Einführung in die Geowissenschaften I

Minerals and Rocks

Thomas Ulrich



- A few definitions
- The 3 main rock types
- The rock cycle





• Why do you think you need to take this course?



- Why do you think you need to take this course?
- What do you expect from the course (ask your neighbour)?



- Why do you think you need to take this course?
- What do you expect from the course (ask your neighbour)?
- What is your previous knowledge on minerals and rocks?



- Why do you think you need to take this course?
- What do you expect from the course (ask your neighbour)?
- What is your previous knowledge on minerals and rocks?
- What role do minerals and rocks play in (y)our life(s)?

TU Clausthal

Course structure: Minerals and rocks part

- Introduction: Definition of minerals and rocks, rock types, rock cycle
- Minerals: Evolution, classification, properties, crystallography
- Minerals and society, applications
- Magmatic rocks: volcanic and plutonic rocks
- Metamorphic rocks: metamorphic facies, deformation, tectonic settings

Thomas Ulrich Institute for Disposal Research



- After the course you should be able to:
- identify the common minerals and rocks macroscopically
- know the general chemical composition of minerals
- explain how and where different minerals and rocks form
- explain the importance of minerals and rocks in the modern society

TU Clausthal



Thomas Ulrich Institute for Disposal Research



- Element: Na, Cl, O, S
- **Mineral:** halite (NaCI), quartz, feldspar, mica, amphibole, 'Solid, naturally occurring, inorganic material with an ordered structure and a defined chemical composition'
- Rock: a composite of minerals (e.g., granite: quartz+feldspar+mica)
- Crystal: 'any solid material in which the component atoms are arranged in a <u>definite pattern'</u> (Britannica)



https://virtual-museum.soils.wisc.edu/display/gypsum/#:~:text=In%20gypsum%2C%20the%20structure%20is,2O%20to%20CaSO4





Atoms

https://virtual-museum.soils.wisc.edu/display/gypsum/#:~:text=In%20gypsum%2C%20the%20structure%20is,2O%20to%20CaSO4

Thomas Ulrich Institute for Disposal Research

TU Clausthal Minerals: Structure



Atom€rystal structure of gypsum (CaSO4) xH2O

https://virtual-museum.soils.wisc.edu/display/gypsum/#:~:text=In%20gypsum%2C%20the%20structure%20is,2O%20to%20CaSO4

Thomas Ulrich Institute for Disposal Research

TU Clausthal Minerals: Structure



Atom€rystal structure of gypsum (CaSO4) xH200ystal of gypsum

https://virtual-museum.soils.wisc.edu/display/gypsum/#:~:text=In%20gypsum%2C%20the%20structure%20is,2O%20to%20CaSO4

Thomas Ulrich Institute for Disposal Research

TU Clausthal Minerals: Structure



Atom€rystal structure of gypsum (CaSO4) xH200ystal of gypsum

Aggregate of gypsum crystals

https://virtual-museum.soils.wisc.edu/display/gypsum/#:~:text=In%20gypsum%2C%20the%20structure%20is,2O%20to%20CaSO4

Thomas Ulrich Institute for Disposal Research

Economic Geology



www.GeologyPage.com

TU Clausthal





TU Clausthal Rocks: Assemblage of minerals

• Rocks consist typically of several different minerals. In some cases only of one type of mineral (limestone, quartzite)





What are rocks telling us?

Discuss in pairs



What are rocks telling us?

Discuss in pairs







Thomas Ulrich Institute for Disposal Research









Rammelsberg ore





Thomas Ulrich Institute for Disposal Research



Thomas Ulrich Institute for Disposal Research







TU Clausthal Rocks: the 3 rock types



Thomas Ulrich Institute for Disposal Research



Magmatic rocks

Metamorphic rocks

These general groups are based on the formation processes, and there are many different rocks in each group (see later).

Sedimentary rocks


Pay attention to the processes that lead from one rock type to another one.



Pay attention to the processes that lead from one rock type to another one.

ROCK CYCLE



Thomas Ulrich Institute for Disposal Re



Pay attention to the processes that lead from one rock type to another one.

ROCK CYCLE



Thomas Ulrich Institute for Disposal Re



If erupted on land surface: lava



Thomas Ulrich Institute for Disposal Research







Volcanic (extrusive)



Thomas Ulrich Institute for Disposal Research



Thomas Ulrich Institute for Disposal Research



Thomas Ulrich Institute for Disposal Research



Thomas Ulrich Institute for Disposal Research



Thomas Ulrich Institute for Disposal Research

TU Clausthal Rocks: Magmatic rocks, characteristics

Fine-grained, glassy, no minerals visible, except for phenocrysts.

Feldspar phenocrysts



Some volcanic rocks are porous (vesicles). These pores are formed due to degassing during decompression of the melt.

Course-grained, minerals visible and irregularly intergrown

TU Clausthal Rocks: Magmatic rocks, characteristics



Volcanic (extrusive)

Fine-grained, glassy, no minerals visible, except for phenocrysts.

Feldspar phenocrysts



Some volcanic rocks are porous (vesicles). These pores are formed due to degassing during decompression of the melt.

Course-grained, minerals visible and irregularly intergrown

TU Clausthal Rocks: Magmatic rocks, characteristics



Volcanic (extrusive)

Plutonic (intrusive)





Fine-grained, glassy, no minerals visible, except for phenocrysts.

Feldspar phenocrysts



Some volcanic rocks are porous (vesicles). These pores are formed due to degassing during decompression of the melt.

Course-grained, minerals visible and irregularly intergrown

Thomas Ulrich Institute for Disposal Research TU Clausthal Rocks: Sedimentary rocks All rocks exposed at the Earth surface will experience weathering and erosion.

These *physical and chemical* processes break down rocks into single minerals or new minerals



Sandstone

Thomas Ulrich Institute for Disposal Research

TU Clausthal Rocks: Sedimentary rocks

Sedimentary rocks form due to accumulation (sedimentation) of weathered material.

Sandstone (quartz grains)





Shale (clay minerals)



Thomas Ulrich Institute for Disposal Research

TU Clausthal Rocks: Sedimentary rocks

Some sedimentary rocks form due to precipitation from sea water or deposition of dead (micro)organisms.

Evaporites (e.g., salt)

Thomas Ulrich Institute for Disposal Research



Limestone



TU Clausthal Rocks: Sedimentary rocks, characteristics

LayeringCross bedding







Thomas Ulrich Institute for Disposal Research

TU Clausthal Rocks: Metamorphic rocks

All rock types can be exposed to high temperature and/or pressure. **METAMORPHISM**

This will commonly change the mineralogy in the rock (formation of new minerals). New rock name.



Thomas Ulrich Institute for Disposal Research

TU Clausthal

Rocks: Metamorphic rocks, characteristics Due to pressure and temperature changes the texture in the rock will also change (banding).



Granite

Thomas Ulrich Institute for Disposal Research



Institute for Disposal Research



Gneiss

Thomas Ulrich Institute for Disposal Research





Thomas Ulrich Institute for Disposal Research



Thomas Ulrich Institute for Disposal Research Not to confuse with sedimentary layering!



Thomas Ulrich Institute for Disposal Research

• Minerals are the building blocks of rocks and ultimately of our planet.

- Minerals are the building blocks of rocks and ultimately of our planet.
- Minerals have a defined crystal structure and inorganic chemistry.

- Minerals are the building blocks of rocks and ultimately of our planet.
- Minerals have a defined crystal structure and inorganic chemistry.
- The 3 rock types: magmatic, metamorphic, sedimentary

- Minerals are the building blocks of rocks and ultimately of our planet.
- Minerals have a defined crystal structure and inorganic chemistry.
- The 3 rock types: magmatic, metamorphic, sedimentary
- The rock cycle and the processes associated

- Minerals are the building blocks of rocks and ultimately of our planet.
- Minerals have a defined crystal structure and inorganic chemistry.
- The 3 rock types: magmatic, metamorphic, sedimentary
- The rock cycle and the processes associated
- Magmatic rocks are either volcanic (fine-grained, glassy) or plutonic (coarse-grained).

- Minerals are the building blocks of rocks and ultimately of our planet.
- Minerals have a defined crystal structure and inorganic chemistry.
- The 3 rock types: magmatic, metamorphic, sedimentary
- The rock cycle and the processes associated
- Magmatic rocks are either volcanic (fine-grained, glassy) or plutonic (coarse-grained).
- Sedimentary rocks are the products of weathering and erosion of other rocks, or deposition/precipitation in water. They show often layering.

- Minerals are the building blocks of rocks and ultimately of our planet.
- Minerals have a defined crystal structure and inorganic chemistry.
- The 3 rock types: magmatic, metamorphic, sedimentary
- The rock cycle and the processes associated
- Magmatic rocks are either volcanic (fine-grained, glassy) or plutonic (coarse-grained).
- Sedimentary rocks are the products of weathering and erosion of other rocks, or deposition/precipitation in water. They show often layering.
- Metamorphic rocks are the product of changing temperature and pressure conditions. They can show banding and deformation.

Thomas Ulrich Institute for Disposal Research



- Definition of mineral
- Crystal
- Rock
- Lava vs. magma
- Banding
- Layering
- Plutonic vs. volcanic
- Evaporite

Thomas Ulrich Institute for Disposal Research

[•]



'last minute paper'

- Write down what was difficult to understand
- Write down what was easy to understand

TU Clausthal

Minera

Thomas Ulrich Institute for Disposal Research

ogy



- The origin of minerals
- The mineral evolution
- The mineral classification



Thomas Ulrich Institute for Disposal Research


Thomas Ulrich Institute for Disposal Research



Atom structure

- Minerals

Thomas Ulrich Institute for Disposal Research



Thomas Ulrich Institute for Disposal Research



Thomas Ulrich Institute for Disposal Research



Thomas Ulrich Institute for Disposal Research





Thomas Ulrich Institute for Disposal Research

Economic Geology













Thomas Ulrich Institute for Disposal Research





Thomas Ulrich Institute for Disposal Research







Crust: Feldspar, quartz, pyroxene **Upper mantle:** Olivine **Lower mantle:** Bridgmanite

But how did minerals originate?

Thomas Ulrich Institute for Disposal Research



http://success.shoreline.edu



Crust: Feldspar, quartz, pyroxene **Upper mantle:** Olivine **Lower mantle:** Bridgmanite

But how did minerals originate?





Crust: Feldspar, quartz, pyroxene **Upper mantle:** Olivine **Lower mantle:** Bridgmanite

But how did minerals originate?





Crust: Feldspar, quartz, pyroxene **Upper mantle:** Olivine **Lower mantle:** Bridgmanite

But how did minerals originate?





Crust: Feldspar, quartz, pyroxene **Upper mantle:** Olivine **Lower mantle:** Bridgmanite

But how did minerals originate?





Crust: Feldspar, quartz, pyroxene **Upper mantle:** Olivine **Lower mantle:** Bridgmanite

But how did minerals originate?





Crust: Feldspar, quartz, pyroxene **Upper mantle:** Olivine **Lower mantle:** Bridgmanite

But how did minerals originate?



http://success.shoreline.edu

Institute for Disposal Research

Thomas Ulrich



Thomas Ulrich Institute for Disposal Research © Cambridge University Press 2016

• Solar nebula and gravitational collapse and star formation (H, He, Si, Fe....). Information from meteorites.



Thomas Ulrich Institute for Disposal Research © Cambridge University Press 2016

- Solar nebula and gravitational collapse and star formation (H, He, Si, Fe....). Information from meteorites.
- Supernovae (star explosions), formation of heavier elements.



Thomas Ulrich Institute for Disposal Research © Cambridge University Press 2016

- Solar nebula and gravitational collapse and star formation (H, He, Si, Fe....). Information from meteorites.
- Supernovae (star explosions), formation of heavier elements.
- Mineral evolution



Thomas Ulrich Institute for Disposal Research © Cambridge University Press 2016



Minerals: Element abundances solar system vs. bulk earth Element Bulk solar system Bulk Earth



Thomas Ulrich Institute for Disposal Research © Cambridge University Press 2016

Economic Geology

TU Clausthal The very beginning...

"Ur"-Mineralogy

Pre-solar grains contain about a dozen micro- and nano-mineral phases:

- Diamond (C)
- Graphite (C)
- Moissanite (SiC)
- Osbornite (TiN)
- Nierite (Si₃N₄)
- Rutile (TiO₂)
- Corundum (Al₂O₃)
- Spinel (MgAl₂O₄)
- Hibbonite (CaAl₁₂O₁₉)
- Forsterite (Mg₂SiO₄)
- Nano-particles of TiC, ZrC, MoC, FeC, Fe-Ni metal within graphite
- Silicate glass



Hazen 2019 (from you tube presentation)

https://www.youtube.com/watch?v=vvsRXWxOX-w Economic Geology

TU Clausthal Minerals: Mineral classification and evolution





What about minerals?

Thomas Ulrich Institute for Disposal Research

TU Clausthal Min<u>eral evolution</u>

Stage 1: Primary Chondrite Minerals

Minerals formed ~4.56 billion years ago in the Solar nebula by melting and cooling.



Thomas Ulrich Institute for Disposal Research

TU Clausthal Mineral evolution Stage 2: Alteration of planetesimals by heat, water, and impacts ~250 mineral species (4.56-4.55 billion years) Feldspars

- Quartz •
- Micas •
- Clays
- Zircon
- Calcite







Hazen 2019 (from you tube presentation) https://www.youtube.com/watch?v=vvsRXWxOX-w

Thomas Ulrich Institute for Disposal Research

TU Clausthal Mineral evolution

Stage 4: Granite Formation (More than 3.5 billion years ago)

>1000 mineral species (pegmatites)





Stage 4: Granite Formation (More than 3.5 billion years ago)

>1000 mineral species (pegmatites)

Partial melting of basalt and/or sediments.



Hazen 2019 (from you tube presentation) https://www.youtube.com/watch?v=vvsRXWxOX-w Economic Geology 100

Pollucite

TU Clausthal Mineral evolution

Stage 5: Plate tectonics (More than 3 billion years ago)





Mayon Volcano, Philippines

New modes of volcanism

Thomas Ulrich These processes get us up to 1500 minerals Institute for Disposal Research

TU Clausthal Min<u>eral evolution</u>

Stage 6: Anoxic Archean biosphere (4.0-2.5 billion years ago)

~1,500 mineral species (BIFs, carbonates)

Now life becomes an imp<mark>ortant factor to get more minerals</mark>

Minerals play an important role for life: Protector (molecules can hide) catalyst (mineral surfaces)

> Hazen 2019 (from you tube presentation) https://www.youtube.com/watch?v=vvsRXWxOX-w

TU Clausthal Mineral evolution

Stage 7: Atmospheric Oxidation (2.5-1.85 billion years ago) >4,500 mineral species, including perhaps >3,000 new oxides/hydroxides/carbonates



Thomas Ulrich Institute for Disposal Research Photosynthesis/oxidation

TU Clausthal Mineral evolution

Stage 7: Paleoproterozoic Oxidation (2.5-1.85 billion years ago)

Desautelite

What other mineral species won't form?

~220 of 233 U minerals

~400 of 499 Mn minerals

>100 of 142 Ni minerals Mg₆Mn³⁺2CO₃(OH)₁₆4H₂O

>700 of 1025 Fe minerals

Only thanks to oxidation (life)

This is possibly the most important diversification moment (>4600 minerals)

Thomas Ulrich Institute for Disposal Research

>400 of 650 Cu Minerals Won't Form

Aurichalcite



Azurite & Malachite

Blatonite UO₂CO₃·H₂O

Turquoise





TU Clausthal Min<u>eral evolution</u>

Stage 8: The "Intermediate Ocean" (1.85-0.85 billion years old)

>4600 mineral species (few new species)

Oxidized surface ocean; deep-ocean anoxia.

Thomas Ulrich Institute for Disposal Research

TU Clausthal Mineral evolution

Stage 9: WHITE EARTH 800 Million Years Ago



Thomas Ulrich Institute for Disposal Research

TU Clausthal Mineral evolution Stage 10: GREEN EARTH 400 Million Years Ago



>5.000 mineral species (biominerals, clavs).

Thomas Ulrich Institute for Disposal Research

TU Clausthal Minerals: A new proposal for a classification; Mineral evolution

A concept developed by Robert Hazen and his group (check their publications/presentations <u>https://hazen.carnegiescience.edu</u>)

TABLE 1 THREE ERAS AND TEN STAGES OF EARTH'S MINERAL EVOLUTION			
Era/Stage		Age (Ga)	Cumulative no. of species
Prenebular "Ur-Minerals"		>4.6	12
Era of Planetary Accretion (>4.55 Ga)			
1.	Primary chondrite minerals	>4.56 Ga	60
2.	Achondrite and planetes- imal alteration	>4.56 to 4.55 Ga	250
Era of Crust and Mantle Reworking (4.55 to 2.5 Ga)			
3.	Igneous rock evolution	4.55 to 4.0 Ga	350 to 500*
4.	Granite and pegmatite formation	4.0 to 3.5 Ga	1000
5.	Plate tectonics	>3.0 Ga	1500
Era of Biologically Mediated Mineralogy (>2.5 Ga to Present)			
6.	Anoxic biological world	3.9 to 2.5 Ga	1500
7.	Great Oxidation Event	2.5 to 1.9 Ga	>4000
8.	Intermediate ocean	1.9 to 1.0 Ga	>4000
9.	Snowball Earth events	1.0 to 0.542 Ga	>4000
10.	Phanerozoic era of biomineralization	0.542 Ga to present	4400+

* Depending on the volatile content of the planet or moon

Thomas Ulrich Institute for Disposal Research
TU Clausthal Minerals: A new proposal for a classification; Mineral evolution

A concept developed by Robert Hazen and his group (check their publications/presentations https://hazen.carnegiescience.edu)

10 stages of mineral evolution

Thomas Ulrich Institute for Disposal Research

A	THREE ERAS AND TEN	I STAGES OF EARTH'S MIN	NERAL EVOLUTION	
Era/Stage		Age (Ga)	Cumulative no. of species	
Prenebular "Ur-Minerals"		>4.6	12	
Era of Planetary Accretion (>4.55 Ga)				
1.	Primary chondrite minerals	>4.56 Ga	60	
2.	Achondrite and planetes- imal alteration	>4.56 to 4.55 Ga	250	
Era of Crust and Mantle Reworking (4.55 to 2.5 Ga)				
3.	Igneous rock evolution	4.55 to 4.0 Ga	350 to 500*	
4.	Granite and pegmatite formation	4.0 to 3.5 Ga	1000	
5.	Plate tectonics	>3.0 Ga	1500	
Era of Biologically Mediated Mineralogy (>2.5 Ga to Present)				
6.	Anoxic biological world	3.9 to 2.5 Ga	1500	
7.	Great Oxidation Event	2.5 to 1.9 Ga	>4000	
8.	Intermediate ocean	1.9 to 1.0 Ga	>4000	
9.	Snowball Earth events	1.0 to 0.542 Ga	>4000	
10.	Phanerozoic era of biomineralization	0.542 Ga to present	4400+	

* Depending on the volatile content of the planet or moon

TU Clausthal

Minerals: A new proposal for a classification; Mineral evolution

- A proposal to group minerals depending on their formation processes/environments (Hazen and Morrison, American Mineralogist, 2022)
- 10 stages of earth evolution, 57 environments and mineral formation processes



Thomas Ulrich Institute for Disposal Research

TU Clausthal Minerals: Mineral classification

Strunz classification: based on chemistry and structure, including 10 classes.

Introduced in 1941.

1 Native elements (minerals made of only one element)

2 Sulfides/sulfosalts

3 Halides

4 Oxides

5 Carbonates/Nitrates

6 Borates

7 Sulfates

8 Phosphates

9 Silicates

10(Organic compounds)

TU Clausthal Minerals: Mineral classification

Strunz classification: based on chemistry and structure, including 10 classes.

Introduced in 1941.

1 Native elements (minerals made of only one element)

2 Sulfides/sulfosalts

3 Halides

4 Oxides

5 Carbonates/Nitrates

6 Borates

7 Sulfates

8 Phosphates

9 Silicates

10(Organic compounds)

Why are the mineral groups in bold abundant on Earth?

Thomas Ulrich Institute for Disposal Research



What I always will remember: week 1



What I always will remember: week 1

• Earth crust is dominated of feldspars, quartz and pyroxene



What I always will remember: week 1

- Earth crust is dominated of feldspars, quartz and pyroxene
- Earth mantle is dominated by olivine (upper mantle) and bridgmanite (lower mantle), garnet

TU Clausthal

What I always will remember: week 1

- Earth crust is dominated of feldspars, quartz and pyroxene
- Earth mantle is dominated by olivine (upper mantle) and bridgmanite (lower mantle), garnet
- The abundance of minerals depends on the element abundance

TU Clausthal

What I always will remember: week 1

- Earth crust is dominated of feldspars, quartz and pyroxene
- Earth mantle is dominated by olivine (upper mantle) and bridgmanite (lower mantle), garnet
- The abundance of minerals depends on the element abundance
- Minerals are classified into 10 main classes based on their chemistry and structure



- Write down what was difficult to understand
- Write down what was easy to understand



Mineral properties

TU Clausthal What was difficult to understand?



 Many properties such as hardness, cleavage, conductivity, and density are directly related to the crystal structure.



Thomas Ulrich Institute for Disposal Research

<u>Graphite</u>: one of the softest minerals

• Many properties such as hardness, cleavage, conductivity, and density are directly related to the crystal structure.





Thomas Ulrich Institute for Disposal Research

<u>Graphite</u>: one of the softest minerals

280

70

Fiefe [km]

Diamant

Graphit

Temperatur [°C]

Druck [kbar]

20

3000

^{eothermischer}

• Many properties such as hardness, cleavage, conductivity, and density are directly related to the crystal structure.

• Many properties such as hardness, cleavage, conductivity, and density are directly related to the crystal structure.



• Many properties such as hardness, cleavage, conductivity, and density are directly related to the crystal structure.



Properties of minerals to be used for their identification

- Hardness
- Cleavage/fractures
- Lustre
- Colour
- Streak
- Density
- Magnetism, reaction with HCl, birefringence

TU Clausthal Mineral properties: Lustre

Lustre is the way the mineral reflects light

• Metallic (often ore minerals)







diamond Thomas Ulrich Institute for Disposal Research

Colour is one of the most obvious feature, but not very characteristic for many minerals. Colour is not necessarily a good property for mineral identification. Low concentrations of trace elements in the crystal structure and crystal defects are responsible for different colors.

Colour is one of the most obvious feature, but not very characteristic for many minerals. Colour is not necessarily a good property for mineral identification. Low concentrations of trace elements in the crystal structure and crystal defects are responsible for different colors.



Colour is one of the most obvious feature, but not very characteristic for many minerals. Colour is not necessarily a good property for mineral identification. Low concentrations of trace elements in the crystal structure and crystal defects are responsible for different colors.













Colour is one of the most obvious feature, but not very characteristic for many minerals. Colour is not necessarily a good property for mineral identification. Low concentrations of trace elements in the crystal structure and crystal defects are responsible for different colors.





Thomas Ulrich Institute for Disposal Research



Corundum

Quartz

TU Clausthal Mineral properties: Streak

• The powder of a mineral has a characteristic colour. Therefore, the colour of the streak is a characteristic mineral property.



TU Clausthal Mineral properties: Streak

• The powder of a mineral has a characteristic colour. Therefore, the colour of the streak is a characteristic mineral property.

Gold vs. pyrite				
	Gold	Pyrite		
colour	yellow	yellow		
streak	yellow	black		
density	19.3g/cm3	5g/cm3		
hardness	3	6		

Colduc purito



Thomas Ulrich Institute for Disposal Research

TU Clausthal Mineral properties: Hardness

- A simple test with a set of specific minerals (Moh's hardness scale).
- Finger nail, H: 2.5
- Copper coin, H: 3.5
- Glass plate, H: 5.5
- Pocket knife, H: 5.5



TU Clausthal Mineral properties: Density

A rough distinction can be made between rock-forming minerals and ore minerals. Depends on crystal structure and chemical composition.

Example: Galena (PbS): feels distinctly heavy (7.6g/cm³)



- Rock-forming minerals: 2.2-4.5 g/cm³
- Ore minerals: >5 g/cm³

TU Clausthal Mineral properties: Cleavage/fracture This is the way a mineral breaks. Commonly along one or several planar planes.







Biotite: one perfect cleavage **Feldspar:** good cleavage **Calcite:** 3 good cleavages If there is no cleavage then it is called fracture.



Thomas Ulrich Institute for Disposal Research **Quartz** has no cleavage, but conical fractures

TU Clausthal Mineral properties: specific properties

- Magnetite: magnetic, Pyrrhotite: moderately magnetic
- **Calcite:** reaction with HCl (CaCO₃ +2HCl = CaCl₂ + CO₂ + H₂O), high birefringence



TU Clausthal What I always will remember: week 1

- Mineral properties depend on the crystal structure and chemistry
- The main properties to be used for mineral identification (macroscopically)



• Birefringence



Crystal structures



TU Clausthal

Crystal structures: the arrangement of atoms in a crystal

• Crystal structures can be shown in different ways. Basically, it shows how the atoms are arranged in the crystal.



Thomas Ulrich Institute for Disposal Research

Economic Geology



Crystal structures: the arrangement of atoms in a crystal Not all possible combination of ions are possible due to size

and charge differences.


TU Clausthal

Crystal structures: the arrangement of • Not all possible combination of ions are possible due to size

and charge differences. Ion charge

N ° Li Be B He Na Mg Al Si P S O O O O O $\begin{array}{cccc} Ca & Sc & Ti & V \\ \bigcirc & \bigcirc & \bigcirc & \bigcirc & \bigcirc \\ \end{array}$ Cr Zn Ga Ge As Se Sr Y Zr Nb ○ ○ ○ ○ Mo Sn O Sb Te 0 Te Ce



There are certain combination possible that result in a specific **coordination number (CN).** It indicates how many direct neighbours a central ion will have.

Minimum Coordination Radius Ratie Number Packing Geometry $R_A : R_X$ C. N. < 0.155 2 (a) a Linear linear Corners of an equilateral 0.155 3 triangle (triangular 0 coordination) triangle Corners of a tetrahedron 0.225 4 (tetrahedral coordination) tetrahedra Corners of an octahedron 6 0.414 (octahedral coordination) octahedra Corners of a cube 0 8 0.732 (cubic coordination) cubic Corners of a 1.0 12 cuboctahedron (close packing) cuboctahedra

FIG. 3.36 Atomic packing schemes.

There are certain combination possible that result in a specific **coordination number (CN).** It indicates how many direct neighbours a central ion will have.



FIG. 3.36 Atomic packing schemes.

There are certain combination possible that result in a specific **coordination number (CN).** It indicates how many direct neighbours a central ion will have.

The coordination numbers relate to a range of radius ratios.



FIG. 3.36 Atomic packing schemes.

There are certain combination possible that result in a specific **coordination number (CN).** It indicates how many direct neighbours a central ion will have.

The coordination numbers relate to a range of radius ratios.

Radius ratio = Cation radius/Anion radius

Minimum Radius Ratio R _A : R _X	Coordination Number C. N.		Packing Geometry	1.2
< 0.155	2	Linear	00	۰۰ linear
0.155	3	Corners of an equilateral triangle (triangular coordination)	00	triangle
0.225	4	Corners of a tetrahedron (tetrahedral coordination)	\mathcal{B}	
0.414	6	Corners of an octahedron (octahedral coordination)	Đ	tetrahedra
0.732	8	Corners of a cube (cubic coordination)	88	octahedra
1.0	12	Corners of a cuboctahedron (close packing)	Ð	cubic
			c	uboctahedra

FIG. 3.36 Atomic packing schemes.

There are certain combination possible that result in a specific **coordination number (CN).** It indicates how many direct neighbours a central ion will have.

The coordination numbers relate to a range of radius ratios.

Radius ratio = Cation radius/Anion radius

Minimum Radius Ratio R _A : R _X	Coordination Number C. N.		Packing Geometry	1.5
< 0.155	2	Linear	00	۰۰ linear
0.155	3	Corners of an equilateral triangle (triangular coordination)	00	
0.225	4	Corners of a tetrahedron (tetrahedral coordination)	\mathcal{B}	triangle
0.414	6	Corners of an octah edron (octahedral coordination)	Đ	tetrahedra
0.732	8	Corners of a cube (cubic coordination)	88	octahedra
1.0	12	Corners of a cuboctahedron (close packing)	B	cubic
			c	uboctahedr













of van der Waals bond



+-





TU Clausthal Crystal structures: bonding



В Α δ- δ^+ instantaneous dipole on A induces a dipole on B В Α δ- δ^+ δ- δ^+ weak dipole attraction of van der Waals bond





Thomas Ulrich Institute for Disposal Research

157





Bonding and physical properties of minerals

• Why are metals good conductors (electric, thermal)?

• Depending on size and charge of the ions the crystal structure consists of certain ion combinations (polyhedral) such as triangle, tetrahedra, octahedra, cubic, cuboctahedra

160

Thomas Ulrich Institute for Disposal Research

161

- Depending on size and charge of the ions the crystal structure consists of certain ion combinations (polyhedral) such as triangle, tetrahedra, octahedra, cubic, cuboctahedra
- The radius ratio between cation and anion determines the ideal polyhedral for specific ions.

- Depending on size and charge of the ions the crystal structure consists of certain ion combinations (polyhedral) such as triangle, tetrahedra, octahedra, cubic, cuboctahedra
- The radius ratio between cation and anion determines the ideal polyhedral for specific ions.
- Ions will bond different in crystal structures (ionic, covalent, metallic, van der Waals)



Crystallography: Symmetry and crystal structure systems

- The crystal structure is the repetition of the geometrical arrangement of the atoms in the crystal structure, which is reflected in the form of the crystal.
- There 3 symmetry elements that are used to determine the crystal structure system
- Planes
- Rotation axes
- Symmetry centre



One symmetry plane (SP)



One symmetry plane (SP)





One symmetry plane (SP)



















TU Clausthal Crystallography: Rotation axes

The most common rotation axes are 2, 3, 4, and 6-fold



TU Clausthal Crystallography: Symmetry centre (C)

Crystal planes or edges occur in pairs at opposite sides of a central point in the crystal

Symmetry centre

A tetraheder has no symmetry centre





TU Clausthal Crystallography: the 7 crystal systems

TU Clausthal Crystallography: the 7 crystal systems

CRYSTAL SYSTEM

MINIMUM SYMMETRY
CRYSTAL SYSTEM MINIMUM SYMMETRY

CUBIC

 $4 A_3$

CRYSTAL SYSTEMMINIMUM SYMMETRYCUBIC4 A3TETRAGONAL1 A4

CRYSTAL SYSTEM	MINIMUM SYMMETRY
CUBIC	4 A ₃
TETRAGONAL	1 A ₄
HEXAGONAL	1 A ₆

CRYSTAL SYSTEM	MINIMUM SYMMETRY
CUBIC	4 A ₃
TETRAGONAL	1 A ₄
HEXAGONAL	1 A ₆
TRIGONAL	1 A ₃

CRYSTAL SYSTEM	MINIMUM SYMMETRY
CUBIC	4 A ₃
TETRAGONAL	1 A ₄
HEXAGONAL	1 A ₆
TRIGONAL	1 A ₃
ORTHORHOMBIC	3 A ₂

CRYSTAL SYSTEM	MINIMUM SYMMETRY
CUBIC	4 A ₃
TETRAGONAL	1 A ₄
HEXAGONAL	1 A ₆
TRIGONAL	1 A ₃
ORTHORHOMBIC	3 A ₂
MONOCLINIC	1 A ₂

CRYSTAL SYSTEM	MINIMUM SYMMETRY
CUBIC	4 A ₃
TETRAGONAL	1 A ₄
HEXAGONAL	1 A ₆
TRIGONAL	1 A ₃
ORTHORHOMBIC	3 A ₂
MONOCLINIC	1 A ₂
TRICLINIC	no symmetry



Coordinatesystem with "0" point in the c entre of the crystal

Axes are called a, b and c



ology 188







Thomas Ulrich Institute for Disposal Research

190





CUBIC $a_1 = a_2 = a_3$

Thomas Ulrich Institute for Disposal Research

191

TU Clausthal Halite and pyrite are two examples with cubic crystal systems









Rhombedodecaeder {110}₁₂ is also the cubic crystal system GARNET



TU Clausthal OCTAEDER





Thomas Ulrich Institute for Disposal Research





pyrite



194



Economic Geology



In the **HEXAGONALE** and the **TRIGONAL** system 4 axes are used











Institute for Disposal Research



Important rule



Natural crystals have often irrgular sized planes, <u>but the angles are the</u> <u>same as in ideal crystal shapes</u> (Nicolas Steno, 1669)

Thomas Ulrich Institute for Disposal Research

200



Determine all the symmetry elements in the given figures

TU Clausthal Crystallography: Naming of crystal planes

R

A system to name (to index) crystal planes, proposed by W.F. Miller in 1836 **Miller Index**

It is based on the reciprocal value of the distance from the coordination system centre











Institute for Disposal Research







A cube has 6 identical planes with Miller indices:

(100) $(\overline{1}00)$ (010) $(0\overline{1}0)$ (001) $(00\overline{1})$

CUBE-FORMEN consists of these 6 planes

As a common description we use this type { } of parentheses

 $\{100\}_{6}$



Determine the crystal planes on the different shapes

• The 7 crystal systems and their minimum symmetry elements

- The 7 crystal systems and their minimum symmetry elements
- The angles between crystal planes is diagnostic and characteristic for the crystal systems

- The 7 crystal systems and their minimum symmetry elements
- The angles between crystal planes is diagnostic and characteristic for the crystal systems
- Miller indices



- Write down what was difficult to understand
- Write down what was easy to understand


- Native minerals
- Silicate minerals (Nesosilicates)



• This group of minerals consists of single chemical elements: For example Au, Cu, Ag, S, C



Institute for Disposal Research



• The most important building block of silicates is the (SiO₄)⁴⁻ tetraheder (remember the radius ratio).



- The most important building block of silicates is the (SiO₄)⁴⁻ tetraheder (remember the radius ratio).
- Silicates are the most abundant minerals and many of them are rock-forming.



- The most important building block of silicates is the (SiO₄)⁴⁻ tetraheder (remember the radius ratio).
- Silicates are the most abundant minerals and many of them are rock-forming.
- Other important cations in some of the silicate minerals are: Al³⁺, Fe²⁺, Fe³⁺, Mg²⁺, Ca²⁺, Na⁺, K⁺



SiO₄⁴- tetraheder









Ino silicate (single chain)



Ino silicate (double chain)



Sheet silicate



Framework silicate Economic Geology

SiO₄⁴- tetraheder Neso silicate Olivine Soro silicate Epidote Beryl

Ring silicate

Pyroxene

Ino silicate (single chain)



Ino silicate (double chain)



Sheet silicate



Framework silicate Economic Geology



- Olivine
- Zircon
- Garnet
- Sillimanite, andalusite, kyanite (disthene)
- Staurolite
- Titanite (Sphene)
- Topaz

TU Clausthal Silicate minerals: Nesosilicate: Olivine

- The most abundant mineral in the upper mantle, occurs together with pyroxene +/- garnet (rock called: peridotite)
- Occurs commonly in (mafic and ultra-mafic) magmatic rocks
- Consists of Mg and Fe-rich varieties (forsterite and fayalite)
- Colour typically green
- Easy weathered and altered to serpentine



TU Clausthal Silicate minerals: Nesosilicate: Zircon

- Not a rock-forming mineral, only accessory phase (in many different rocks). Commonly brown, yellow
- Can contain U, Th and therefore used to date rocks

• $^{238}U \longrightarrow ^{206}Pb$ half life time 4,47 billion years

• ${}^{235}U \longrightarrow {}^{207}Pb$ half life time 0,704 billion years



1mm



TU Clausthal Silicate minerals: Nesosilicate: Garnet group

• Garnet occurs typically in **metamorphic rocks**



Cubic General formula: R²⁺₃R³⁺₂[SiO₄]₃ Several varieties



Garnet groups $R^{2+}_{3}R^{3+}_{2}[SiO_{4}]_{3}$

Pyralspitserien: R²⁺₃Al₂[SiO₄]₃

Pyrope	$Mg_{3}Al_{2}[SiO_{4}]_{3}$
Almandine	$Fe_{3}Al_{2}[SiO_{4}]_{3}$
Spessartine	$Mn_3Al_2[SiO_4]_3$

Ugranditserien: $Ca_3R^{3+}_2[SiO_4]_3$ Uvarovite $Ca_3Cr_2[SiO_4]_3$ Grossular $Ca_3Al_2[SiO_4]_3$ Andradite $Ca_3Fe_2[SiO_4]_3$

TU Clausthal Silicate minerals: Garnet group,

OCCURRENCE Pyrope Mg₃Al₂[SiO₄]₃

> Red, occurs in rock called ECLOGITE together with a green pyroxene (omphacite)



Eclogite forms under high pressure metamorphism of basalt

TU Clausthal Silicate minerals: Garnet group, occurrence

Almandine $Fe_3Al_2[SiO_4]_3$



3.8 Gamet. Trapezohedron and Dodecahedron



Gamet. Dodecahedron and Trapezohedron







TU Clausthal Silicate minerals: Garnet group, occurrence Almandine Fe₃Al₂[SiO₄]₃

The most common garnet, dark red-brown. Occurs in metapelitic rocks (gneisses, schists)

METAPELITE is the name for a
metamorphosed, originally clay-rich sedimentary
rock.
Metapelites contain aluminium-rich minerals
e.g., biotite, muskovite, Al₂SiO₅ minerals,
almandine, staurolite,

TU Clausthal Silicate minerals: Garnet group, occurrence Grossular

$Ca_3Al_2[SiO_4]_3$ Colour varies, depending on Al³⁺ - Fe³⁺ substitution Colourless, greenish, redish, yellow, red-brown

Silicate minerals: Garnet group, occurrence Grossular Ca₃Al₂[SiO₄]₃

Metamorphosed marl (limestone + clay). Ca from limestone Al from clay SiO₂ fra quartz



TU Clausthal Silicate minerals: Nesosilicates: Alumosilicates

3 Minerals with the same composition $(Al_2SiO_5) = Polymorphs$

ANDALUSITE - orthorhombic **SILLIMANITE** - orthorhombic **KYANITE (DISTHENE)** - triclinic Pressure K Triple point at S = P 4kbar og 500°C Α

Thomas Ulrich Institute for Disposal Research

Temperature = T

TU Clausthal Silicate minerals: Alumosilicates, occurrences

They are **index minerals** in <u>metamorphic rocks</u> (in Metapelites)

Andalusite, red-brown, white, light red



Sillimanite, white, light brown, fibrous

Kyanite, light blue, tabular





$AI_{2}[Si_{2}O_{5}](OH)_{4} + 2SiO2 = AI_{2}[Si_{2}O_{5}]_{2}(OH)_{2} + H_{2}O$ kaolinite + quartz = pyrophyllite + water

Metamorphism of clay-rich rocks



Economic Geology

TU Clausthal



Silicate minerals: Nesosilicates: Staurolite (Fe,Mg)₂Al₉O₆[SiO₄]₄(O,OH)₂



TU Clausthal Silicate minerals: Staurolite, occurrences



TU Clausthal Silicate minerals: Nesosilicates: Titanite (Sphene)

CaTi[SiO₄](O,OH,F)

Monoklinic



Brown, green yellowish Occurs as an accessory phase in magmatic and metamorphic rocks, similai





TU Clausthal Silicate minerals: Nesosilicates: **Topaz**

 $AI_2[SiO_4](OH,F)_2$

Orthorhombic

Colorless, yellow green, gray

Occurs typically in SiO2-rich magmatic rocks (granite, pegmatites, veins)



Thomas Ulrich Institute for Disposal Research

TU Clausthal Silicate minerals: Sorosilicates: Epidote



Epidote (group)

TU Clausthal Silicate minerals: Epidote, occurrence

Green

Occurs in greenschists (metamorphic rock) <u>Greenschists</u> form at around 300C with the addition of water to mafic rocks (basalt, oceanic crust). Seafloor hydrothermal metamorphism.



TU Clausthal Silicate minerals: Ringsilicates

- Beryl
- Tourmaline



TU Clausthal Silicate minerals: Ringsilicates: Beryl

 $Be_3Al_2[Si_6O_{18}]$

Hexagonal



TU Clausthal Silicate minerals: Ringsilicates: Beryl Be₃Al₂[Si₆O₁₈]



Thomas Ulrich Institute for Disposal Research

TU Clausthal Silicate minerals: Ringsilicates: Tourmaline

 $NaX_{3}Al_{6}(BO_{3})_{3}[Si_{6}O_{18}](O,OH,F)_{4}$

Occurs in pegmatites, which are fractionated SiO_2 and H_2O -rich melt. Together with beryl, topaz, mica. B⁺ and Be⁺ are small cations concentrated in late, fractionated melt.

> Thomas Ulrich Institute for Disposal Research



TU Clausthal Silicate minerals: Inosilicates



Single chains of SiO₄⁴⁻ -tetrahedra (Si₂O₆)⁴⁻

Pyroxenes: <u>Orthopyroxene</u> (orthorhombic, Mg-Fe), <u>Clinopyroxene</u> (monoclinic, Ca-Mg-Fe)



Double chains of SiO₄⁴⁻ -tetrahedra (Si₄O₁₁)⁶⁻

Amphiboles



Fe[SiO₃]

PYROXENES

CLINOPYROXENE Diopside-Hedenbergite

ORTHOPYROXENE Enstatite-Ferrosilite

Thomas Ulrich Institute for Disposal Research

Mg[SiO₃]

Economic Geology



- pyroxenoid



CaMg[Si₂O₆] CaFe[Si₂O₆] **PYROXENES** Mg[SiO₃] Fe[SiO₃]

CLINOPYROXENE Diopside-Hedenbergite

ORTHOPYROXENE Enstatite-Ferrosilite



Institute for Disposal Research
TU Clausthal Silicate minerals: Pyroxene, occurrences

Occurs in mafic and ultramafic rocks. Both volcanic (basalt) and plutonic (gabbro).

Mg-rich members in primitive rocks Fe-rich in more evolved rocks.

In high temperature metamorphic rocks.



TU Clausthal Silicate minerals: Inosilicates: Amphiboles Double chains

General formula

 $A_{0-1}B_2C_5[T_8O_{22}](OH)_2$



A = Na, K B = Ca, Na, Mg, Fe C = Mg, Fe, Al

T = Si, AI

Space for large cations (K⁺) Al³⁺ substitutes for Si⁴⁺

Thomas Ulrich Institute for Disposal Research (OH)-groups

TU Clausthal Silicate minerals: Amphiboles, occurrences







ACTINOLITE - TREMOLITE HORNBLENDE

Green-white/gray black greenschist, metam. dolomitegranite, amphibolite Thomas Ulrich Ca-Mg-Fe Na-Ca-Fe-Mg Institute for Disposal Research GLAUKOPHANE blue blueschist Na-Mg Economic Geology









B: brucite (Mg(OH)₂)

Thomas Ulrich Institute for Disposal Research



Different stacking combinations lead to different kinds of phyllosilicates (mica group, clay minerals, serpentine minerals...)





B: brucite (Mg(OH)₂)

Thomas Ulrich Institute for Disposal Research



Different stacking combinations lead to different kinds of phyllosilicates (mica group, clay minerals, serpentine minerals...)





Institute for Disposal Research



Different stacking combinations lead to different kinds of phyllosilicates (mica group, clay minerals, serpentine minerals...)





Thomas Ulrich Institute for Disposal Research



Different stacking combinations lead to different kinds of phyllosilicates (mica group, clay minerals, serpentine minerals...)

All phyllosilicate contain OH-groups

TU Clausthal Silicate minerals: Phyllosilicates: Serpentine

$Mg_3[Si_2O_5](OH)_4$

Forms during metamorphism of OLIVINE - (Mg,Fe)₂[SiO₄]

Requires the presence of H_2O

Serpentine contains no Fe, and therefore, magnetite (Fe_3O_4) is forming simultaneously

A rock that almost only consists of serpentine is called a <u>SERPENTINITE</u>

TU Clausthal Silicate minerals: Phyllosilicates: Serpentine



Chrysotile and antigorite are varieties of serpentine

Thomas Ulrich Institute for Disposal Research

Commonly green

Sheet structure - But fibrous habitus Veins o fserpentins -Fibres are perpendicular





262

TU Clausthal Silicate minerals: Phyllosilicates: Talc

$Mg_{3}[Si_{4}O_{10}](OH)_{2}$

Defines hardness 1 on the Mohs scale Occurs together with serpentine



H = 1

A rock that almost consists only of talc is called a soapstone

TU Clausthal Silicate minerals: Phyllosilicates: Kaolinite

Kaolinite $Al_2[Si_2O_5](OH)_4$ is a clay mineral

Clay minerals are a large group of minerals and make up the smallest size fraction (<4um) in sediments

H = ca. 2

Clay minerals form during the weathering or alteration of feldspar

Kaolinite occurs in soil and in sedimentary Other clay minerals: Montmorillonite illite Thomas Ulrich Institute for Disposal Research



TU Clausthal Silicate minerals: Phyllosilicates: Micas

Micas are an important group of phyllosilicates and are characterized by perfect basal cleavage

 $XY_{2-3}[Z_4O_{10}](OH)_2$

$$X = K^{+}$$
 $Y = AI^{3+}$, Mg^{2+} , $Fe^{2+} Z = Si^{4+}$, AI^{3+}

Micas have an open structure and space for larger cations such as K⁺

TU Clausthal Silicate minerals: Phyllosilicates: Micas

Muskovite

KAl₂[AlSi₃O₁₀](OH)₂, white, silvery

Occurs in mica schists (metamorphic rock) and some

magmatic granitic rocks

Biotite

K(Mg,Fe)₂[AlSi₃O₁₀](OH)₂, brown, black

Occurs in granitic rocks and some metamorphic ones

(mica schist)

Thomas Ulrich Institute for Disposal Research





266

TU Clausthal Silicate minerals: Phyllosilicates: Micas

Chlorite

 $(Mg,Fe,AI)_{6}[(Si,AI)_{4}O_{10}](OH)_{8}$, green

Occurs in greenschists (metamorphic rock) 100-500C

Lepidolite

K(Li, AI)₂₋₃ [(Si,AI)₄O₁₀](OH, F)₂, lilla

Occurs in pegmatites, source of Li

Thomas Ulrich Institute for Disposal Research



267



TU Clausthal Silicate minerals: Tectosilicates



3D gitter structure of SiO₄⁴⁻ units

Thomas Ulrich Institute for Disposal Research - Quartz

- Feldspars: alkali-feldspar, plagioclase
- Feldspatoids: leucite, nepheline, sodalite
- Zeolites

Feldspars, together with quartz, are among the most abundant and common minerals in the Earth's crust.

269

TU Clausthal Silicate minerals: Feldspars



Thomas Ulrich Institute for Disposal Research

270

Compositions between K[AISi₃O₈] og Na[AISi₃O₈]

K-rich alkalifeldspar occurs in 3 polymorphs:

ORTHOCLASEmonoclinic, slightly pink/whiteIow temperatureMICROCLINEtriclinic, /greyIow temperatureSANIDINEmonoclinic, white/greyhigh temperature

The structural change includes an ordering of Al-Si distribution. At high T disordered, at low T ordered.

Sanidine: occurs only in high temperature rocks such as volcanic rocks and high-grade metamorphic rocks (granulite)

Ortholcase: occurs in 'low' temperature magmatic rocks such such as granite, pegmatite, and metamorphic rocks (gneiss)

Thomas Ulrich Institute for Disposal Research









272

When alkalifeldspar first crystallizes in a magma chamber it is SANIDINE. There is 100% miscibility between Na- og K- feldspat. At fast cooling the sanidine-structure is preserved. During slow cooling the structure is divided into two phases - a K-rich and a Na-rich one.

Thomas Ulrich Institute for Disposal Research

Са

Na

When alkalifeldspar first crystallizes in a magma chamber it is SANIDINE. There is 100% miscibility between Na- og K- feldspat.

At fast cooling the sanidine-structure is preserved.



When alkalifeldspar first crystallizes in a magma chamber it is SANIDINE.
There is 100% miscibility between Na- og K- feldspat.
K At fast cooling the sanidine-structure is preserved.

During slow cooling the structure is divided into two phases - a K-rich and a Na-rich one.



When alkalifeldspar first crystallizes in a magma chamber it is SANIDINE. There is 100% miscibility between Na- og K- feldspat. K At fast cooling the sanidine-structure is preserved.

During slow cooling the structure is divided into two phases - a K-rich and a Na-rich one.

There occurs **EXSOLUTION**

Thomas Ulrich Institute for Disposal Research

Ca

Na

When alkalifeldspar first crystallizes in a magma chamber it is SANIDINE.
There is 100% miscibility between Na- og K- feldspat.
K At fast cooling the sanidine-structure is preserved.

During slow cooling the structure is divided into two phases - a K-rich and a Na-rich one.



Thomas Ulrich Institute for Disposal Research There occurs **EXSOLUTION**

The K-rich phase (ORTHOKLAS) is commonly dominating and includes, the Na-rich phase (ALBIT) as small spots or veinlets

When alkalifeldspar first crystallizes in a magma chamber it is SANIDINE. There is 100% miscibility between Na- og K- feldspat. At fast cooling the sanidine-structure is preserved.

> During slow cooling the structure is divided into two phases - a K-rich and a Na-rich one.



Thomas Ulrich Institute for Disposal Research There occurs **EXSOLUTION**

The K-rich phase (ORTHOKLAS) is commonly dominating and includes, the Na-rich phase (ALBIT) as small spots or veinlets



This exsolution texture ist called a PERTHITE









1 = ALBITE 2 = OLIGOCLASE



1 = ALBITE 2 = OLIGOCLASE 3 = ANDESINE



1 = ALBITE 2 = OLIGOCLASE 3 = ANDESINE 4 = LABRADORITE



1 = ALBITE 2 = OLIGOCLASE 3 = ANDESINE 4 = LABRADORITE 5 = BYTOWNITE



1 = ALBITE 2 = OLIGOCLASE 3 = ANDESINE 4 = LABRADORITE 5 = BYTOWNITE 6 = ANORTHITE



1 = ALBITE 2 = OLIGOCLASE 3 = ANDESINE 4 = LABRADORITE 5 = BYTOWNITE 6 = ANORTHITE 7 = ANORTHOCLASE



1 = ALBITE 2 = OLIGOCLASE 3 = ANDESINE 4 = LABRADORITE 5 = BYTOWNITE 6 = ANORTHITE 7 = ANORTHOCLASE 8 = SANIDINE

Thomas Ulrich 8 = Institute for Disposal Research

Economic Geology 287



1 = ALBITE 2 = OLIGOCLASE 3 = ANDESINE 4 = LABRADORITE 5 = BYTOWNITE 6 = ANORTHITE 7 = ANORTHOCLASE8 = SANIDINE 9 = ORTHOCLASE eller MICROCLINE **Thomas Ulrich**

Institute for Disposal Research

Economic Geology

288


There is complete miscibility between Na and Ca. But it requires a coupled-substitution: Na⁺ + Si⁴⁺ \iff Ca²⁺ + Al³⁺

At high temperature, the anorthite (Ca-rich) endmember crystallizes and the composition changes to more Na-rich (albite) with decreasing temperature.

1 = ALBITE 2 = OLIGOCLASE 3 = ANDESINE 4 = LABRADORITE 5 = BYTOWNITE 6 = ANORTHITE 7 = ANORTHOCLASE 8 = SANIDINE 9 = ORTHOCLASE eller MICROCLINE Institute for Disposal Research

Plagioclase crystals are tabular, lath-shaped. They are white/gray, H= 6

Some plagioclase shows labradorescence (reflection of light along twin lamellas)



Plagioclase crystals are tabular, lath-shaped. They are white/gray, H= 6

Some plagioclase shows labradorescence (reflection of light along twin lamellas)





Plagioclase crystals are tabular, lath-shaped. They are white/gray, H= 6

Some plagioclase shows labradorescence (reflection of light along twin lamellas)









Plagioclase is common in many magmatic rocks both felsic (rhyolite/granite) and mafic (basalt/gabbro)







Granite

Plagioclase is also common in several metamorphic rocks (greenschists, amphibolite, gneiss)



Amphibolite with plagioclase (white) and amphibole (black). The red mineral is garnet.

293

TU Clausthal Silicate minerals: Tectosilicates: Feldspatoids

This group of minerals is related to feldspar, buthas lower SiO₂ content

Nepheline $Na[AlSiO_4]$ $Na[AlSi_3O_8] - 2SiO_2 = Na[AlSiO_4]$ albite nepheline Leucite $K[AlSi_2O_6]$ $K[AlSi_3O_8] - SiO_2 = K[AlSi_2O_6]$ K-feldspar leucite

Feldspatoids never occur together with quartz

TU Clausthal Silicate minerals: Tectosilicates: Feldspatoids

Nepheline: hexagonal, white/grey, H=5.5.-6 and occurs in SiO₂ undersaturated <u>plutonic</u> rocks



Leucite: cubic, white/grey, H=5.5.-6 and occurs in SiO₂ undersaturated <u>volcanic</u> rocks (e.g. Vesuvius)





TU Clausthal Silicate minerals: Tectosilicates: Feldspatoids

Sodalite: cubic, colourless to dark blue, H= 5-6 occurs in SiO₂ undersaturated, alkaline <u>magmatic</u> rocks. Related to nepheline. Na₈(Al₆Si₆O₂₄)Cl₂



Nosean: cubic, colourless to variable colours, H= 5-6 occurs in SiO₂ undersaturated, alkaline <u>magmatic</u> rocks. Related to nepheline. Na₈(Al₆Si₆O₂₄)(SO₄). H₂O.



Thomas Ulrich Institute for Disposal Research

296

TU Clausthal Silicate minerals: Tectosilicates: **Zeolites**

Zeolites are a large group (>45) of minerals with special properties due to their crystal structure that contain open channels.

Analcime Na [AlSi2O6] · H2O Natrolite Na2 [Al2Si3O10] · 2H2O Chabasite Ca [Al2Si4O12] · 6H2O





Zeolites are colourless, white, grey and occur in low-grade metamorphic rocks (zeolite facies, 50-150C) and in volcanic rocks as secondary fillings in vesicles.

Thomas Ulrich Institute for Disposal Research



297





- Many of the minerals in this group are economically important and provide metals for our technologies.
- They all contain <u>sulfur</u> in their formula and form during hydrothermal or magmatic processes.
- Many sulfides have a metallic lustre (-glanz) and their density is typically >4g/cm³. H between 2-5.
- They are not 'rock-forming' and occur disseminated in the rocks, in veins or more massive patches.







1cm



Sudbury Ni-Cu-PGE

TU Clausthal Sulfides: pyrite, markasite

- **Pyrite (FeS₂):** cubic, yellow, (fool's gold).
- Most common sulphide, occurs in many different rock types. It is <u>not</u> used to extract iron, but S for sulfuric acid. Can contain gold.
- Markasite (FeS₂) orthorhombic, low T (<300C) polymorph of pyrite. Less common than pyrite, hydrothermal or sedimentary.



TU Clausthal Sulfides: pyrrhotite, cinnabar

• **Pyrrhotite (FeS):** dark/dull yellow, light bronze, magnetic. Often together with pentlandite in Ni deposits. Rarely used as iron ore.

 Cinnabar (HgS): red, red-brown, D = 8, most important quicksilver ore, famous mine in Almadén (Spain), toxic, occurs in volcanic areas.





TU Clausthal Sulfides: galena, sphalerite

• Galena (PbS): cubic, light grey/silver, high density (heavy), forms often cubes. Can contain high concentrations of silver (Ag)

• Sphalerite (ZnS): cubic, yellowbrown to dark brown. High lustre, good cleavage

These two sulphides occur often together

Thomas Ulrich Institute for Disposal Research







TU Clausthal Sulfides: chalcocite, chalcopyrite

 Chalcocite (Cu₂S): grey, Cu ore, hydrothermal or most commonly as secondary mineral in copper deposits such as the Kupferschiefer and supergene enrichment zones.

 Chalcopyrite (CuFeS₂): dark yellow, surface tarnishes quickly, most important Cu ore, hydrothermal or magmatic. Weathering products are azurite/malachite



TU Clausthal Sulfides: Molybdenite, Stibnite

 Molybdenite (MoS₂): grey, silver, soft, flacky, hydrothermal and major Mo ore



 Stibnite (Sb₂S₃): light-grey, easily tarnished. Important Sb ore, hydrothermal, prismatic crystals



TU Clausthal Sulfides: Pentlandite

 Pentlandite (Ni,Fe)₉S₈): bronze, important Ni ore. Forms commonly magmatic, often together with pyrrhotite





- Oxides are a large group of minerals. They form minerals with formulas such as XO₂, X₂O₃, XY₂O₄
- Several minerals in the oxide group are economically important and include, hematite, magnetite, chromite, pyrolusite, rutile, ilmenite, cassiterite, wolframite, uraninite, high-purity quartz

TU Clausthal Oxides: Quartz

- Quartz (SiO₂) is one of the most abundant minerals in the Earth's crust (remember the abundance of Si and O).
- Quartz is found in all different rock types (magmatic, metamorphic, sedimentary and in hydrothermal veins).
- Quartz is in the oxide group, but the structure is made up of SiO₄⁴⁻ tetraheder and belongs to the tectosilicates (framework).
- Quartz occurs in many colours and crystallinity varies from microcrystalline to large single crystals.
- Quartz has many polymorphs, depending under which P-T conditions it forms.

TU Clausthal Oxides: Quartz polymorphs



Modifikation	Kristallsystem	Dichte (g/cm ³)
Tief-Quarz α -Quartz	trigonal	2,65
$Hoch-Quarz\beta$ -Quartz	hexagonal	2,53
Tief-Tridymit	monoklin	2,27
Hoch-Tridymit	hexagonal	2,26
Tief-Cristobalit	tetragonal	2,32
Hoch-Cristobalit	kubisch	2,20
Coesit	monoklin	3,01
Stishovit	tetragonal	4,35
Opal (SiO ₂ \cdot nH ₂ O)	amorph	2,1-2,2

TU Clausthal Oxides: Quartz polymorphs

The high temperature polymorphs <u>tridymite</u> and <u>cristobalite</u> are rare and occur in some volcanic rocks and sediments.

The high pressure polymorphs <u>coesite</u> and <u>stishovite</u> occur in some metamorphic rocks and rocks that experienced meteorite impact.

The polymorphs α -quartz and β -quartz have a reversible phase transition at 573C. There occurs a slight volume increase in β -quartz.

Many microcrystalline quartz varieties such as agate, chalcedony, onyx, flint, opal are not polymorphs.

TU Clausthal Oxides: Quartz varieties

The coloured varieties are due to crystal lattice defects and in-cooperation of trace elements

Thomas Ulrich Institute for Disposal Research

311

TU Clausthal Oxides: Quartz varieties

CARNELIAN - red chalcedony

CHRYSOPRAS - green chalcedony

FLINT

Thomas Ulrich Institute for Disposal Research

OPAL

TU Clausthal Oxides: Rutile, Cassiterite

- Rutile (TiO₂): red-brown, yellowish, is an accessory phase in magmatic and metamorphic rocks. Occurs as small, stubby or needle-shaped crystals. Forms secondary ore deposits (heavy sands). After ilmenite most important Ti ore. Polymorphs are called brookite and anatas.
- Cassiterite (SnO₂): light to dark brown, heavy.
 Occurs in hydrothermal veins in magmatic rocks, pegmatites. Found also in heavy sands. Most important Sn ore.

TU Clausthal Oxides: Pyrolusite, Uraninite

 Pyrolusite (MnO₂): dark grey, occurs in weathered zones together with iorn-hydroxides. Forms also on the seafloor (Mn nodules). Most important Mn ore.

Uraninite (UO₂): black, radioactive, heavy.

Occurs in hydrothermal veins, but commonly in sediments where it is precipitated due to redox change (U⁶⁺ (soluble) to U⁴⁺ (insoluble)). Found also in heavy sands. Most important U ore.

TU Clausthal Oxides: Wolframite, Corundum

Wolframite ((Fe,Mn)WO₄): black, heavy.
 Important W ore. Occurs in hydrothermal veins together with cassiterite (+/- molybdenite, pyrite). Also in heavy sands.

 Corundum (Al₂O₃): colourless, red (<u>ruby</u>), blue (<u>sapphire</u>), hard (9). Occurs in metamorphic and magmatic (pegmatites) rocks. Requires high content of Al in the rocks.

TU Clausthal Oxides: Hematite, Ilmenite

- Hematite (Fe₂O₃): red, red-brown, grey. Stroke: red. Most important Fe ore. Occurs in in sedimentary rocks (banded iron formations), hydrothermal veins and in <u>skarns (metasomatized</u> limestone). Gives a red hue to many rocks/minerals.
- Ilmenite (FeTiO₃): brown-black. Most important Ti ore. Occurs in magmatic rocks and secondary in heavy sands.

TU Clausthal Oxides: Spinel, Chromite, Magnetite

- Spinel (MgAl₂O₄): different colours, hard. Occurs mainly in metamorphic rocks
- Chromite (FeCr₂O₄): black, semi-metallic lustre. Most important Cr ore. Occurs in ultramafic magmatic rocks and secondary in heavy sands.
- Magnetite (Fe₃O₄): black, magnetic. Important Fe ore. Occurs in hydrothermal veins and in magmatic rocks and secondary in heavy sands. Occurs also together with hematite in BIFs and skarns.

TU Clausthal Hydroxides: Goethite, Limonite, Bauxite

Hydroxides are typically weathering products of former oxides or sulphides when they get in contact with water and oxidized conditions. They occur often together with other secondary minerals and clay minerals.

- Goethite (FeOOH): yellow-brown, dark brown, dull lustre.
- Limonite (FeOOH): yellow-brown, dull lustre. A mineral mix of Fe-hydroxides and
- Balaxite : yellow-red-brown, dull lustre. Most important ore for Al. A mixture of different Alhydroxides (Al(OH₃): Gibbsite, AlOOH: Diaspore, Boehmite). Strong weathering and leaching of 'all' elments except for Al.

TU Clausthal Halogenides: Halite, Sylvite, Carnallite Halogenides have highly ordered structures and their bonding is typically ionic.

- Often cubic and good cleavage. Their density is generally low.
- Halite (NaCl): cubic, white, but also other colours. Soluble in water and crystallizes due to evaporation (Evaporites)
- Sylvite (KCI): cubic, white, very similar to halite, occurs also in evaporites. Important potassium source
- Carnallite (KMgCl₃.H2O): white, grey, red. Easy dissolvable, Important potassium ore. Evaporites and salt deposits.

TU Clausthal Halogenides: Fluorite

 Fluorite (CaF₂): cubic, different colours, H
 = 4, perfect cleavage (octahedral) occurs in hydrothermal and pegmatitic veins and rocks. Also in sediments.

TU Clausthal Carbonates

This mineral group is making up mostly sedimentary rocks (limestones) and in rarer cases magmatic rocks (carbonatites). They occur as metamorphic rocks (marble).

The minerals contain CO_3^{2-} in their formula, and many of them have a trigonal crystal system.

Ionenradius

Thomas Ulrich Institute for Disposal Research

TU Clausthal Carbonates: Calcite, Aragonite

Calcite (CaCO₃): white, colourless, H = 3, it is the most common carbonate mineral. Aragonite is less stable, but slightly harder. It is the high-pressure polymorph, and is also mother of pearl. Occurs in vesicles of volcanic rocks.

Calcite has high birefringence and reacts with hydrochloric acid.

Calcite occurs as gangue material in hydrothermal veins. Carbonatites (magmatic carbonates) contain calcite. Limestone consists of either biogenic (shells of microorganism) or chemically precipitated calcite.

http://www.itp.unihannover.de/~zawischa/ITP/ kalcal.html Economic Geology

TU Clausthal Carbonates: Rhodochrosite, Siderite, Magnesite

- Rhodochrosite (MnCO₃): red, pink, forms in hydrothermal systems. Also in weathering zones. In place used as Mn ore.
- Siderite (FeCO₃): brown, grey-yellow, occurs hydrothermal, metamorphic and sedimentary. Can be used as Fe ore.
- Magnesite (MgCO₃): grey, white. Occurs sedimentary and metamorphic. When fired to 1800C it becomes MgO (periclase), used as insulation in high-T ovens.

TU Clausthal Carbonates: Dolomite, Malachite, Azurite

- Dolomite (CaMg(CO₃)₂): grey, white, forms in metasomatized rocks (dolomitization) and under diagenetic conditions where Mg is available.
- Malachite (Cu₂(CO₃)(OH)₂): green, secondary Cu ore, often together with azurite. Occurs in supergene enrichment zones. Locally, Cu ore
- Azurite (Cu₃(CO₃)₂(OH)₂): blue, secondary Cu ore, often together with malachite when more water is added and oxidation happnes. Occurs in supergene enrichment zones.

TU Clausthal Sulfates/Wolframites/Phosphates: Baryte, Anhydrite, Gypsum

These minerals have either SO_4^{2-} , WO_4^{2-} or PO_4^{2-} units in their formula

- Baryte (BaSO₄): grey, white, 'heavy' D = 4.5g/cm³.
 Forms in low-temperature hydrothermal systems and sedimentary
- Anhydrite (CaSO₄): colorless, grey, lila, light blue.
 Occurs together with halite in evaporites and also hydrothermal.
- Gypsum (CaSO₄. H₂O): white, colourless, soft H =
 2. Forms in evaporites and from anhydrite by taking up water (volume increase). Hydrothermal.

Thomas Ulrich Institute for Disposal Research



Sulfates/Wolframites/Phosphates: Scheelite, Apatite

 Scheelite (CaWO₄): grey-white, light yellowish, heavy. Blueish under UV light. Occurs in magmatichydrothermal systems and in skarns. Together with cassiterite. Important W ore after wolframite.







under UV light





Thomas Ulrich Institute for Disposal Research