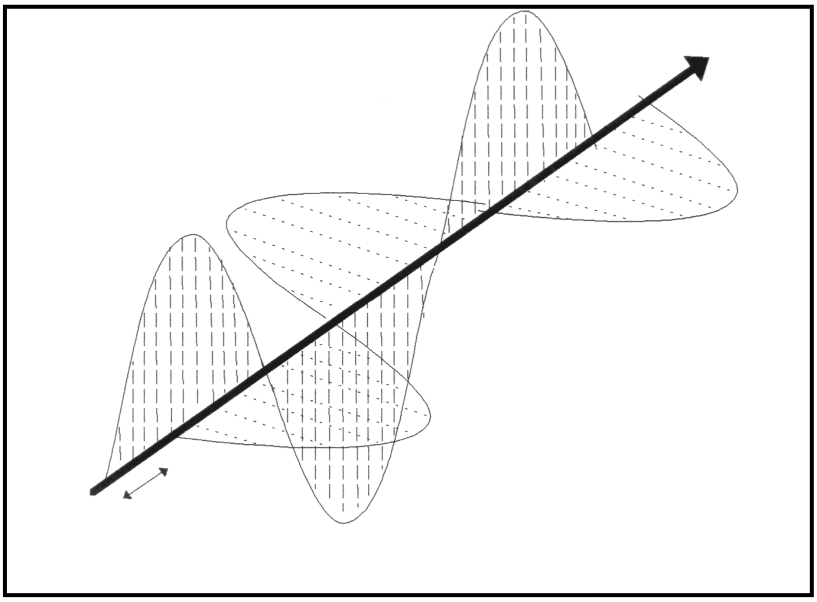
Examples:

- There is no difference in phase and in amplitude. The resulting wave is linearly polarized and the directions of vibration make an angle of 45° with each of the original directions.
- There is no difference in phase, but a difference in amplitude. The resulting wave is linearly polarized and the directions of vibration make an angle of 45° with each of the original directions.
- There is a difference in phase, but not in amplitude. The resulting wave is not linearly polarized.

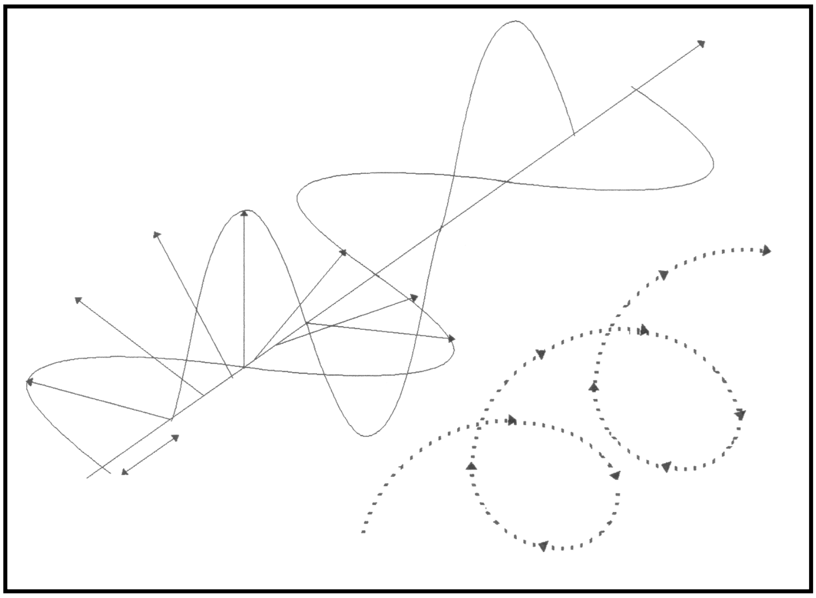
The resulting wave is elliptically polarized, and propagates itself in a screw like fashion.
At equal amplitude we can distinguish two cases:

a) The phase difference is equal to $(2n+1)/4\lambda, \quad (n = 0,1,2,3,4,...)$.

The minimum of the one wave coincides with the maximum of the other wave. From this originates circular polarization. The vibration vectors are always of equal length, but they rotate, following the line of propagation, around this line. When we look in a plane perpendicular to the direction of propagation, the cross section of the wave is circular.
b) The phase difference is not equal to $(2n+1)/4\lambda, \quad (n = 0,1,2,3,4,...)$
(The waves are out of phase by another number than ¼ λ or multiples of this).
The minimum of the one wave does not coincide with the maximum of the other wave. The vibration vectors in this case are also not always of equal length. The cross section of the wave, viewed in a plane perpendicular to the direction of propagation, is ellipsoidal. (In case the waves would be out of phase by ¼ λ, the vibration vectors would be of equal length, and the cross section would be circular). The previous case is called elliptic polarization. In case there is difference of phase and of amplitude, we also get elliptical polarization.



Schematic representation of the phase difference.



Schematic representation of the resulting wave,
which spirals like a cork screw in the direction of movement.

C. REFLECTION OF MONOCHROMATIC LINEARLY POLARIZED LIGHT BY AN ISOTROPIC SURFACE.

When a beam of linearly (plane) polarized light is reflected from an isotropic surface, which is perfectly *flat*, and when the incident light beam is *perpendicular*, then the polarization of the beam of light is ***not*** changed. ***R*** is then given by the Fresnel Equation. The indicating surface is a ***sphere***. The reflection ***R*** of an isotropic material is the same in all directions.

D. REFLECTION OF MONOCHROMATIC LINEARLY POLARIZED LIGHT BY AN ANISOTROPIC SURFACE.

Just like in transmitted-light polarization microscopy, we can divide the minerals in uni-axial and bi-axial minerals. Minerals with tetragonal, hexagonal or original symmetry are uni-axial; those with a monoclinic or triclinic symmetry are bi-axial.

Now there are also isotropic sections through crystals from these systems. Just like in transmitted light polarization microscopy, the following sections are isotropic:

- Basal sections through crystals with a tetragonal symmetry (section perpendicular to the c-axis).
- Basal sections through crystals with a hexagonal symmetry (section perpendicular to the c-axis).
- Basal sections through a crystal with a trigonal symmetry ((section perpendicular to the c-axis).

1. Uni-axial minerals.

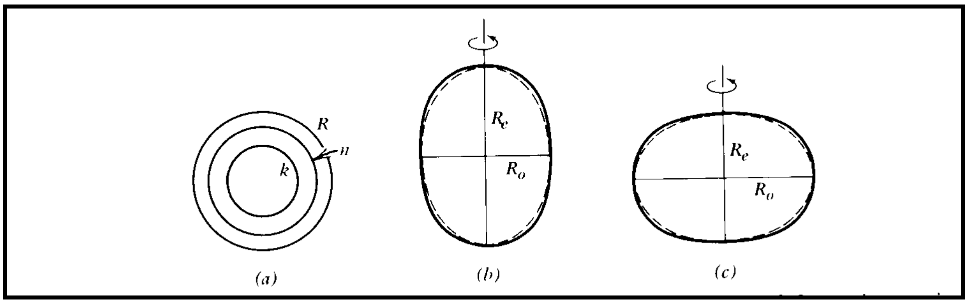
The indicating surface is an ellipsoid of revolution. Analogous to the situation with transparent minerals, there is a section through the indicating surface which is circular. The line perpendicular to this section is also called the *optical axis*.

Also analogous are the names of the directional vibrations:

- Parallel to the optical axis: extra ordinary direction. The reflection in this direction is indicated with $\boldsymbol{R}_e$
- Perpendicular to the optical axis: The reflection in this direction is indicated with $\boldsymbol{R}_o$

Again analogous to the optics of transparent minerals is the indication of the optical sign:
$\boldsymbol{R}_e > \boldsymbol{R}_o$: positive, +
$\boldsymbol{R}_e < \boldsymbol{R}_o$: negative, -

The optical axis is with uni-axial minerals parallel to c-axis and $\boldsymbol{R}_o$ is parallel to the optical isotropic basal plane. Examples of uni-axial opaque minerals are: c*ovellite, nickeline (niccolite), chalcopyrite.*



Sections through indicating surfaces: (a) R, n, k (cubic material,) (b) only the R-surface: uni-axial (+), (c) idem, uni-axial (-). After Galopin & Henry (1972).

For the refractive index ***n*** and the absorption coefficient k other indicating surfaces are defined, but they have the ***same*** optical axis in common. The dashed lines in the figure indicate the ellipsoids.

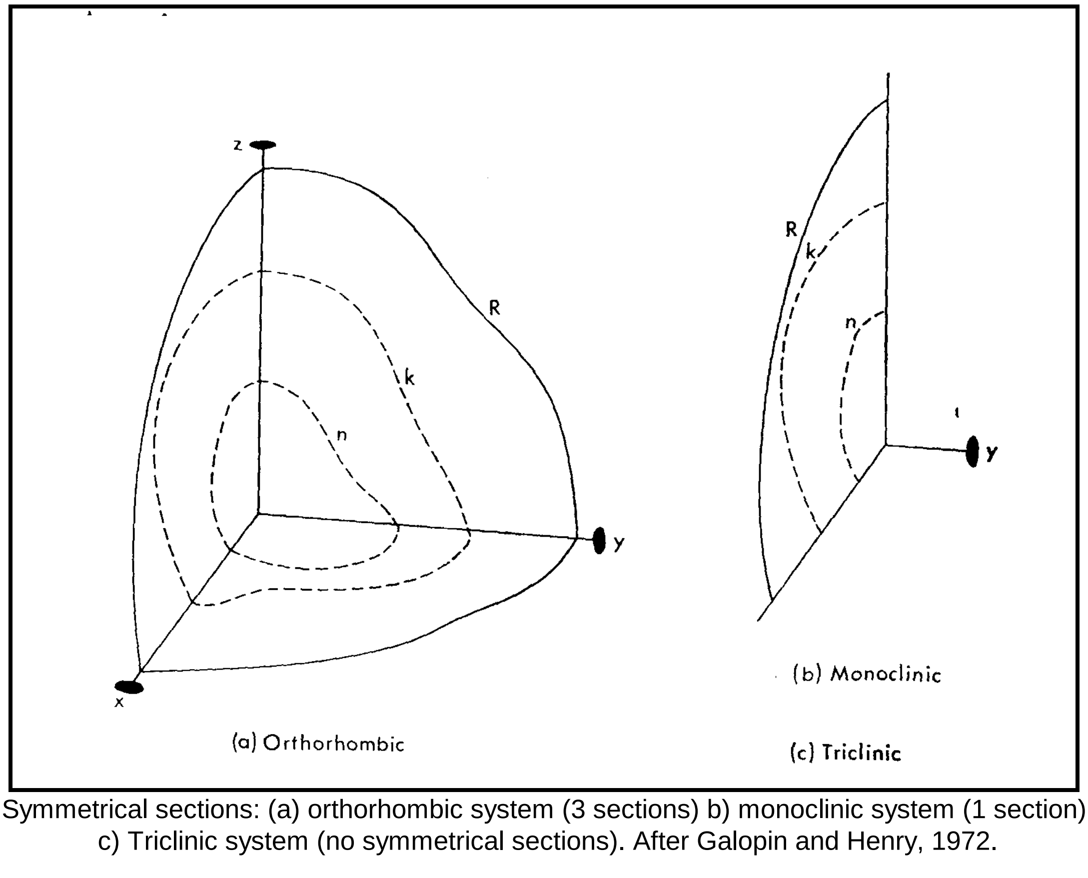
The difference between $\boldsymbol{R}_e$ and $\boldsymbol{R}_o$ is called the *bireflection* of the uni-axial mineral. The bireflection is very important in identification.

Perpendicular incident light which is reflected from an isotropic section of the mineral remains linearly polarized. This is not true for any other section.

2. Bi-axial Minerals

Minerals from the rhombic, monoclinic or triclinic system may be called bi-axial, analogous to the situation for transparent minerals. The difference with transparent minerals has, however, become very large now. The bi-axial indicatrix for transparent minerals is called this way, because there are two circular cross sections, with perpendicular to them the optical axes. Along these axes, the light is transmitted in a linearly polarized way, without change in the polarization. For bi-axial opaque minerals, there are just as well two axes, but they do ***NOT*** coincide for ***n*** (refractive index), ***k,*** (absorption) and ***R (***reflection). ***Therefore there are no isotropic sections!*** In order to be able to say something more, we have to make a distinction between crystals from the rhombic, monoclinic and triclinic system. Also we will have to discuss the concept of ***symmetrical sections.***

In the rhombic system there are three perpendicular symmetry planes. Perpendicular to every plane there is a twofold symmetry axis. Linearly polarized light, which is incident on such a plane remains linearly polarized on reflection. Such a plane contains therefore two mutually perpendicular symmetry lines. ***These lines are called symmetrical sections.***



Symmetrical sections: (a) orthorhombic system (3 sections) b) monoclinic system (1 section) c) Triclinic system (no symmetrical sections). After Galopin and Henry, 1972.

Such a section exhibits extinction with 90° crossed polars, if one of the symmetry lines is parallel to the analyzer or polarizer. On rotating the microscope table, this occurs 4 times for every full revolution (analogous to the situation in transmitted light). For all other directions through a rhombic crystal, in reflection elliptical polarization occurs. These sections will NOT extinguish with 90° crossed polars: there is always light that can pass the analyzer.

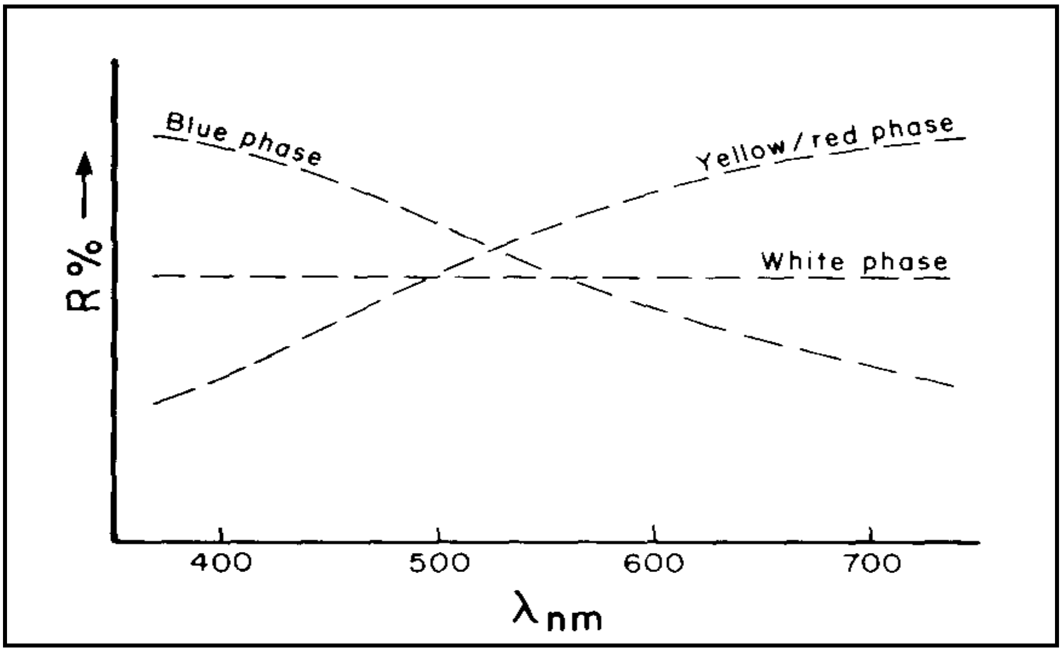
For a *monoclinic crystal,* ***only a section perpendicular to the twofold axis*** is symmetrical, and will ***show extinction.*** *Triclinic crystals* **do not have any** symmetrical sections. ***No section through the crystal of whatever orientation will show extinction.***

However, in the not extinguishing sections in these systems there are ***maxima*** and ***minima*** in the light intensity, when rotating the table by 360°. It can be shown, that these positions do ***not necessarily*** have to coincide with the 45° positions (Galopin and Henry, 1972).

For a rhombic, monoclinic or triclinic crystal there are three values for the reflection ($\boldsymbol{R}_{\alpha}$, $\boldsymbol{R}_{\beta}$, $\boldsymbol{R}_{\gamma}$). For determination, only the difference between the largest and the smallest value is of importance, analogous to the situation for transparent minerals. This difference between minimum and maximum reflection is called ***bireflection***. Examples of bi-axial minerals; *enargite (orthorhombic), rammelsbergite (orthorhombic), jamesonite (monoclinic), wolframite (monoclinic), arsenopyrite (triclinic).*

E. REFLECTION OF LINEARLY POLARIZED “WHITE” LIGHT.

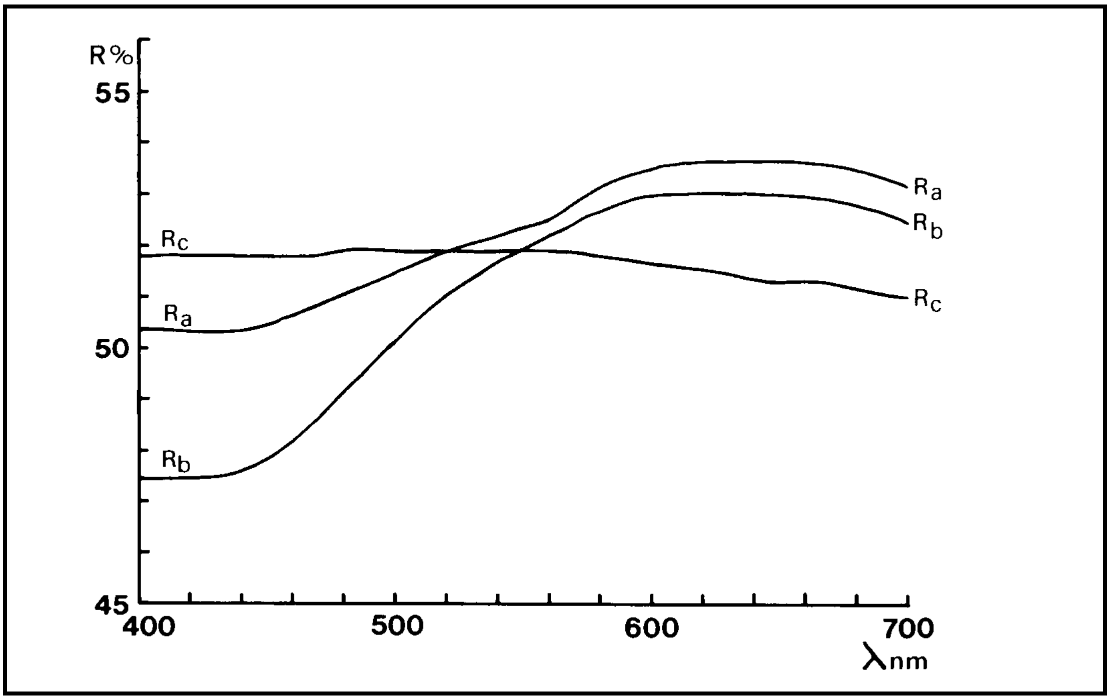
When dealing with "white" light (meaning ***non-monochromatic light***, but light consisting a variety of wavelengths), we must take into account that ***N***, ***k*** as well as ***R*** may ***vary with change of orientation*** and ***with change of wavelength.***



Examples of dispersion curves for a yellow/red material, a blue material and a white material. (After Craig and Vaughan, 1994).

The variation of the reflection with wavelength is called ***dispersion***, and has been measured for many minerals. A general example is given in the figure above. Here the dispersion curves are given for a (not further specified) red material (higher reflection around 700 nm), a blue material (higher reflection around 400 nm), and a white material (horizontal line).

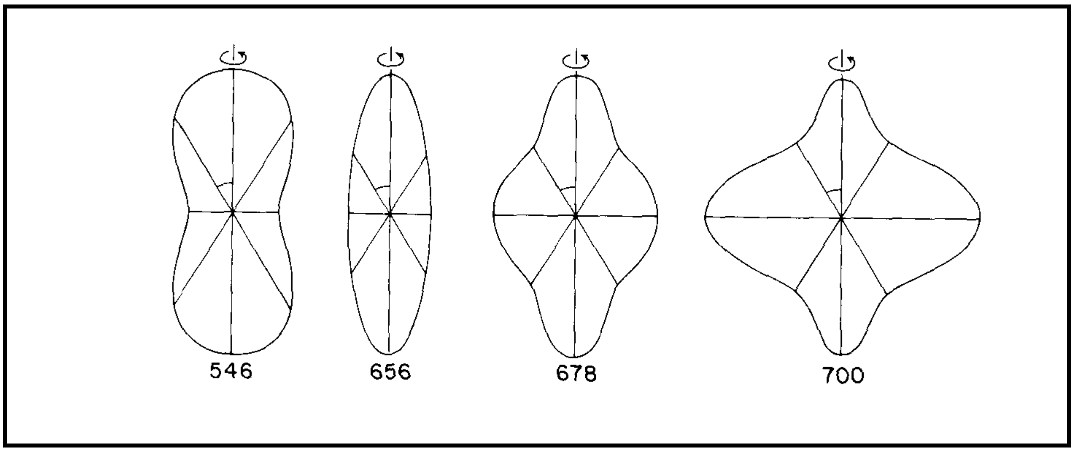
For uni-axial minerals we get spectral dispersions for $\boldsymbol{R}_e$ and $\boldsymbol{R}_o$ and if the dispersion curves differ appreciably, the material shows another color with change of orientation: ***Reflection pleochroism.*** For bi-axial minerals the situation is analogous: we have then an $\boldsymbol{R}_\alpha$, an $\boldsymbol{R}_ß$, and an $\boldsymbol{R}_\gamma$. A real example is shown in the figure below.



Spectral reflection curves of arsenopyrite. After Bowie and Simpson, in Zussman (1977)

As told before, we work with the difference between the largest and the smallest value of the reflection. The color changes that belong to these are tabulated. By the way, the color changes may be difficult to see, while the value for the reflection differs significantly. ***Bireflection always accompanies reflection pleochroism.***

In the figure below we see sections through the indicating surface of covellite at different wavelengths. The large variation is also an expression of the strong reflection pleochroism of this mineral. You may compare this with ***the elliptical section*** (Dutch: ellips van doorsnede) of a transparent mineral.



Sections through the reflectivity surface of covellite (CuS) for different wave lengths (after Craig and Vaughan (1994).

F. REFLECTION BETWEEN CROSSED POLARS ("WHITE"[9] LIGHT)

For many opaque minerals, the optical constants ***n*** and ***k*** change with the wavelength, and so does the reflection (dispersion). The mineral acquires a color. Also the degree of anisotropy may change with wavelength. This leads to anisotropic interference colors, which may be seen with crossed polars. In the figure below, it is shown schematically how this works for a symmetrical section. The analyzer A is vertical, the polarizer P is horizontal. E is the original direction of vibration. The section has been turned by an angle α out of its extinction position. E_1 and E_2 are the resolved directions of vibrations. R_1 and R_2 are the resolved reflections. In the figure, the reflection R1 is not equal for red and blue. As a result of this the amplitude transmitted by the analyzer (OT) will be greater for blue than for red. In this position, the section shows a blue shade.

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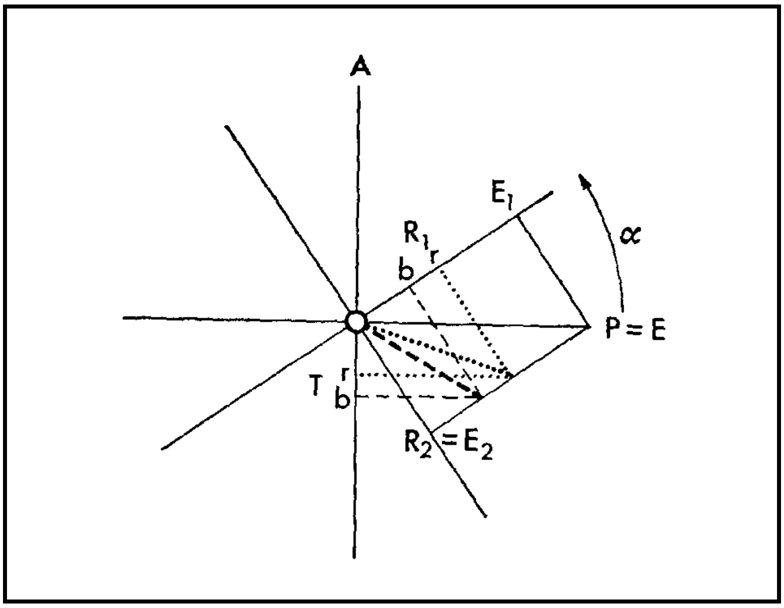
[9] White light means here non-monochromatic light, so light consisting of a variety of wavelengths.



Dispersion of the rotation in a symmetric section. Crossed polars. A= Analyzer, P=Polarizer, E=original direction of vibration, E_1, E_2 = resolved components. After Craig and Vaughan (1994).

When the analyzer and polarizer are not perfectly crossed (so not at 90°), one usually sees other shades of colors than when the polars are crossed exactly at 90°. There is a certain systematic in this, per mineral, which tells something about the dispersion, but for diagnostics this is not applicable.

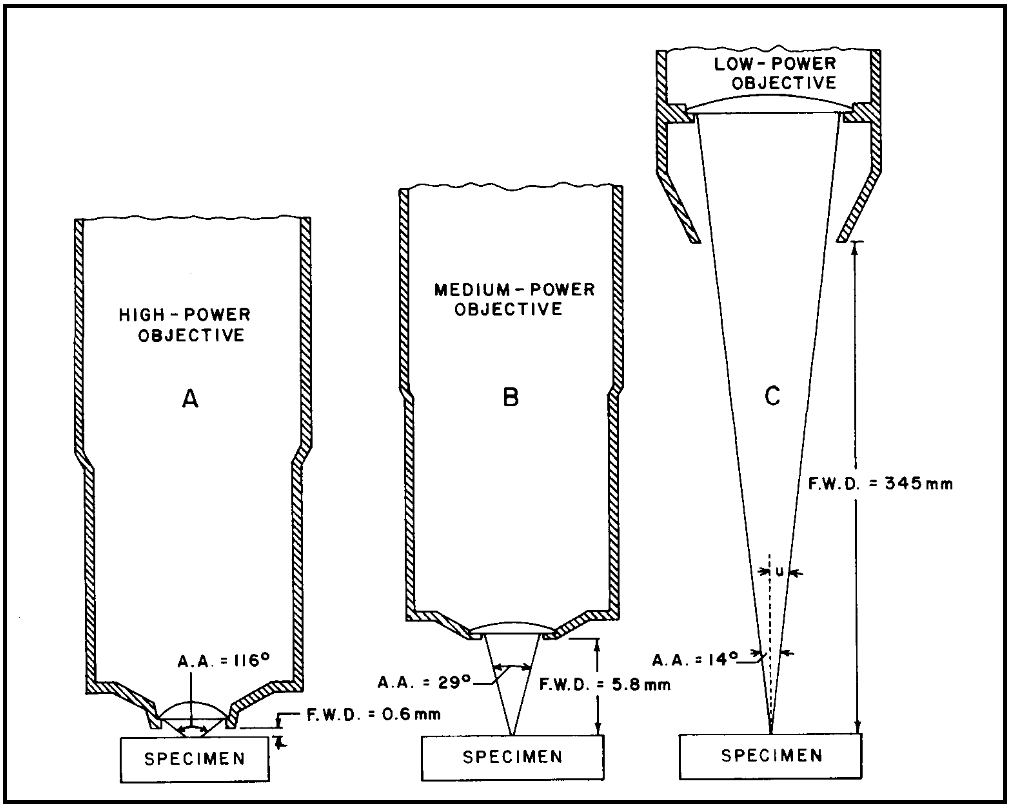
For minerals with weak anisotropy, the analyzer is usually not crossed at 90°, but "uncrossed" with 2 to 5 degrees. Besides en slight change of the shades of the colors, also the light intensity of the interference colors is increased substantially. The anisotropy then becomes better visible. This can be understood by examining the figure above. When we turn the analyzer a little from the vertical position, the length of OT(r) and OT(b) becomes larger.

In reflection one usually encounters dispersion, with a result that the interference colors are "anomalous". There is NO systematic relationship between the interference colors, as in the case of transparent minerals (Michel Levy Color Chart).

G. CHANGE OF THE POLARIZATION BY OBLIQUE INCIDENCE OF LIGHT.

When linearly polarized light has oblique incidence on a reflecting material, a distortion of the polarization occurs. Oblique incidence of light on a polished section causes the section to be lighted up. If complete extinction would be present, this will be cancelled.

In case of an isotropic material, the intensity of the light does not change when rotating the table. Also the color does not change. When there is reflection on a non-isotropic surface, the rotation of the polarization is superimposed the rotation caused by the anisotropy. As we always deal in microscopy with a light cone, an isotropic mineral will in reflection never be completely dark. The degree of oblique incidence becomes larger when a higher magnification is used. The rotation effect will then become stronger. See the figure below.

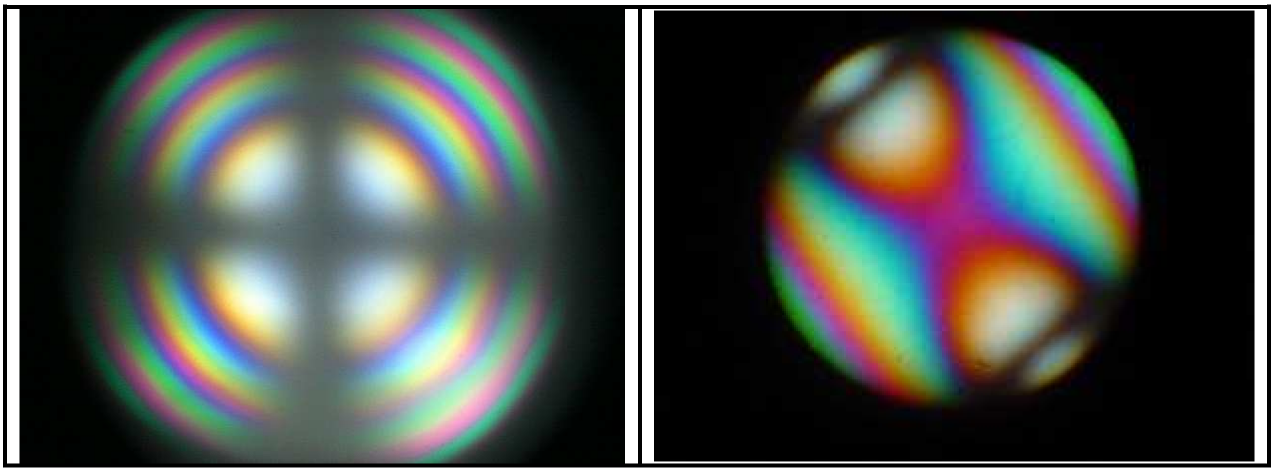


Aperture angles (A.A.) of different microscope objective lenses, after Bloss, (1961)

The effects of anisotropy will therefore become diluted at high magnification. Anisotropy will thus be more difficult to see at high magnification. Isotropic crystals (e.g. pyrite) are slightly colored at high magnification (greenish/brownish), but the color will not change when the table of the microscope is rotated.

H. KONOSKOPIC INVESTIGATION.

Under a microscope, a cone of incident light is produced by the objective lens, and the top angle of the light cone increases with increasing numerical aperture of the objective. When we are dealing with a large top angle, we may make an image in convergent light. With increasing obliqueness of the incident light, the reflection rotation increases. When we use a Bertrand lens, (or remove the ocular lens), we will see an image that resembles the well-known convergent light images of transparent minerals. See image below. Every point in the image represents a different direction of the incident light.



Convergent light images of ***transparent*** minerals. In the left figure, the image of an uni-axial mineral is given, in the right that of a bi-axial mineral in the 45° position. As there is ***no effective ray path through an opaque mineral,*** in ore microscopy such images are ***meaningless*** for the mineral under consideration, and only represent information on the objective lens.

1. Isotropic sections

Along the crosshairs, only one component of the light is present. Here there is no rotation of the polarization. The image is black. At other places there is rotation, and this increases going outward. An image results that strongly resembles that of an uniaxial mineral (left image above). ***When rotating the table, the cross remains stationary.*** The same holds for isotropic sections of uni-axial minerals.

2. Anisotropic sections

The effect of the reflection rotation is superimposed on the anisotropic rotation of the polarization. As a result, when rotating the table, the cross will split into two isogyres (right image). ***This happens for uni-axial and bi-axial minerals!!!***

3. Relevance of konoskopic images (convergent light images) for determination

In contrast to transparent minerals, where konoskopic images are important, in reflection polarization microscopy (ore microscopy) such images contain no information that could not be accessed by orthoscopic images. ***This is because there is no effective ray path through the mineral.***

An isotropic mineral gives an interference figure which is a non-opening black cross, analogous to the image for an uni-axial transparent mineral. An opening cross can be observed for uni-axial and bi-axial minerals.

Konoskopic images are irrelevant in ore microscopy!!!

I. LITERATURE

This text is compiled using the following reference works:

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