TECNOLOGIA DOS MATERIAIS CERÂMICOS

I - CERAMIC RAW MATERIALS

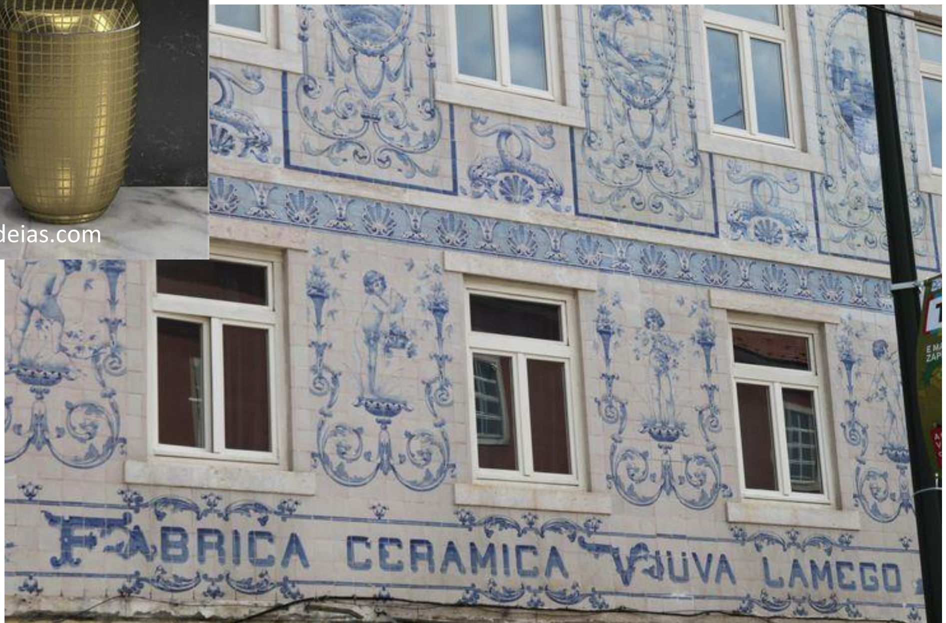
1.1 Ceramic Products: Traditional

Table ware

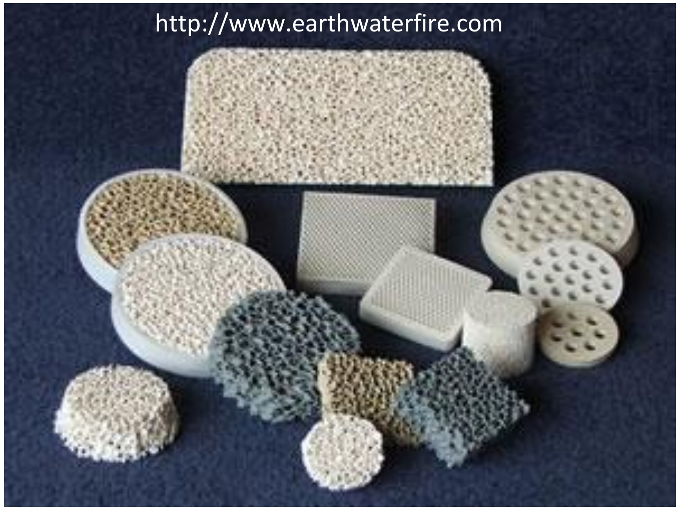
Sanitary ware

Bricks

Tiles



1.1 Ceramic Products: Refractory



Membranes and filters

Crucibles and other lab artifacts

Kiln and furnaces

Ball (for *ballmill*)

1.1 Ceramic Products: Mechanical and *Cutting-tools*

Mechanical tools

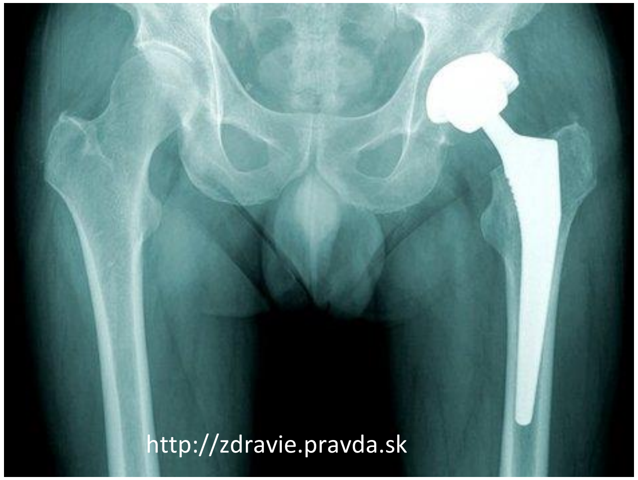
Mechanical tools

Cutting tools

Cutting tools

1.1 Ceramic Products: Medical and Healthcare

Ceramic teeth



Ceramic hip implant

Water filter

1.1 Ceramic Products: Bulletproof

Ceramic bulletproof plate ,
Bulletproof protects armor , Ballistic helmet

Bulletproof plate, armor and helmet

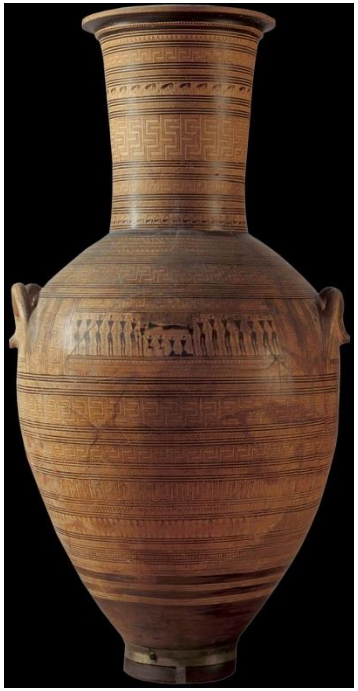
http://www.defensereview.com/prototype-mini-battle-shieldmini-combat-shield-gets-shoot-tested-pics/

Bulletproof shield

1.1 Ceramic Products: na old history….

29000 b.C. - 25000 b.C.
Věstonice, Tcheck Republic

Chan Chan – Pre-Coulombian, South America's Mud-Brick City

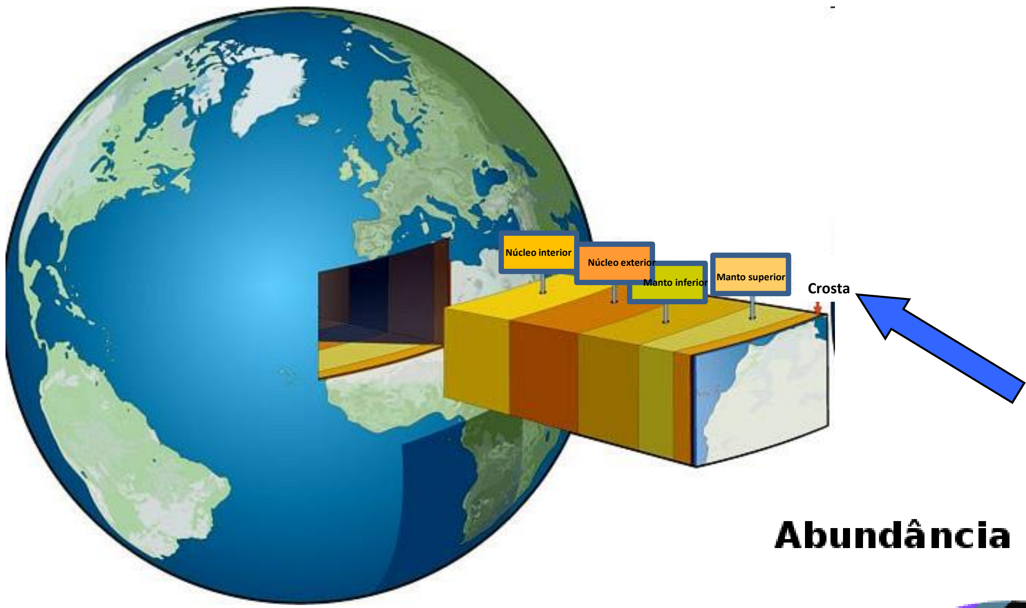


750 b.C.
Dipylon Cemetery, Athens

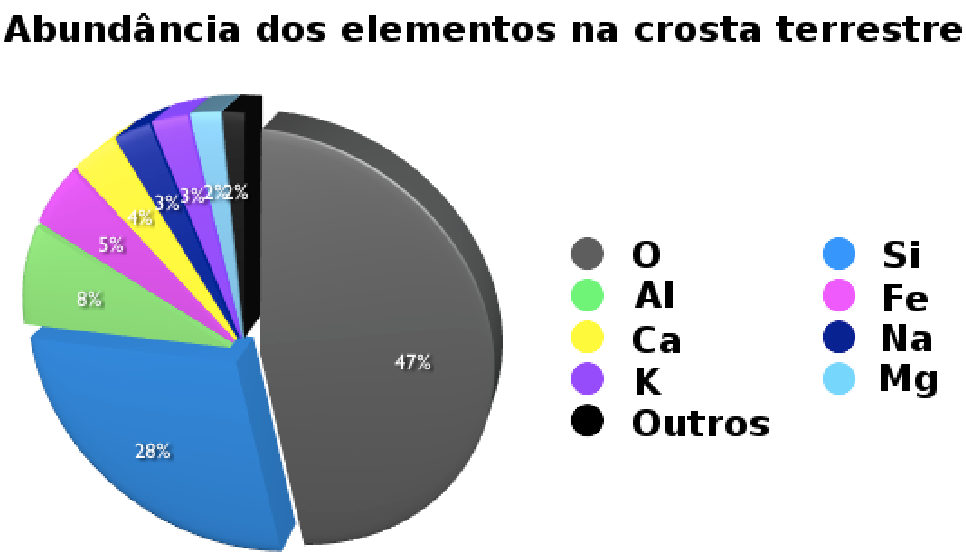
Dinasty Ming (1368-1644)
French embassy, Lisboa

209-210 b.C.
The Terracotta Warriors and Horses of Qin Shi Huangin, China.
Terracotta Army held more than 8,000 soldiers, 130 chariots with 520 horses and 150 cavalry horses.

Silica in earth crust



O, Si, Al, Fe, Ca, Na, K, Mg



Ref: Lutgens and Tarbuck, Essentials of Geology (2000)

CERAMICS COMPOSITIONS

1.2 1950...

	PROPERTIES	COMPOSITION
ELECTRICAL	ISOLATION FERROELECTRIC PIEZOELECTRIC SUPERCONDUTOR	α-Al_2O_3, MgO, porcelain $BaTiO_3$, $SrTiO_3$ $PbZr_{0.5}Ti_{0.5}O_3$ $Ba_2YCu_3O_{7-x}$
MAGNETIC	FERRITES	$Mn_{0.4}Zn_{0.6}Fe_2O_4$, $BaFe_{12}O_{19}$, $SrFe_{12}O_{19}$
MECHANICAL	STRUCTURAL REFRACTORY MECHANICAL RESISTANCE CUTTING/ABRASION CIVIL CONSTRUCTION (BRICK, ROOF TILE, CEMENT)	α-Al_2O_3, MgO, SiC, Si_3N_4, $Al_6Si_2O_{13}$ α-Al_2O_3, ZrO_2, SiC, Si_3N_4 α-Al_2O_3, ZrO_2, SiC, TiC, Si_3N_4 , SIALON Al_2O_3-SiO_2, CaO-Al_2O_3-SiO_2
FUNCTIONAL	FAIENCE / PORCELAIN	FAIENCE, PORCELAIN CaO-SiO_2-H_2O

CERAMICS COMPOSITION

1.2 2015...

	PROPERTIES	COMPOSITION
ELECTRICAL	ISOLATION FERROELECTRIC PIEZOELECTRIC SUPERCONDUTOR	α-Al_2O_3, MgO, porcelain $BaTiO_3$, $SrTiO_3$ $PbZr_{0.5}Ti_{0.5}O_3$ $Ba_2YCu_3O_{7-x}$
MAGNETIC	FERRITE	$Mn_{0.4}Zn_{0.6}Fe_2O_4$, $BaFe_{12}O_{19}$, $SrFe_{12}O_{19}$
NUCLEAR	FUEL COATING/ SHIELD	UO_2, UO_2- PuO_2 SiC, B_4C
OPTICAL	TRANSPARENCY COLOR MEMORY	α-Al_2O_3, $MgAl_2O_4$ $ZrSiO_4$, ZrO_2, Al_2O_3 dopados $PbZr_{0.5}Ti_{0.5}O_3$
MECHANICAL	STRUCTURAL REFRACTORY MECHANICAL RESISTANCE CUTTING/ABRASION CIVIL CONSTRUCTION (BRICK, ROOF TILE, CEMENT)	α-Al_2O_3, MgO, SiC, Si_3N_4, $Al_6Si_2O_{13}$ α-Al_2O_3, ZrO_2, SiC, Si_3N_4 α-Al_2O_3, ZrO_2, SiC, TiC, Si_3N_4 , SIALON Al_2O_3-SiO_2, CaO-Al_2O_3-SiO_2
THERMAL	ISOLATION	α-Al_2O_3, ZrO_2, $Al_6Si_2O_{13}$, SiO_2
CHEMICAL	RADIATOR GAS SENSOR CATALITIC CARRIER ELECTROD FILTER COATING	ZrO_2, TiO_2 ZnO, ZrO_2, SnO_2, Fe_2O_3 $Mg_2Al_4Si_5O_{18}$, Al_2O_3 TiO_2, TiB_2, SnO_2, ZnO SiO_2, α-Al_2O_3 NaO-CaO-Al_2O_3-SiO_2
BIOLOGICAL	PROSTHESIS CEMENT	α-Al_2O_3, PORCELAIN $CaHPO_4.2H_2O$
FUNCTIONAL	FAIENCE / PORCELAIN	FAIENCE, PORCELAIN CaO-SiO_2-H_2O

1.3 Classification of the main materials groups

Materials

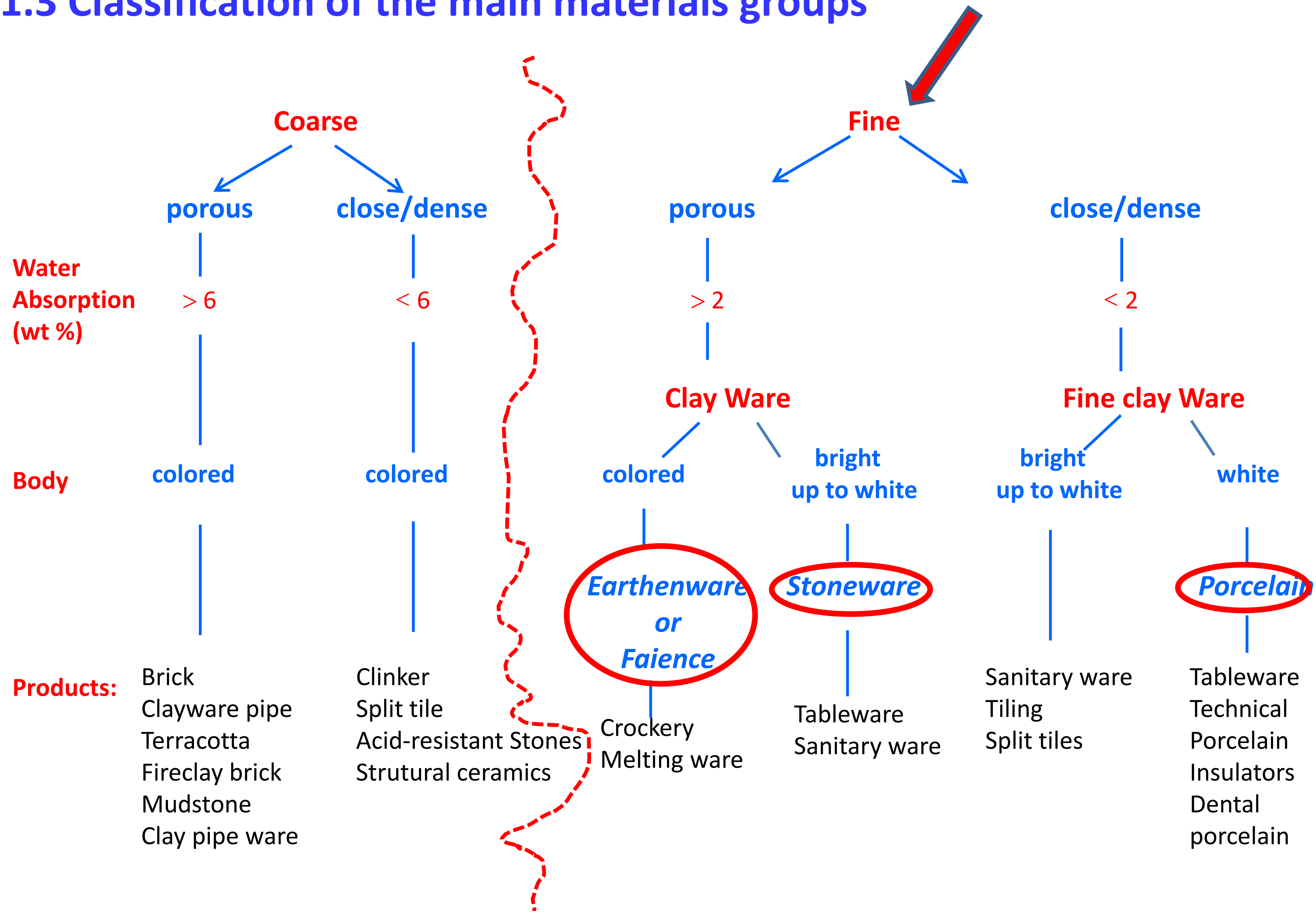
- **Natural Materials:** Wood; Leather; Cellulose; Chitin; **Minerals**
- **Synthetic Materials**
  - **Non-Metallic Materials**
    - **Inorganic Materials: Ceramics, Glasses**
      - **Silicate ceramics**
      - **Oxide ceramics**
      - **Non-oxide ceramics**
      - **Glasses**
    - Organic Materials: Polymers
      - Standard Polymers
      - Technical Polymers
      - Special Polymers
  - **Semiconductor**
  - **Metals**
    - Traditional Metals
    - Light Weight Construction Alloys
    - High Temperature Materials
    - Functional Metals

1.3 Classification of the main materials groups

CERAMICS

- **Oxide ceramics**
  - **Silicon Ceramics** (Natural Raw materials) →
    - **Porcelain**
    - **Sanitary Porcelain**
    - **Stoneware**
    - ***Earthenware or* Faience**
    - Brick
    - Tiling
    - Insulators
  - **Metal Oxides** (Synthetic raw materials) →
    - Alumina
    - Zirconia
    - Silica
    - Mullite
    - Cordierite
    - Apatite
    - Zinc Oxide
    - Tantal Oxide
    - Titanates
    - Niobates
    - Zirconates
    - Ferrites
- **Non-Oxide ceramic** (Synthetic raw materials)
  - Carbides:
    - Silicon Carbide
    - Boron Carbide
    - Titanium Carbide
  - Nitrides:
    - Silicon Nitride
    - Aluminium Nitrade
    - Boron Nitride
    - Titanium Nitrade
  - Borides
  - Silicides
  - Graphite
  - Diamond

1.3 Classification of the main materials groups



1.4 Ceramic ternary diagram

Faience or Earthenware

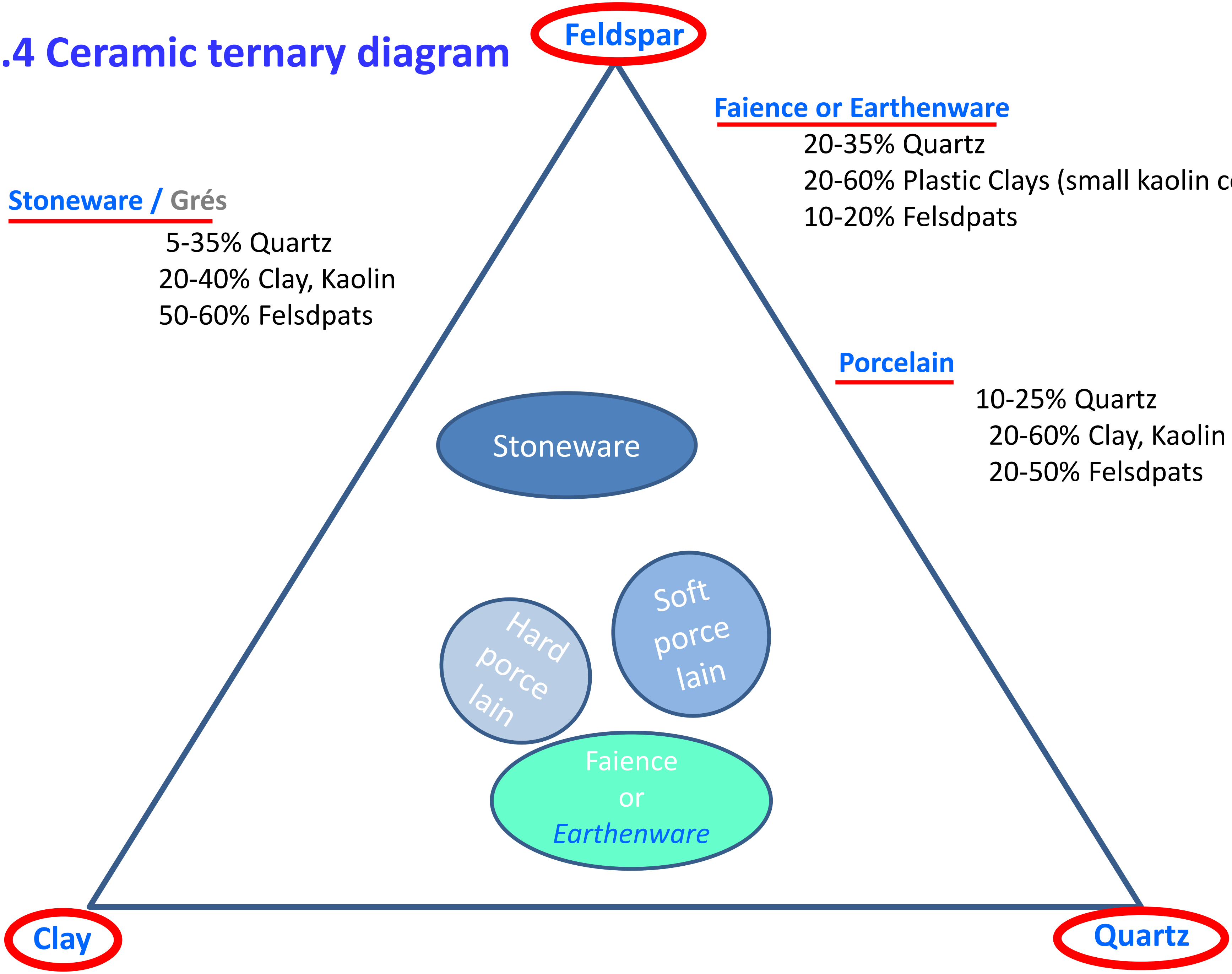
20-35% Quartz
20-60% Plastic Clays (small kaolin content)
10-20% Felsdpats

Stoneware / Grés

5-35% Quartz
20-40% Clay, Kaolin
50-60% Felsdpats

Porcelain

10-25% Quartz
20-60% Clay, Kaolin
20-50% Felsdpats

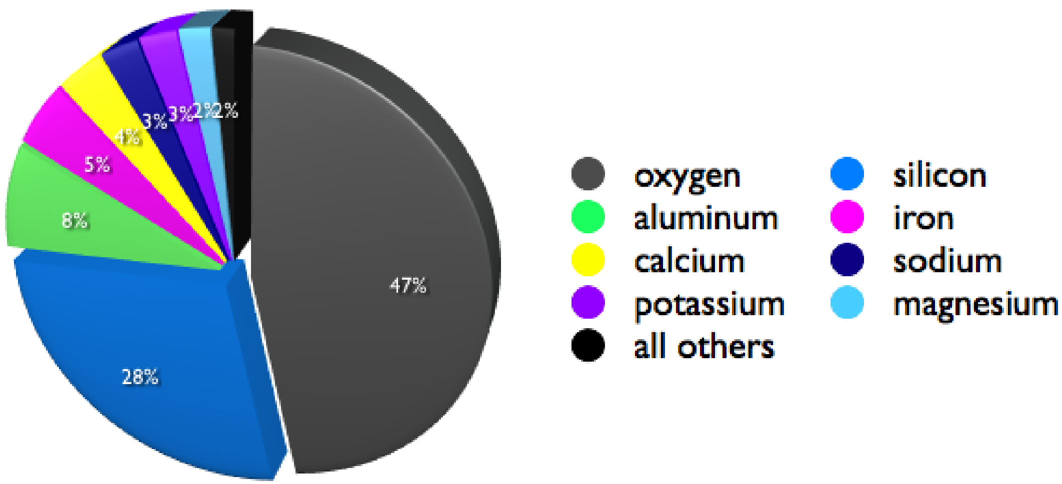


CLAYS and Quartz

1.5 Ceramic raw materials

Silica Abundance

abundances of the elements in the earth's crust



Ref: Lutgens and Tarbuck, Essentials of Geology (2000)

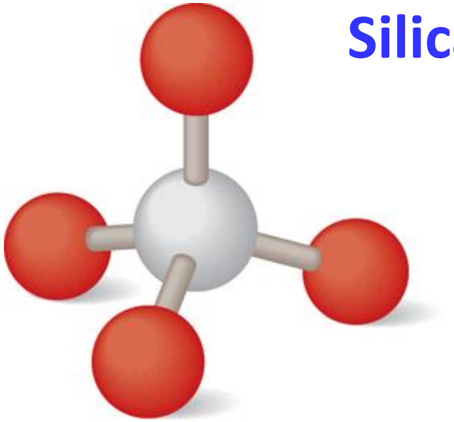
https://fundamateria.wordpress.com/category/seed/

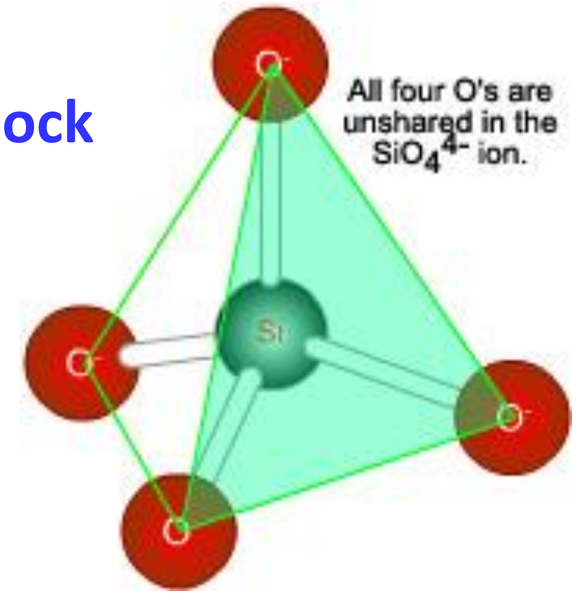
→ Silicon is one of **the most abundant elements in the earth's crust**, but it occurs chiefly in combination with oxygen as silica, **SiO_2**, and with oxygen and other elements as **silicates**.

→ **Silica** is a **polymorphic substance**, capable of existing in several different forms, all having the same empirical formula but differing in the arranjement of the structural units – **quartz**, **tridimite** and **cristobalite** are the most abundant forms in earth's crust.

1.5 Ceramic raw materials

Silica Tetrahedron – the building block





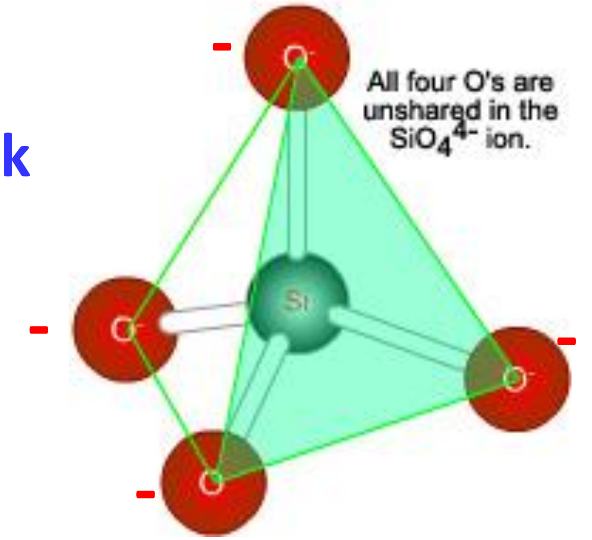
→ The Si-O bond has sufficient **ionic character** to enable us to regard all forms of SiO_2 as being composed of **Si^{4+}** and **O^{2-}** ions.

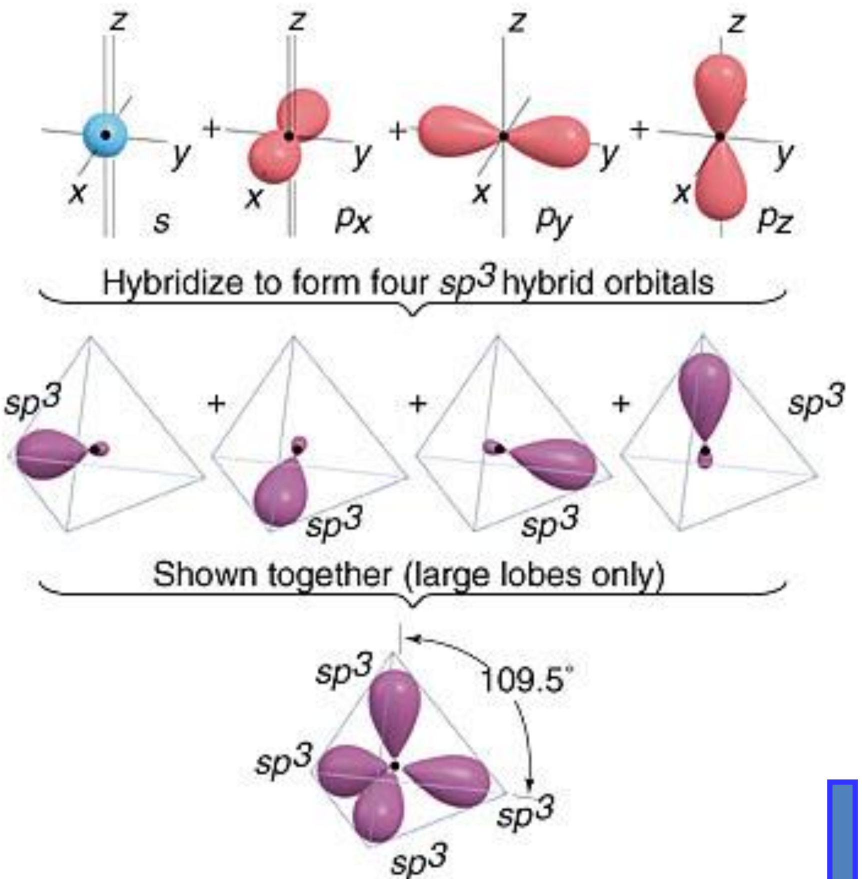
→ The **radius ratio of silicon to oxygen is 0.28** corresponding to a predicted **coordination number of 4**, which agrees with the observed value for the majority of crystalline and amorphous forms of silica.

→ Each **Si^{4+} ion** in silica is sorrounded by **four oxygen ions**, forming a **tetrahedron**, having a triangular base and three triangular sides meeting at na appex.

1.5 Ceramic raw materials

Silica Tetrahedron – the building block





σ O $2p^1$ σ O $2p^1$

Si $3(sp_3)^1$ $3(sp_3)^1$ $3(sp_3)^1$ $3(sp_3)^1$

σ O $2p^1$ σ O $2p^1$

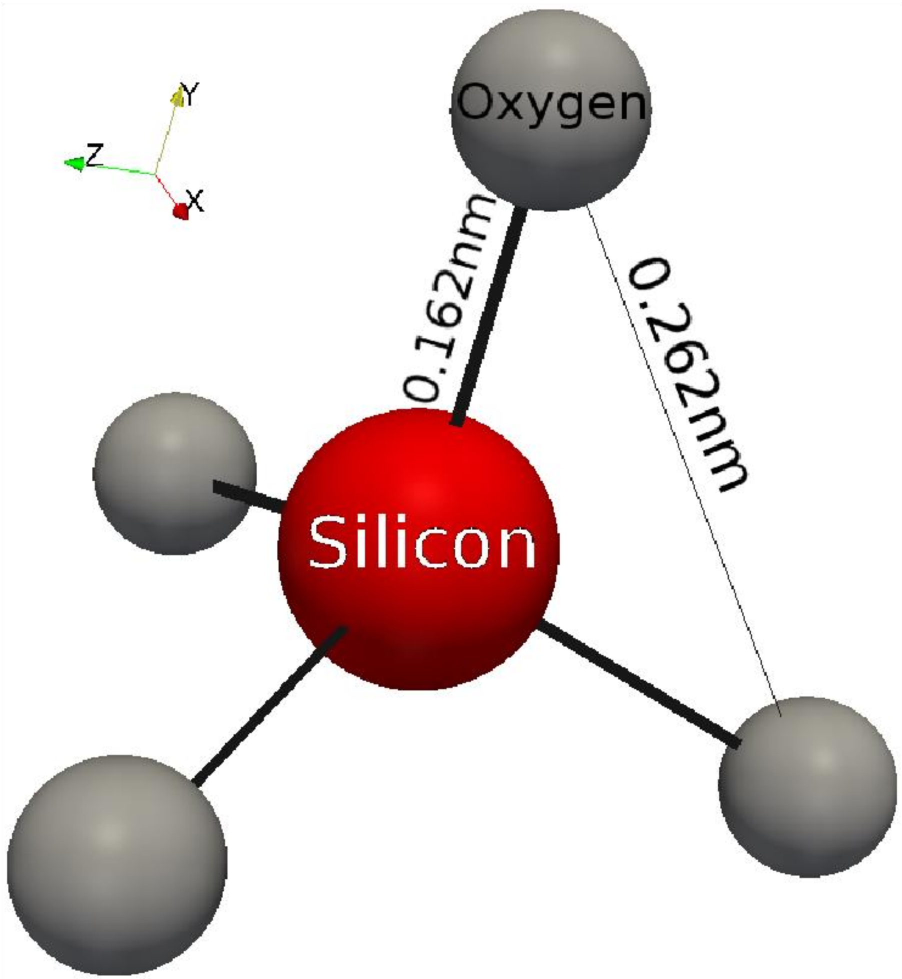
$[O] = [He]\ 2s^2\ 2p_x^2\ 2p_y^1 2p_z^1$

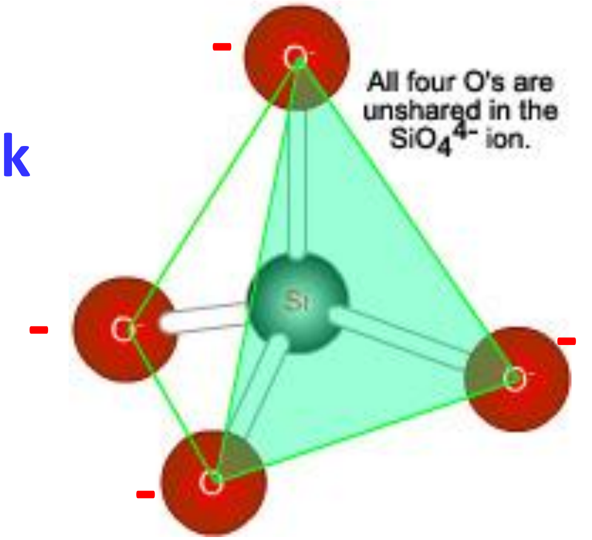
$[O^-] = [He]\ 2s^2\ 2p_x^2\ 2p_y^2 2p_z^1$ σ

Si $3(sp_3)^1$

1.5 Ceramic raw materials

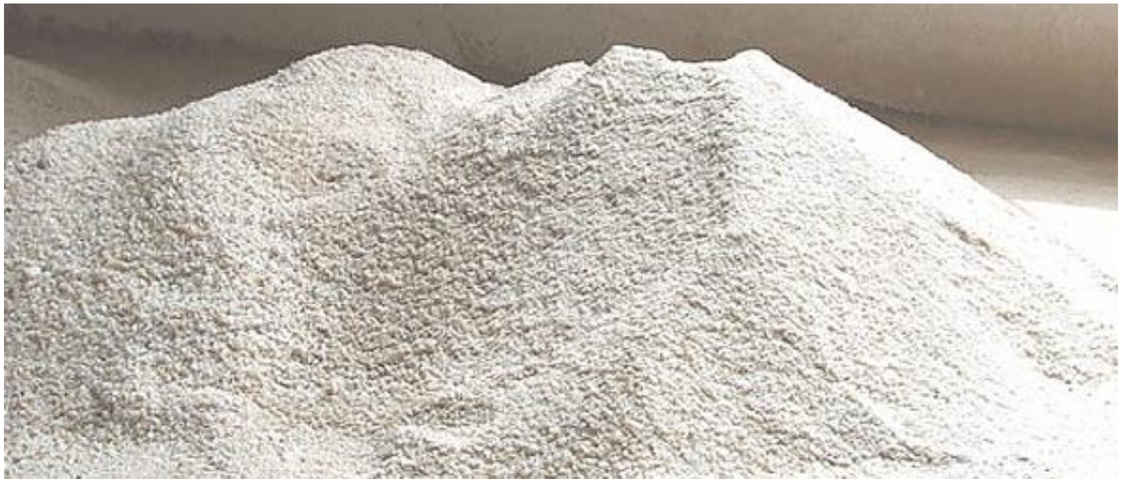
Silica Tetrahedron – the building block

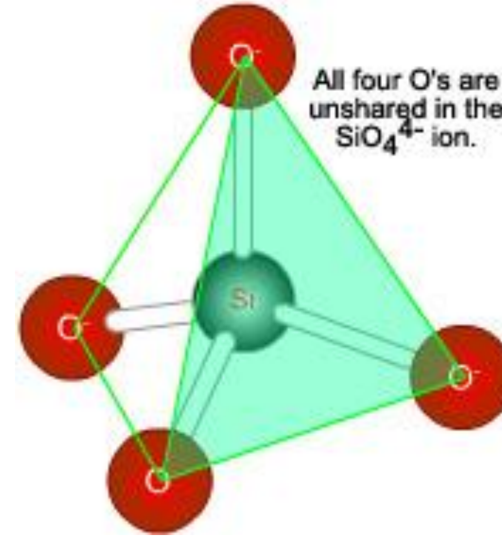




1.5 Ceramic raw materials

Silica Tetrahedron – the building block



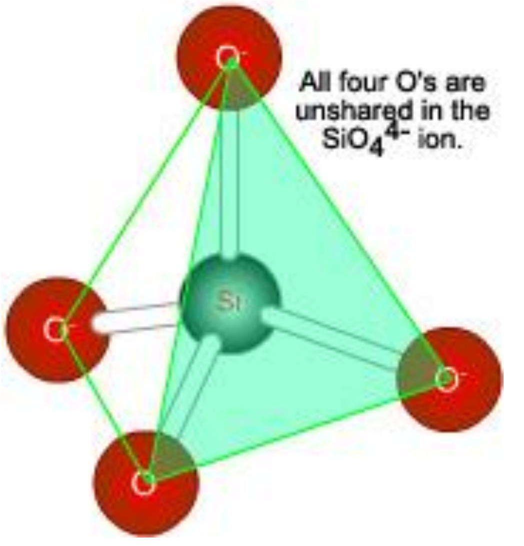


→ The $[SiO4]^{4-}$ **group** is of course **incapable of independent existence** and **requires four positively charged units to balance the negative charges**; these groups may be other **SiO_2 groups**, as in **silica**, or other **cations**, as in **silicates**.

→ This fundamental unit is **repeated**, **linked** and **joined** in different ways giving rise to **different types of silicate structures**.

1.5 Ceramic raw materials

Silica Tetrahedron – the building block



AND NOW LET'S PLAY WITH THE

SILICA TETRAHEDRON!

https://www.youtube.com/watch?v=8q-Hzq0WXXw

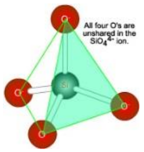
1.5 Ceramic raw materials

Silica Tetrahedron – the building block

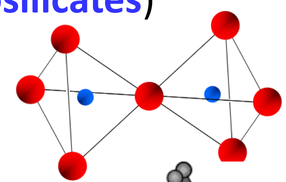
→ **Silicon** is located in the **center of the tetrahedron** and **surrounded by 4 oxygens at the corners**. This group is **electrically unbalanced ((SiO_4)$^{4-}$)**, so that **the oxygen atoms are combined with other cations to compensate their negative charges.** The number of vertices shared by each tetrahedron may be 0, 1, 2, 3 or 4.

→ Tetrahedra may also join by their bases to form hexahedral molecules **((Si_2O_4)$_n^{2n-}$).** Depending on the number of oxygens that coordinate with other silicon cations, large groups of silicates may form in different shapes:

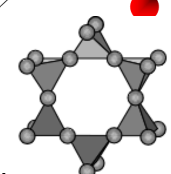
- **Q^0** no oxygens shared: isolated molecules (**orthosilicates**)



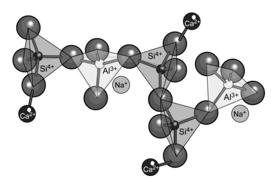
- **Q^1** one oxygen shared: pairs (**sorosilicates**)



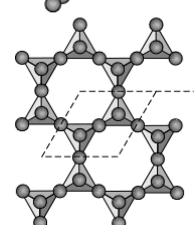
- **Q^2** two oxygens shared: rings (**cyclosilicates**)



- **Q^2-Q^3** two-three oxygens shared: chains (**inosilicates**)



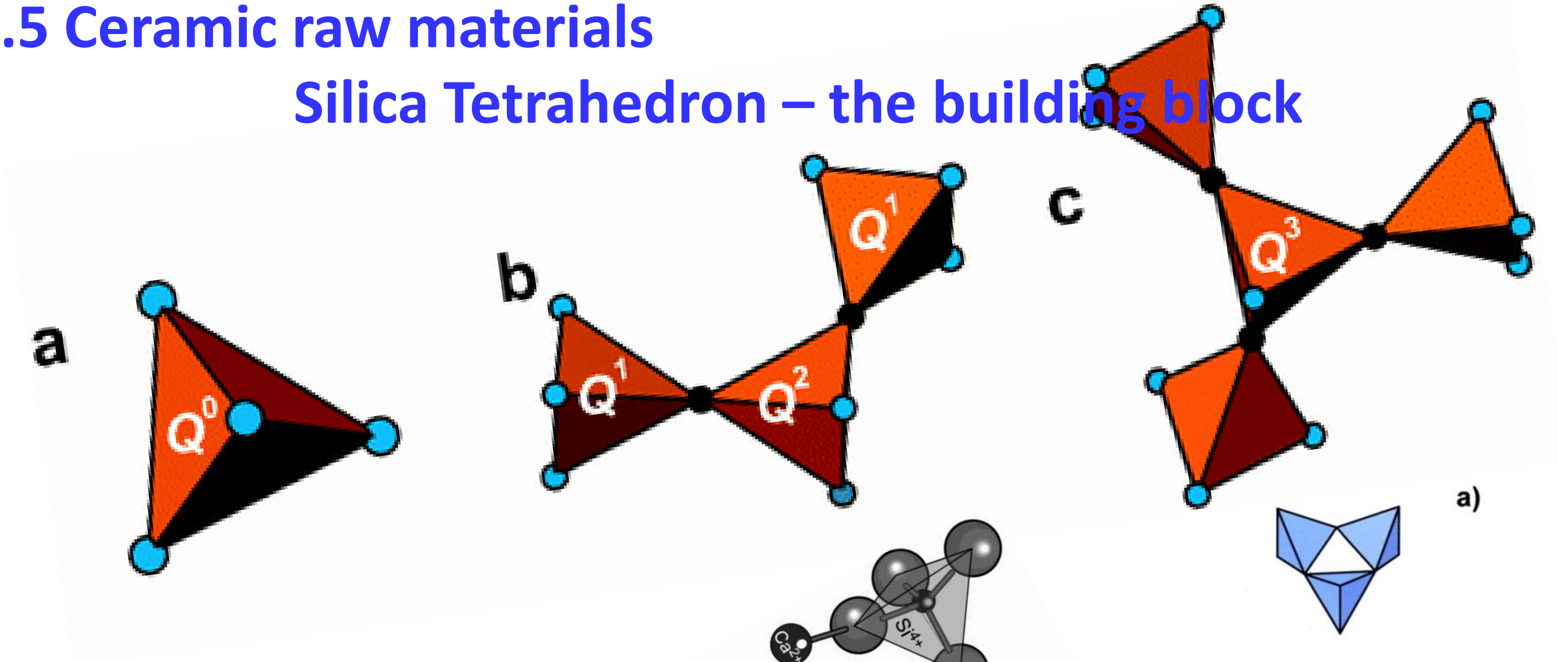
- **Q^3** three oxygens shared: planes (**phyllosilicates**)

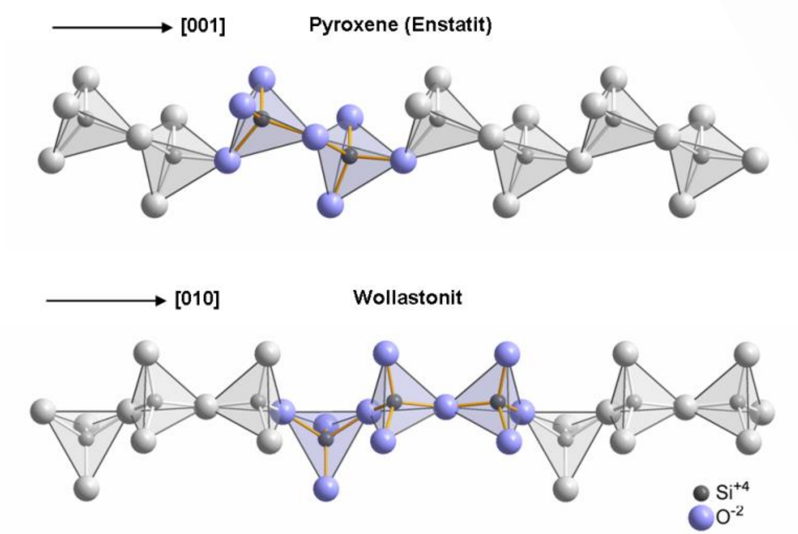


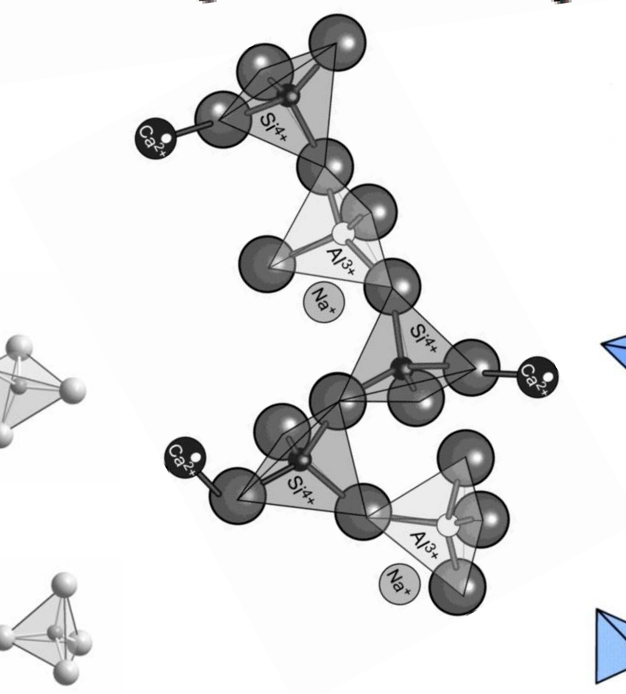
- **Q^4** four oxygens shared: tridimensional structures (**tectosilicates**)

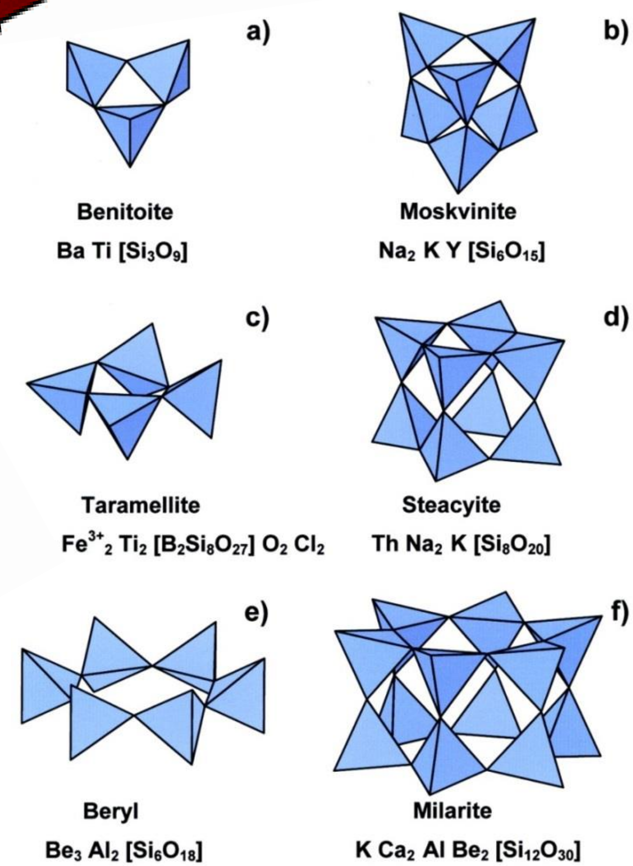
1.5 Ceramic raw materials

Silica Tetrahedron – the building block



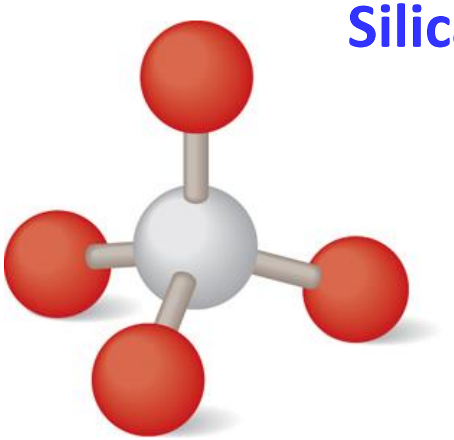


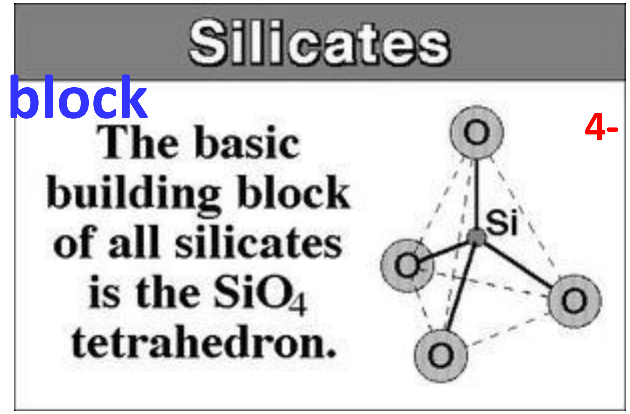




1.5 Ceramic raw materials

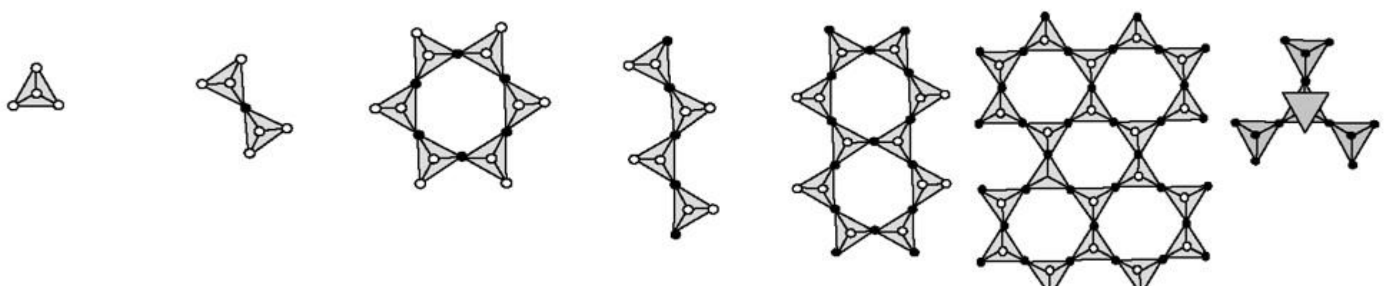
Silica Tetrahedron – the building block





	Q^0		Q^2	Q^2	Q^3	Q^3	Q^4
Anionic unit	SiO_4^{4-}	$Si_2O_7^{6-}$	$Si_6O_{18}^{12-}$	$Si_2O_6^{4-}$	$Si_4O_{11}^{6-}$	$Si_2O_5^{2-}$	SiO_2
Silicate subclass	Isolated tetrahedra	Paired tetrahedra	Ring	Chain	Double chain	Sheet	Framework
NBO/T	4	3	2	2	1 or 2	1	0
Approx. Raman band (cm^{-1})	790-850	890-950	-	930-1000	-	1020-1100	1150-1200 1060-1070

○ NBO
● BO
△ Silicon Tetrahedra



1.5 Ceramic raw materials

Silica Tetrahedron – the building block

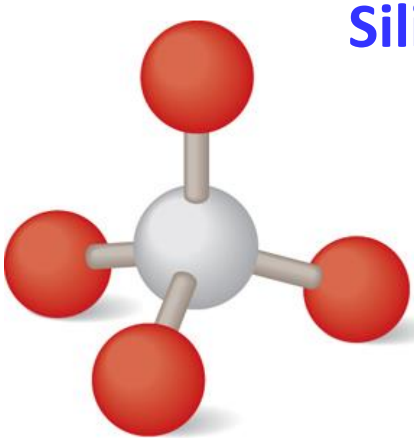
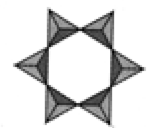
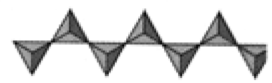
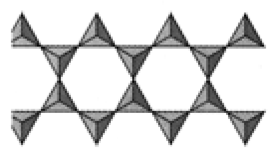
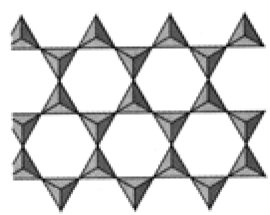
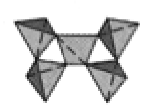
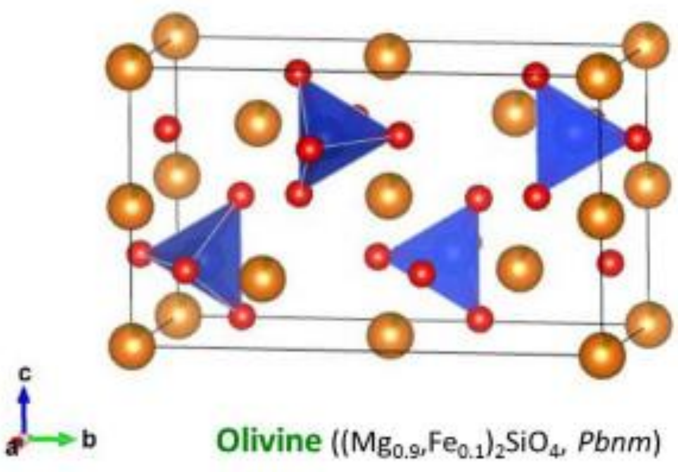


TABLE 2.2
Major Silicate Structures

GEOMETRY OF LINKAGE OF SiO_4 TETRAHEDRA		EXAMPLE MINERAL	CHEMICAL COMPOSITION
Isolated tetrahedra: No sharing of oxygens between tetrahedra; individual tetrahedra linked to each other by bonding to cation between them		Olivine Q^0	Magnesium-iron silicate
Rings of tetrahedra: Joined by shared oxygens in three-, four-, or six-membered rings		Cordierite Q^2	Magnesium-iron-aluminum silicate
Single chains: Each tetrahedron linked to two others by shared oxygens; chains bonded by cations		Pyroxene Q^2	Magnesium-iron silicate
Double chains: Two parallel chains joined by shared oxygens between every other pair of tetrahedra; the other pairs of tetrahedra bond to cations that lie between the chains		Amphibole Q^3	Calcium-magnesium-iron silicate
Sheets: Each tetrahedron linked to three others by shared oxygens; sheets bonded by cations		Kaolinite Mica (muscovite) Q^3	Aluminum silicate Potassium-aluminum silicate
Frameworks: Each tetrahedron shares all its oxygens with other SiO_4 tetrahedra (in quartz) or AlO_4 tetrahedra		Feldspar (orthoclase) Quartz Q^4	Potassium-aluminum silicate Silicon dioxide

1.5 Ceramic raw materials

Q^0: Island Structures (orthosilicates)



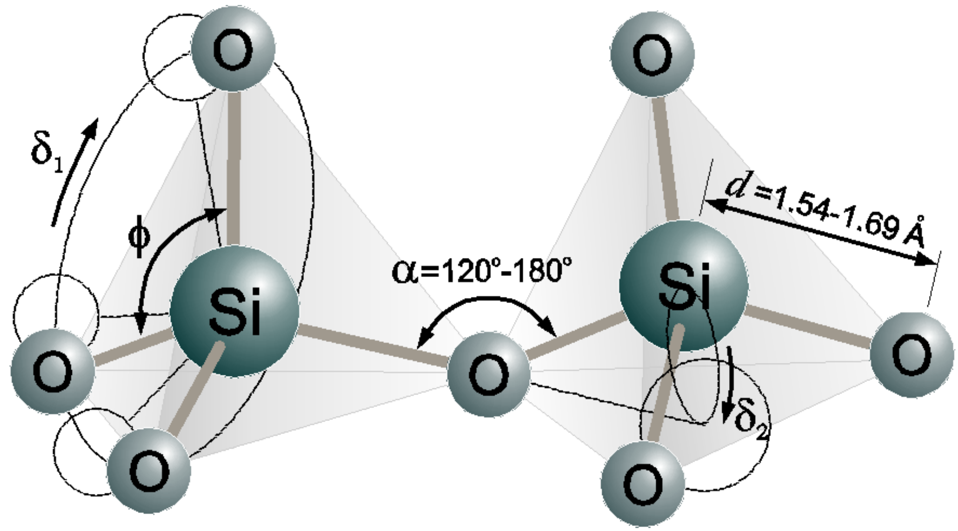
→ A good example of this structure is **olivine**.

→ In **olivine**, **neutrality** is achived by **metallic cations** (principally **Fe** and **Mg**) being attached to the four oxygen ions of the $[SiO_4]^{4-}$.

→ A complete crystal of olivine contains a very large number of SiO_4 units with their appropriate cations; it forms a **continuous network** because each atom is shared by two or more other atoms.

1.5 Ceramic raw materials

Q[1]: Group Structures (sorosilicates)



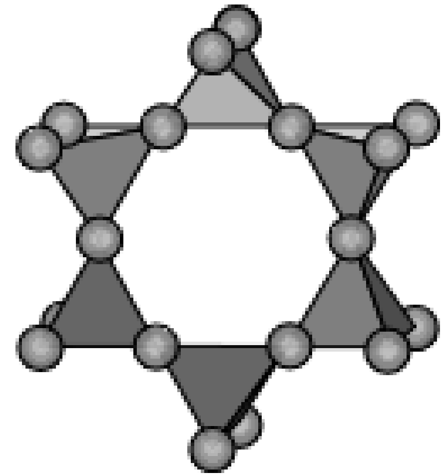
Beryl or emerald

→ Instead of all the free oxygen valancies being satisfied by metallic cations, **two or more silica tetrahedra** may be **joined**, **corner to corner**, to form a group structure.

→ Joining two groups together gives the group Si_2O_7. Minerals of this type are rare (ex. **beryl** or **emerald**, with the formula $(Be_3Al_2)Si_6O_{18}$).

1.5 Ceramic raw materials

Q^2: Group Structures (cyclosilicates)



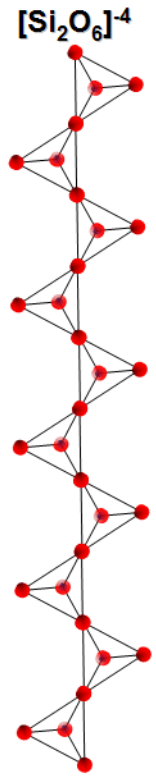
Cordierite

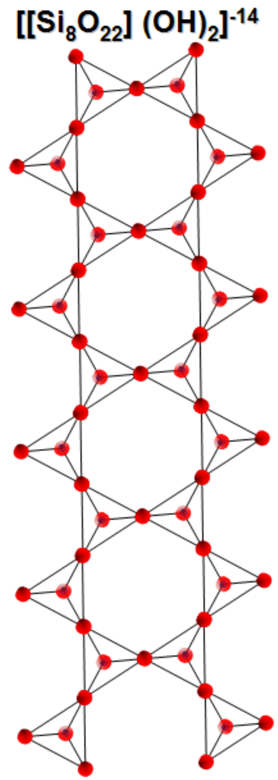
→ Instead of all the free oxygen valancies being satisfied by metallic cations, **two or more silica tetrahedra** may be **joined**, **corner to corner**, to form a group structure.

→ Six units can be linked to form a ring structure, where the basic structure is $Si_6O_{18}^{12-}$. An example is mineral **cordierite**, $Al_3Mg_2(Si_5Al)O_{18}$, where one of the six silicons in the ring has been isomorphous substituted by an aluminium ion. The substitutiton of Al^{3+} for Si^{4+} upsets the charge balance, being the neutrality maintained by increasing the ratio of trivalent to divalent cations.

1.5 Ceramic raw materials

Q^2-Q^3 : Chain Structures (inosilicates)





Pyroxenes Q^2

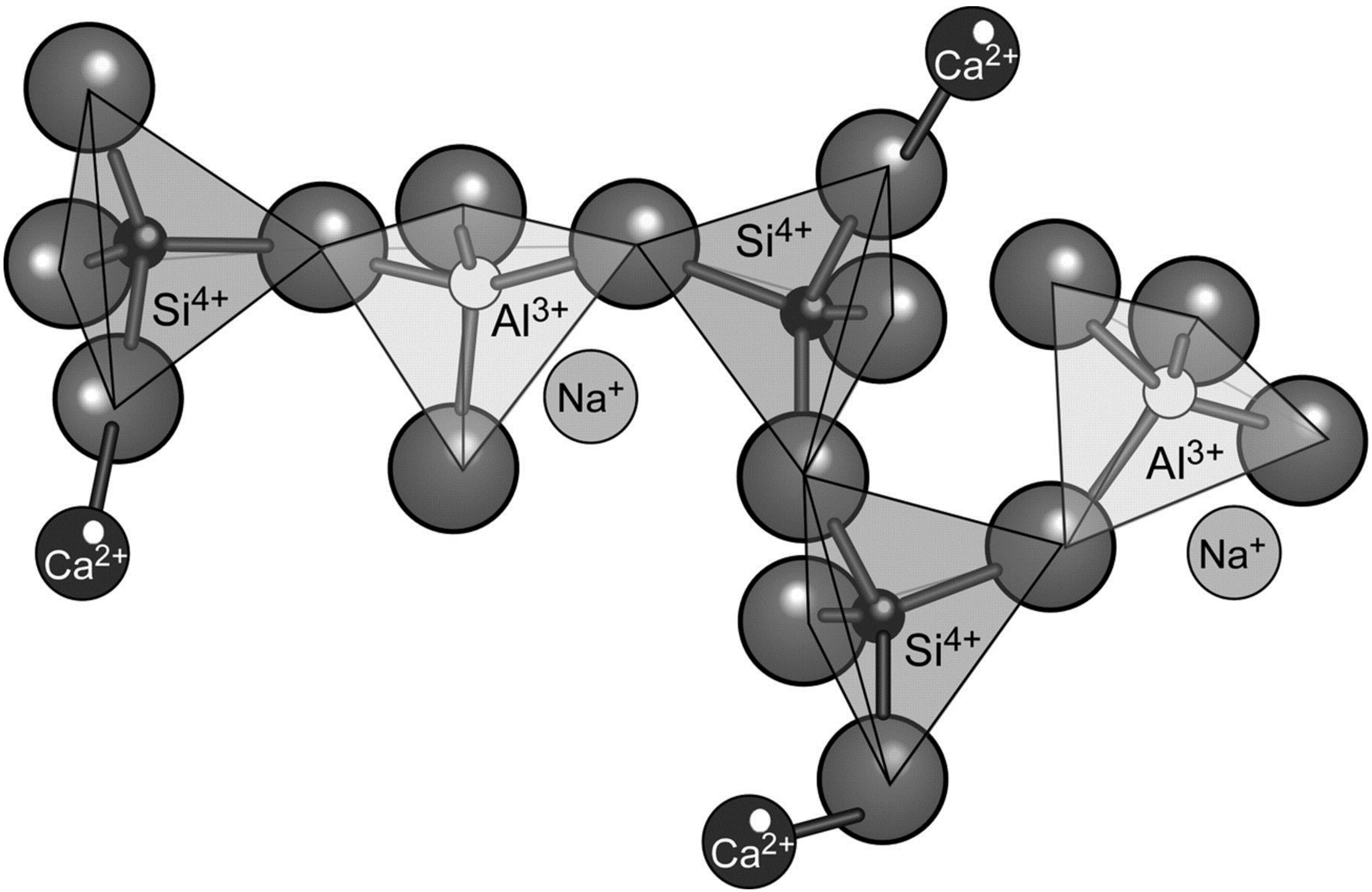
Q^2-Q^3 **Amphiboles**

→ By joining na indefinitely large number of silica tetrahedra together, we arrive at a chain structure, which is common to two classes of minerals – the **pyroxenes** and the **amphiboles**.

→ **Pyroxenes** have SiO_3^{2-} as the repeated group while **amphiboles** have the $SiO_4O_{11}^{6-}$ group.

→ Owing to their chain structure, the piroxenes and amphiboles are fibrous, **asbestos like minerals**.

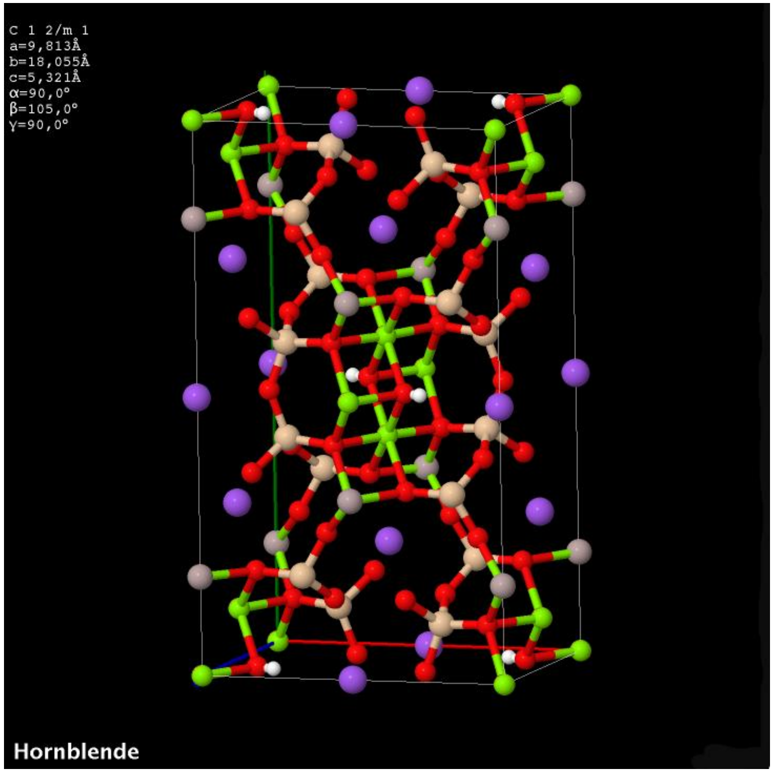
Q^2-Q^3: Chain Structures (inosilicates)



1.5 Ceramic raw materials

Q^2-Q^3: Chain Structures (inosilicates)

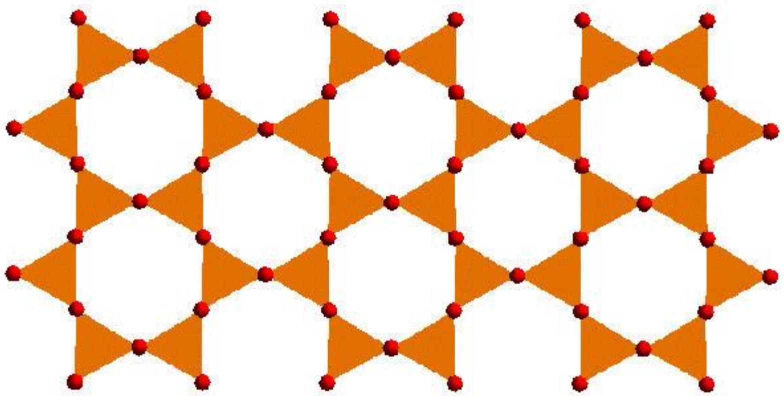
Hornblende

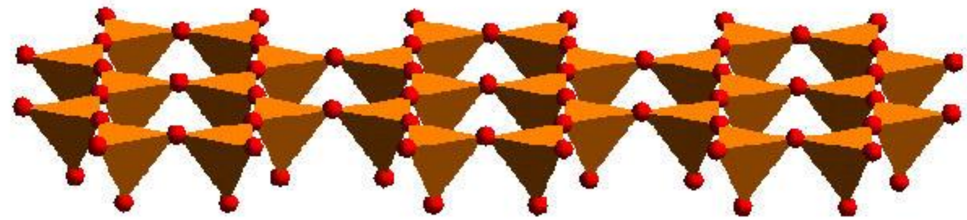


→ **Hornblende**, a naturally occuring amphibole found in igneous rocks, has the generaL formula **$(Ca, Na, K)_{2\text{-}3}(Mg, Fe, Al)_5(Si,Al)_2Si_6O_{22}(OH)_2$**. As the formula implies, many varieties and degrees of substituion occur in this mineral.

1.5 Ceramic raw materials

Q^3: Sheet Structures (phyllosilicates)





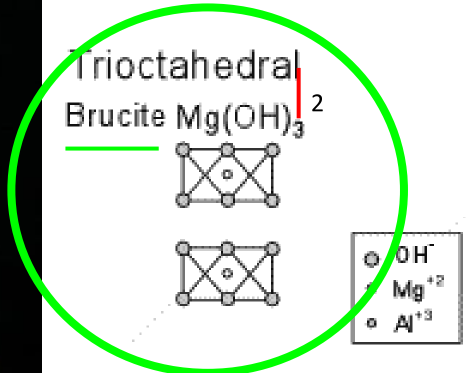
→ Carrying the notion of linking silica tetrahedra a stage further, a **complete sheet of silicon-oxygen six-membered rings** is formed just by condensing a number of pyroxene or amphibole units.

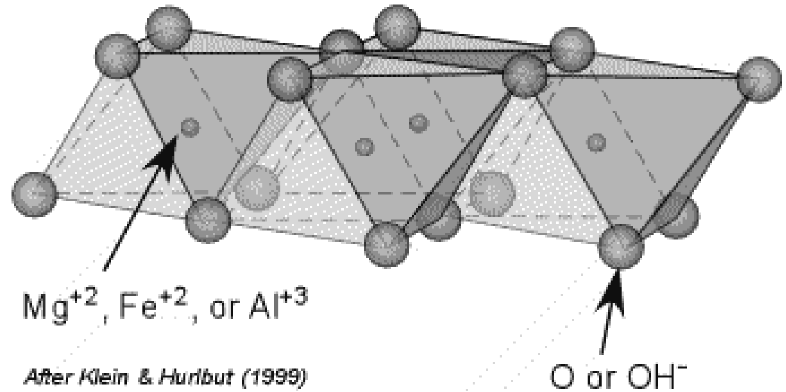
→ Such sheets, with a repeat formula $Si_2O_5^{2-}$ are capable of **indefinite extension in two dimensions**; this is because the oxygen valancies within the plane are itself are satisfied by being joined to two silicons, except for those at the boundaries, which are available for linking to other similar units.

→ The only **free oxygen valencies** are those **at the apices** of the silica tetrahedra, shown immediately above each silicon atom in the diagram; **these oxygens can not form sheets but may serve to link one sheet to another**.

1.5 Ceramic raw materials

Other Sheet Structures: Brucite





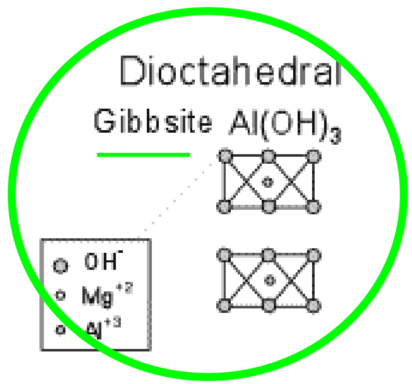
→ **Brucite** is the mineral form of **magnesium hydroxide**, with the chemical formula **$Mg(OH)_2$**.

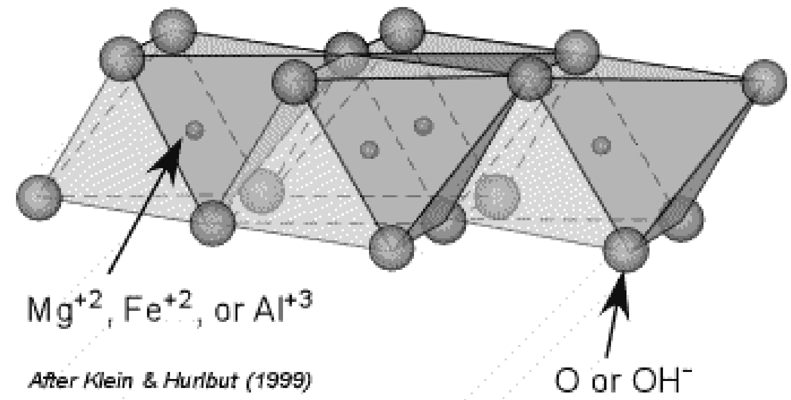
→ The basic structure forms **stacked sheets of octahedrons of magnesium hydroxide**. The octahedrons are composed of **magnesium ions** with a **+2 charge bonded to six octahedrally coordinated hydroxides** with a **-1 charge**. Each hydroxide is bonded to three magnesiums. The result is a **neutral sheet** since +2/6 = +1/3 (+2 charge on the magnesiums divided among six hydroxide bonds) and -1/3 = -1/3 (-1 charge on the hydroxides divided among three magnesiums); thus the charges cancel.

→ The lack of a charge on the **brucite** sheets means that there is no charge to retain ions between the sheets and act as a "glue" to keep the sheets together. The **sheets** are only held together **by weak residual bonds** and this results in a **very soft easily cleaved mineral**.

1.5 Ceramic raw materials

Other Sheet Structures: Gibbsite





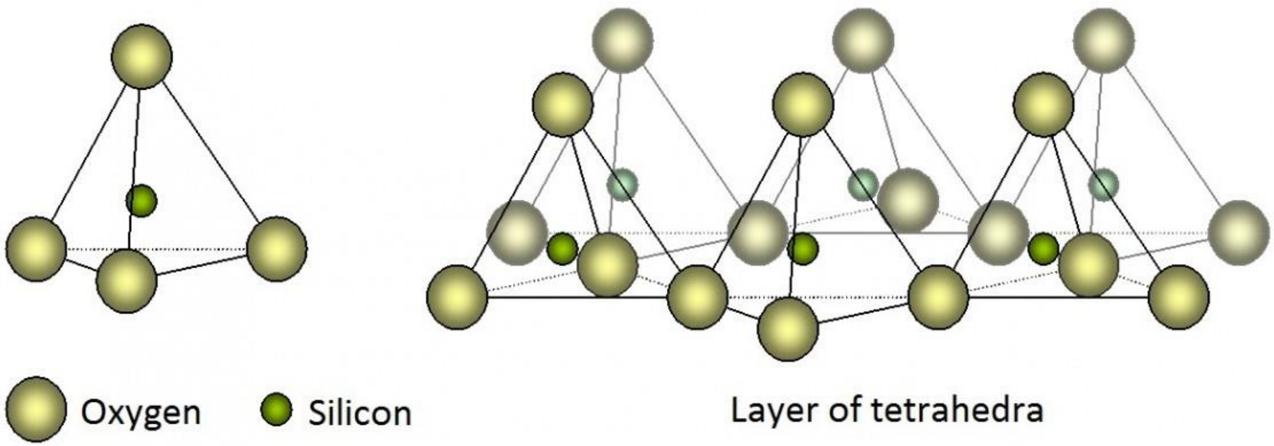
→ Brucite is closely related to **gibbsite**, **$Al(OH)_3$**. However the extra charge in gibbsite's aluminum (+3) as opposed to brucite's magnesium (+2) requires that **one third of the octahedrons to be vacant of a central ion in order to maintain a neutral sheet**.

→ The octahedral layers take on the structure of either **Brucite** [**$Mg(OH)_3$**], if the cations are +2 ions like Mg^{+2} or Fe^{+2}, or **Gibbsite** [**$Al(OH)_3$**], if the cations are +3 like Al^{+3}. In the **brucite structure**, **all octahedral sites are occupied and all anions are OH^-**. In the **gibbsite** structure **every 3rd cation site is unoccupied and all anions are OH^-**.

1.5 Ceramic raw materials

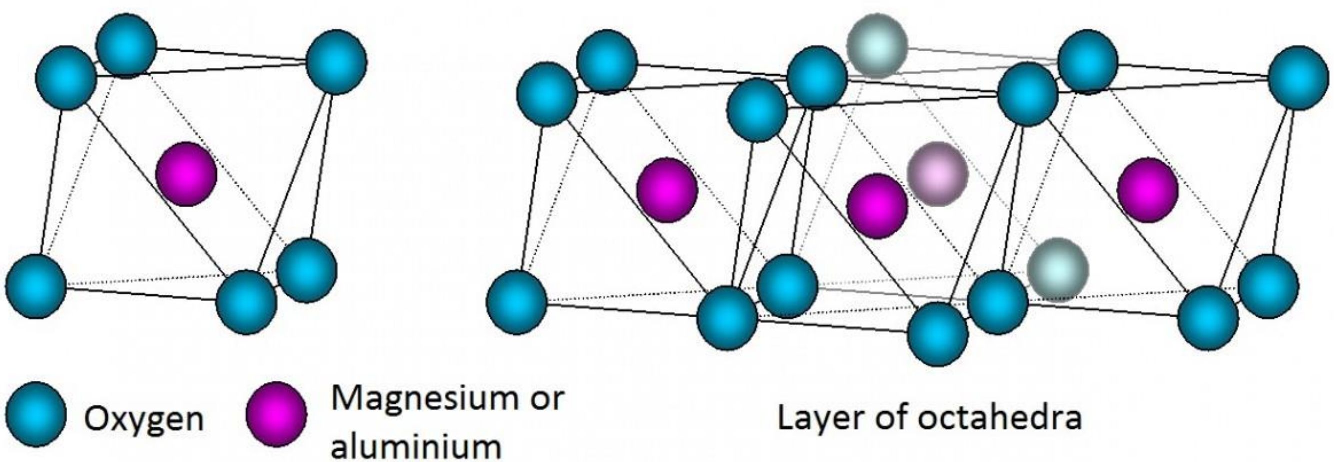
Q^3: Clay Minerals (phyllosilicates)

→ In the synthesis of natural clay minerals, the first step is the production of sheet minerals like $Si_2O_5^{2-}$ **(silica-like) plus $Mg(OH)_2$ (brucite) or $Al(OH)_3$ (gibsite).**

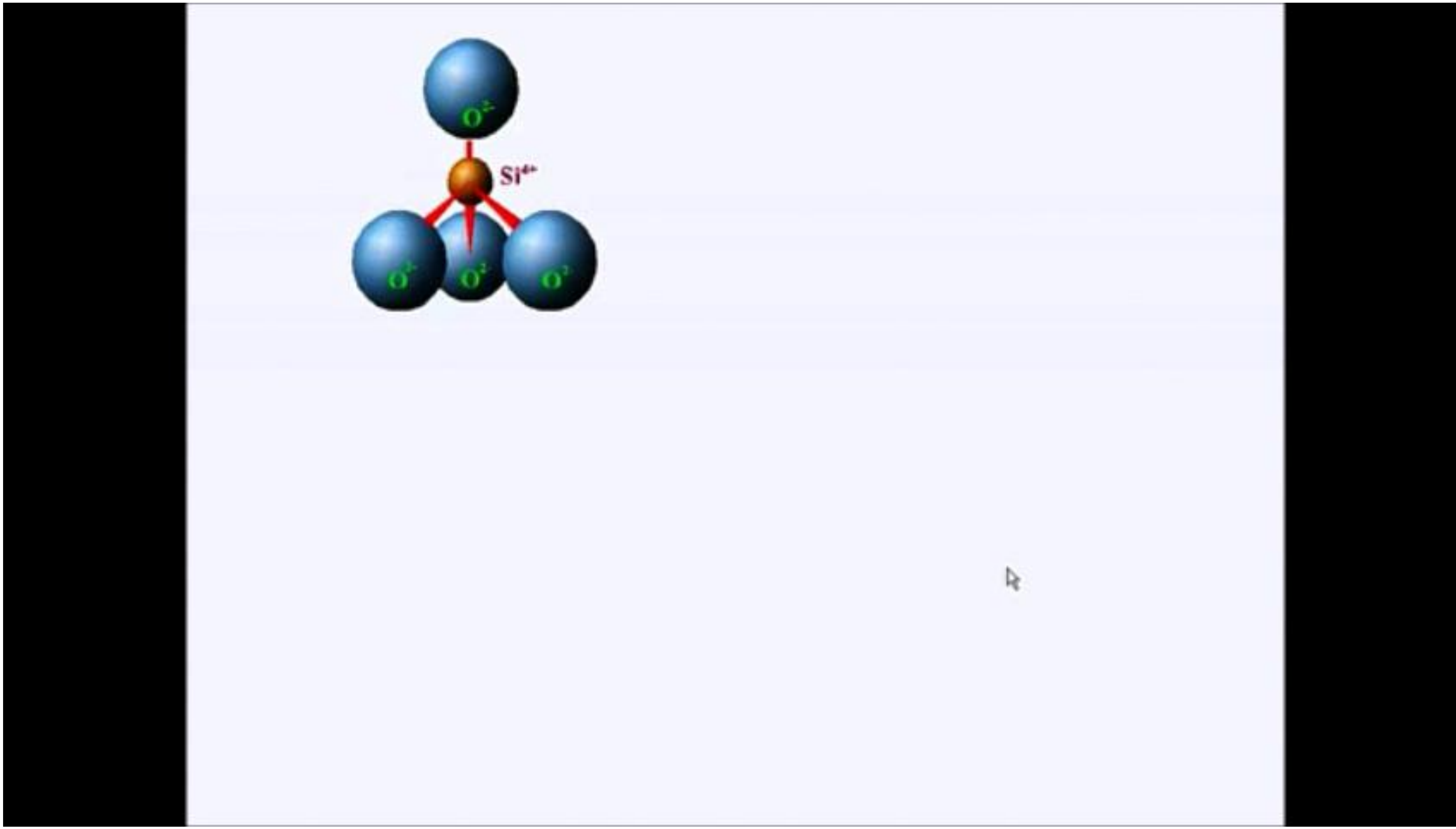


$Si_2O_5^{2-}$

http://blogs.egu.eu/divisions/sss/tag/clay-mineralogy/



$Mg(OH)_2$
or
$Al(OH)_3$

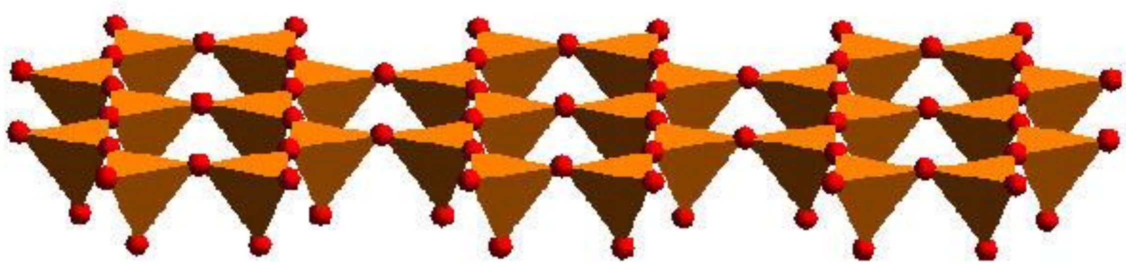


https://www.youtube.com/watch?v=iqSYnfW_tFU&t=60s

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

→ We can build the structures of **sheet silicates** by adding **octahedral layers** similar to the structures of **gibbsite** or **brucite** to **silicate layers**.



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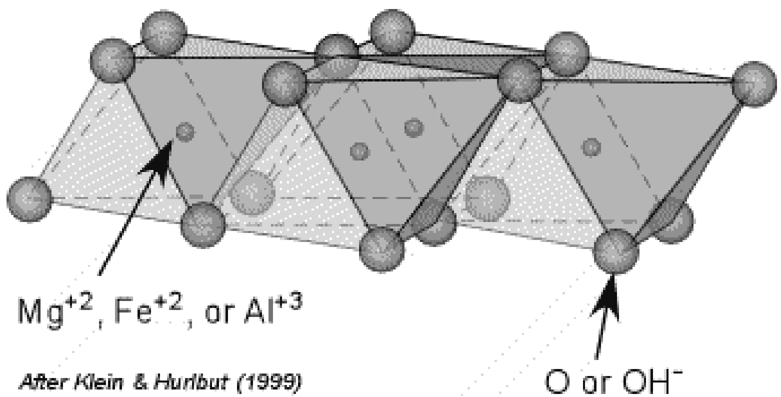
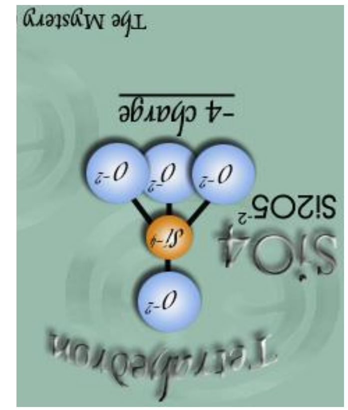
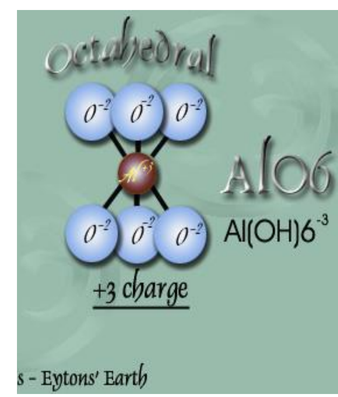






http://www.eytonsearth.org/clay-chemistry.php

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

→ **Clays** are one of the **major mineral components of the soil**, with a wide diversity of chemical and and physical properties.

→ The study of soil clay minerals allows a general idea of composition and genesis of soils. **Clays** are a group of **secondary minerals** (minerals formed by the subsolidus alteration of a pre-existing primary mineral; maybe a mineral in an igneous rock or another clay mineral after chemical weathering).

→ Clay mineral are **aluminossilicates**. These are **basically constituted** by **Si**, **Al** and **O**, as well as other elements such as **Na**, **K**, **Ca**, **Mg** or **Fe** in variable proportion.

→ **Clays** have a **colloidal size** (**bellow 2 μm**), with a well defined **crystal structure** and a **large surface/volume ratio**.

→ From the chemical point of view, **clays are the most important component of the soil**, as it is constituted by **charged colloidal particles able to interact with the soil solutions**.

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

→ **Phyllosilicates** are the most important group of soil. Phyllosilicates form by **silica tetrahedron (T) sharing three vertices**; **the fourth vertices binds to the central cation of an octahedron** (**apical O**), usually **magnesium** or **aluminum** (gibbsite or brucite).

→ The structure of **phyllosilicate** minerals is composed of a **stack of layers of tetrahedron and octahedron**, forming **lamellar structures**. Layers are linked by shared oxygens, being consequently **strongly covalently bonded** and are very difficult to separate.

→ According to the repeating pattern, two types of structures are formed:

→ **1:1 structure** (with a tetrahedral layer and another octahedral T:O)

→ **2:1 structure** (with two layers of tetrahedrons and another octahedral T:O:T)

→ Although we have shown that the **octahedral layers** fit perfectly between the **tetrahedral layers**, this is an **oversimplification**. **If the tetrahedral layers were stacked perfectly so that apical oxygens were to occur vertically aligned**, then the structure would have hexagonal symmetry. But, because this is not the case, most of the **phyllosilicates are monoclinic**.

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

1:1 structure (with a tetrahedral layer and another octahedral T:O)

Gibbsite layer + **silica layer**

Kaoline group

brucite layer+**silica layer**

Serpentine group

2:1 structure (with two layers of tetrahedrons and another octahedral T:O:T)

Silica + Gibbsite + **silica**

Pyrophyllite group

Montmorillonite

Mica group

silica+**brucite** +**silica**

Talc group

Montmorillonite

Chlorite group

http://scmwaterproofporous.blogspot.pt/2010/10/clay.html

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The kaolin-type group (1:1)

→ The **kaolin group** includes the clay minerals **nacrite**, **dickite**, **kaolinite** and **halloysite**. Their structure have one thing in common – **they are composed of silica sheets linked to modified gibbsite sheets**.

→ Imagine a **gibbsite sheet** placed directly over a **silica sheet** in such a way that **one in three of the OH groups is removed and replaced by the unsaturated apical oxygens of the silica sheets**. These latter oxygens now form a bridge between the two sheets, forming a composite layer of kaolin type.

→ If we write the modified gibbsite layer as $[Al_2(OH_4]^{2+}$ (i.e. **having removed two OH groups**) and the **silica sheet** as $(Si_2O_5)^{2-}$, we arrive at the composite formula $Si_2O_5.Al_2Si_2O_5(OH)_4$, or $Al_2Si_2O_5(OH)_4$, the **unit formula of the kaolin group**.

→ A **crystal of kaolinite mineral** consists not of one composite layer but of a **very large number of such layers**, which may be linked to a book, where each page represents a single layer.

Q^3: Clay Minerals (phyllosilicates)

The kaolin-type group (1:1)

→ One important feature of the octahedral layer in the **kaolins** is that only two out of three possible sites are occupied by aluminum ions, the remainder being vacant; such structures are therefore called **dioctahedral**.

→ There are **three possible ways of filling three sites by two ions**, thus giving rise to **one source of variation in the unit layers.**

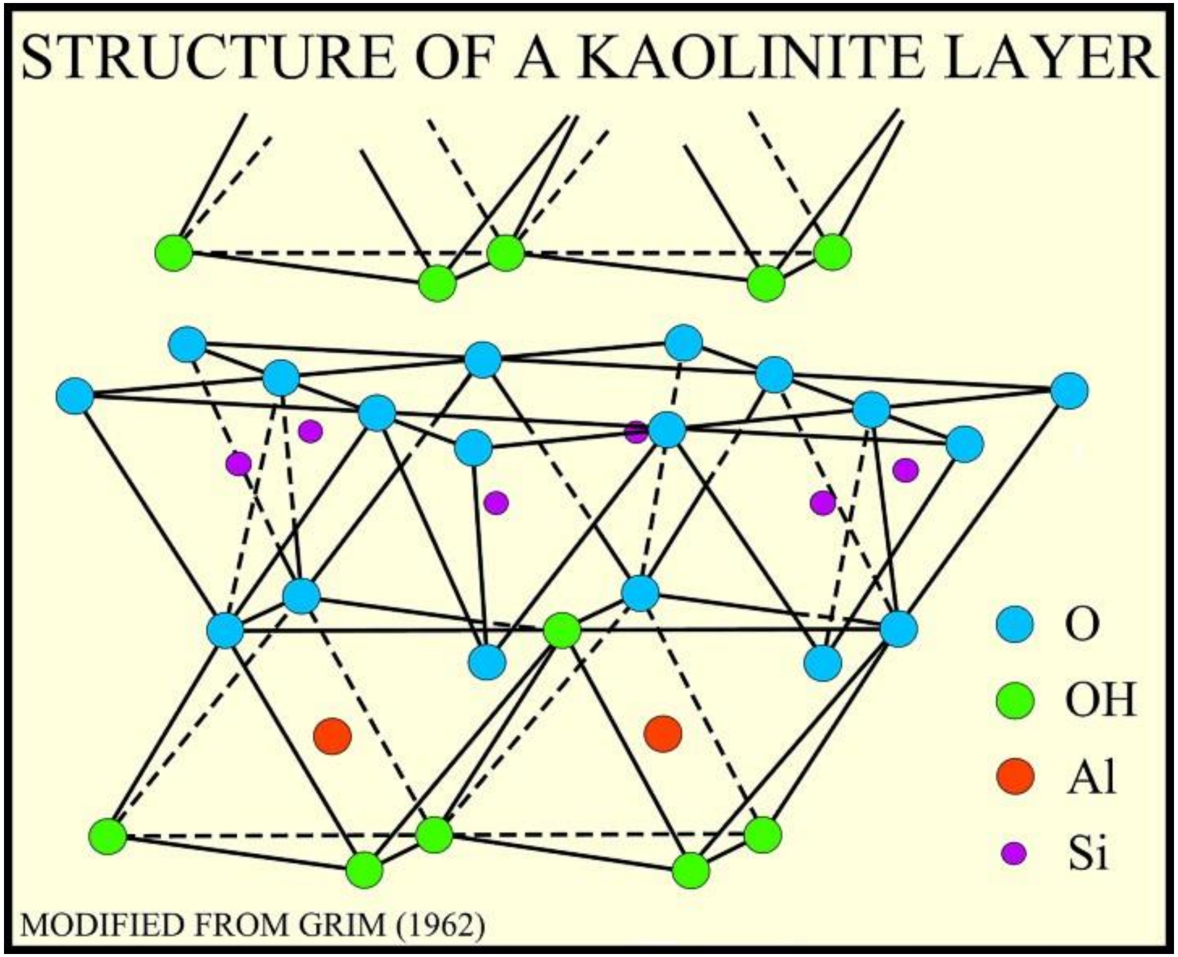
→ Note that there is no ionic bonding between neighboring units; the whole **crystal is held together by hydrogen bonds**, acting between **OH groups of the gibbsite layers** and **oxygen atoms of adjacent silica layers**.

→ For this relatively weak secondary bounds to be effective, the appropriate oxygens and OH groups must be closed together; there are several ways in which one unit can be stacked upon another to achieve this bonding and this give rise two four distinct minerals of kaolin type - **nacrite**, **dickite**, **kaolinite** and **halloysite.**

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

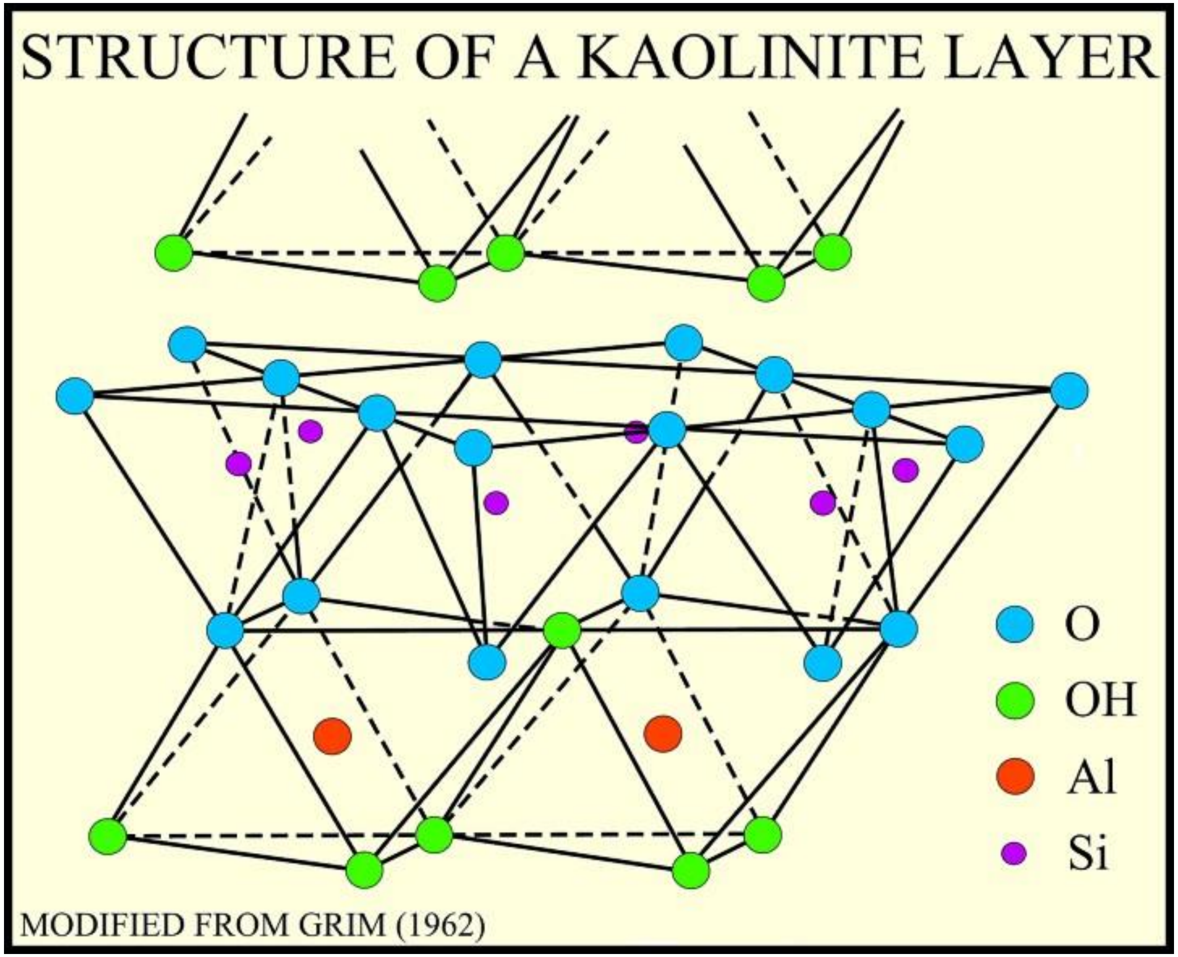
The kaolin-type group (1:1)



1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The kaolin-type group (1:1)



Kaolinite layer charge balance

6 O^{2-}......................-12
4 Si^{4+}.....................+16

4 O^{2-}, 2 OH^{-} ....-10
4 Al^{3+}....................+12
6OH^{-}........................-6

Charge Net..............0

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The kaolin-type group (1:1)

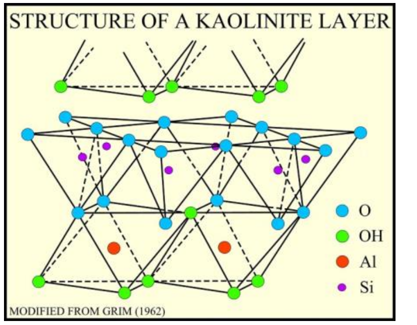
http://www.guptagrinding.com/kaolin-powder.htm

→ In **kaolin**, the unit are again displaced regularly along the a-axis, so that although **γ=90 °**, the **β-angle** is **104.5 °** and the **α-angle 91.8 °**.

→ The unit cell is **triclinic**, with **a=5.15Å**, **b=8.95Å** and **c=7.39Å**.

1.5 Ceramic raw materials

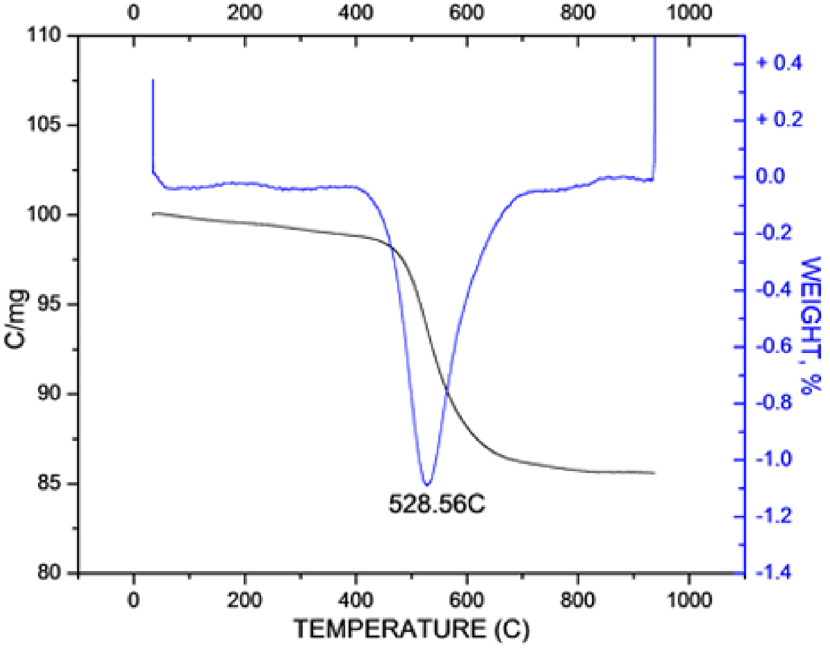
Q^3: Clay Minerals (phyllosilicates)



The kaolin-type group (1:1)

Kaolinite

DSC, TGA



http://www.opticon1826.com/articles

→ A **small endothermic peak** occurs at about **100ºC**, caused by the evolution of **adsorbed water**.

→ At about **500ºC** the **main endothermic peaks starts**, corresponding to the **decomposition of the mineral (structural breakage)**, with the **elimination of the hydroxyl groups as water**.

→ A further peak, which is **exothermic**, occurs at about **1000ºC**, and is associated with a **recrystallization** process.

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The kaolin-type group (1:1)

Halloysite

→ In **halloysite**, unit kaolin layers are still present but are displaced along both **a-** and **b-axis** in a **random fashion**, so that no values can be assigned to the α- and β-angles, though the γ-angle is still 90 ° and the unit cell dimensions for the meta-form are **similar to those of kaolin**.

→ Owing to the **absence of hydrogen bonding between successive units**, the structure is **penetrable to water** and a hydrated form exists, with the formula $Al_2Si_2O_5(OH)4_2H_2O$.

→ The **extra 2H_2O** in hydrated **halloysite increases the c-dimension** by about **2.9Å**.

→ **Halloysite** is an **expanding type sheet silicates;** as the water is incorporated into the structure the mineral increases its volume.

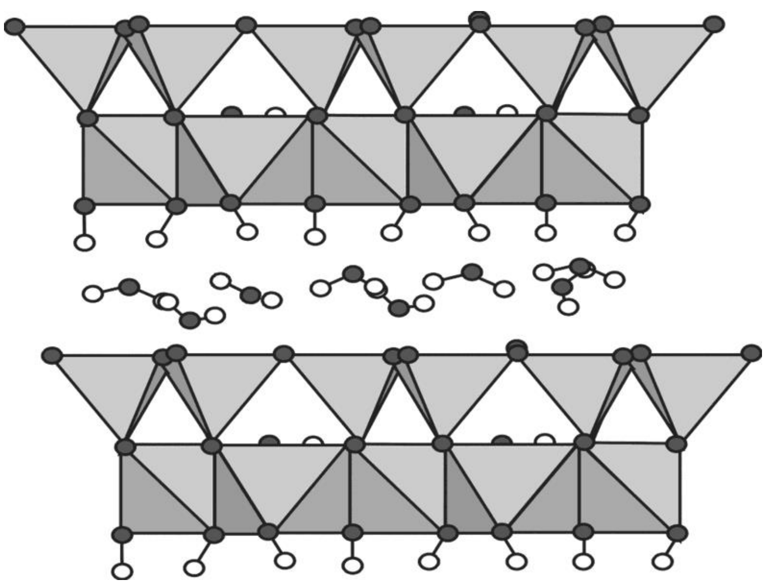
1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The kaolin-type group (1:1)

Expanding type sheet silicate

Halloysite



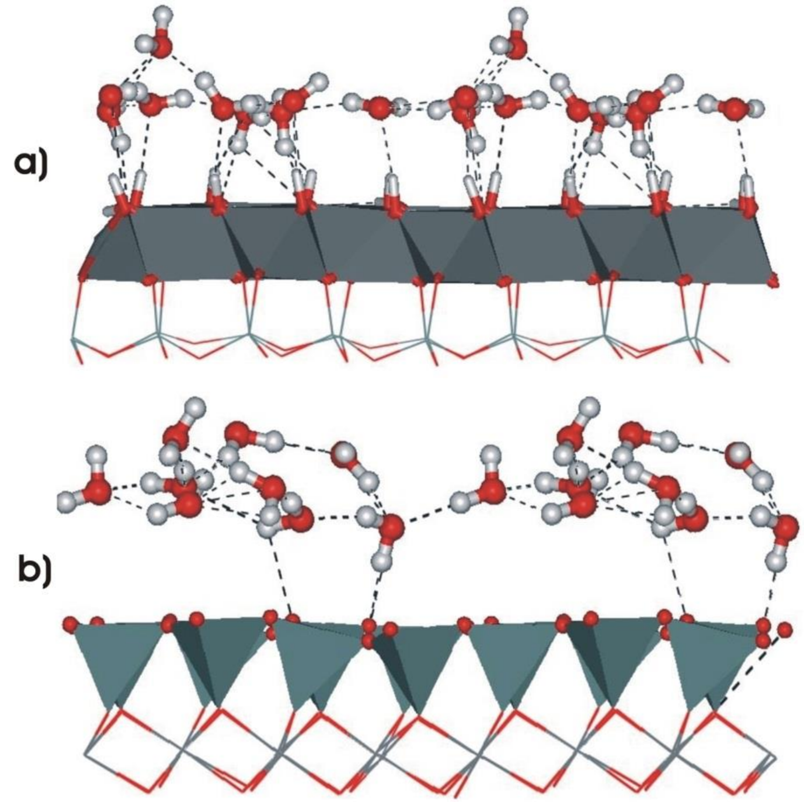


Figure1. Distribution of the monomolecular water layer on the a) octahedral and b) tetrahedral surfaces of the kaolinite layer.

http://www.univie.ac.at/qccd/hpsc/2003/Tunega/report2003.html

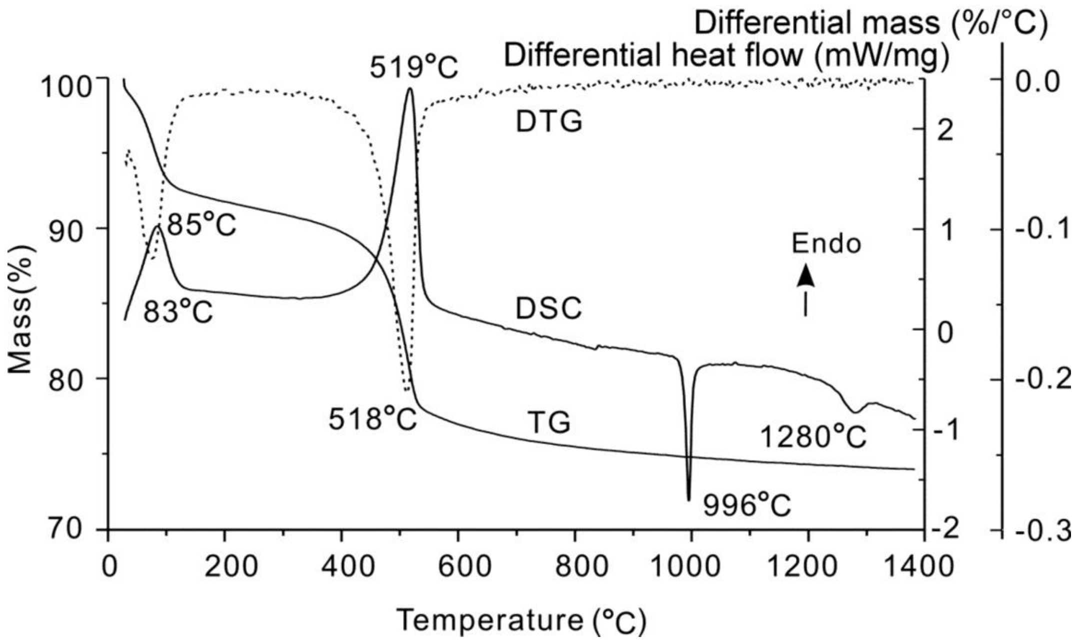
Expanding type sheet silicate

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

Halloysite

DSC, TGA



→ The halloysite starts loosing water at temperatures above 60 °C and eventually is converted to the meta form.

→ Compared to kaolinite, there is an additional endothermic peak at 150ºC, due to the huge loss of water.

→ The main endothermic peak for halloysite occurs, as for kaolinite, at around 600ºC.

→ There is also the exothermic peak, as for kaolinite, at 1000ºC.

1.5 Ceramic raw materials

Q³: Clay Minerals (phyllosilicates)

The kaolin-type group (1:1)

https://commons.wikimedia.org/wiki/File:Nacrite_-_Mineralogisches_Museum_Bonn2.jpg

→ In **nacrite**, the layers are stacked so that the atoms in one silica layer are directly above corresponding atoms in every other silica layer. Thus **α- and β- angles (in addition to γ-angle) are very nearly equal to 90°**.

→ Owing to the different ways of populating the octahedral positions, the structure only repeats after every sixth kaolin unit, making the **c-dimension of the unit cell** equal to **43 Å**.

→ The **a-dimension** is **5.15 Å** and the **b-dimension 8.98 Å**, the unit cell as a whole being therefore practically **orthorhombic**.

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The kaolin-type group (1:1)

https://wgnhs.uwex.edu/minerals/dickite/

→ In **dickite**, the unit layers are displaced **regularly along the a-axis** (and possibly the b-axis) so that the **b-angle** is no longer 90° but is equal to **96.8 °**.

→ In the unit cell, **$\alpha=\gamma=90$ °** and **a=5.15 Å**, **b=8.95 Å** and **c=14.4 Å**.

→ There are thus two kaolin units in each unit cell, the latter being **monoclinic**.

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The montmorillonite-type group (2:1)

→ We can carry the process of layer condensation a stage further by condensing two silica layers (one each side) with one gibbsite or one brucite layer, giving us respectively the minerals **pyrophyllite**, $Al_2Si_4O_{10}(OH)_2$, and **talc**, $Mg_3Si_4O_{10}(OH)_2$. **Montmorillonite** may be considered as derived from them by the process of substitution.

→ In **montmorillonite** a single crystal is composed of a large number of units approximating to one or other of the above formulas. Since **adjacent layers** in these units are now **silica layers**, there can be no outer hydroxyl bonds and **the units are bonded by van der Waals forces**. That is why the **montmorillonite** are **easily cleaved** and **feel soapy** when rubbed between fingers.

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The montmorillonite-type group (2:1)

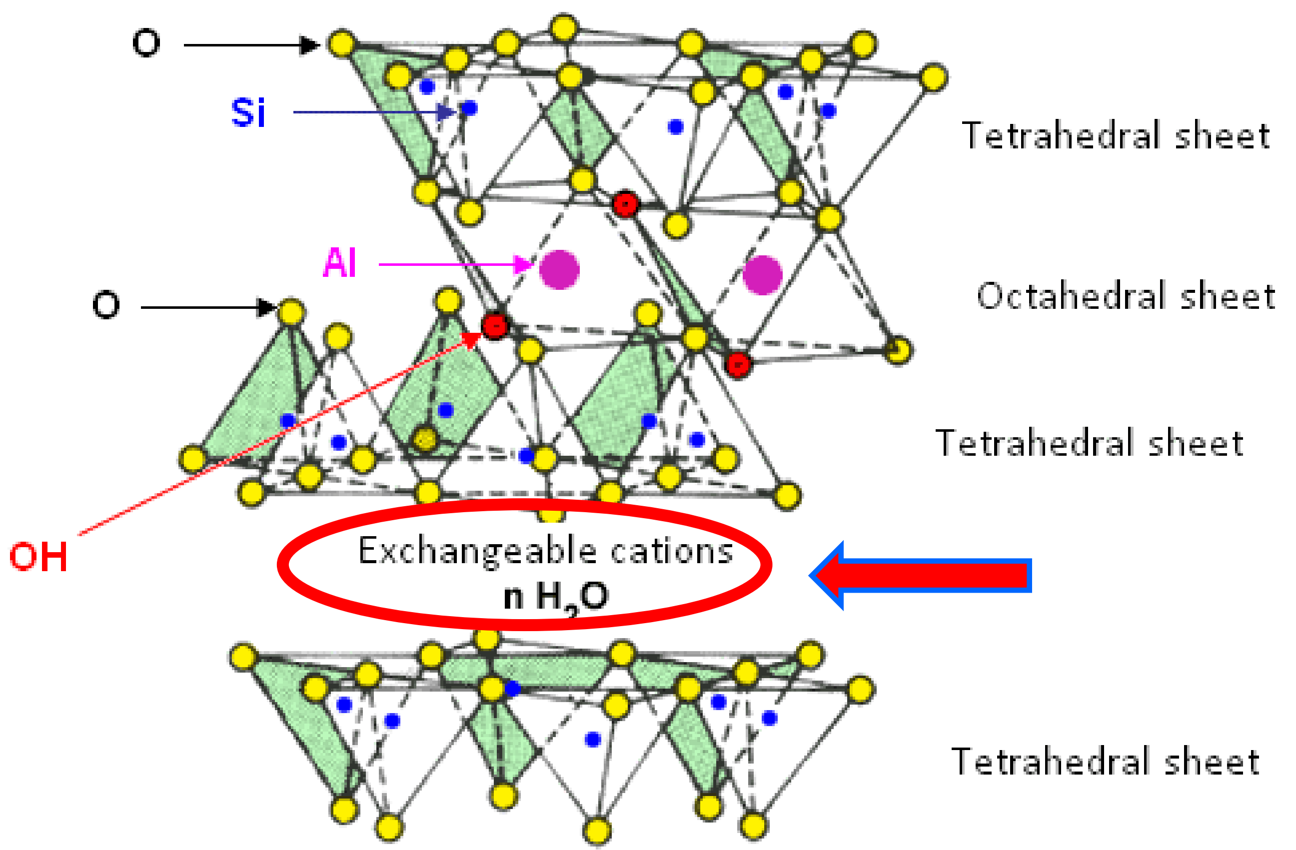
→ Although X-ray diffraction may enable a montmorillonite-type mineral to be recognized, it cannot readily distinguish between members of the same group. The **Al atoms** in **pyrophyllite** are **partly substituted by magnesium, iron or litium**; similarly, the **silicon atoms may be partly substituted by aluminium**, the only cation of similar radius.

→ Since the replacement of trivalent aluminium by divalent magnesium, atom for atom, results in **an overall negative charge on the structure**, **electrical neutrality has to be maintained by other cations external to the lattice**; these **cations** are thus **exchangeable**. The very high cation exchange capacity of montmorillonite is thus adequately explained by the high degree of substitution.

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

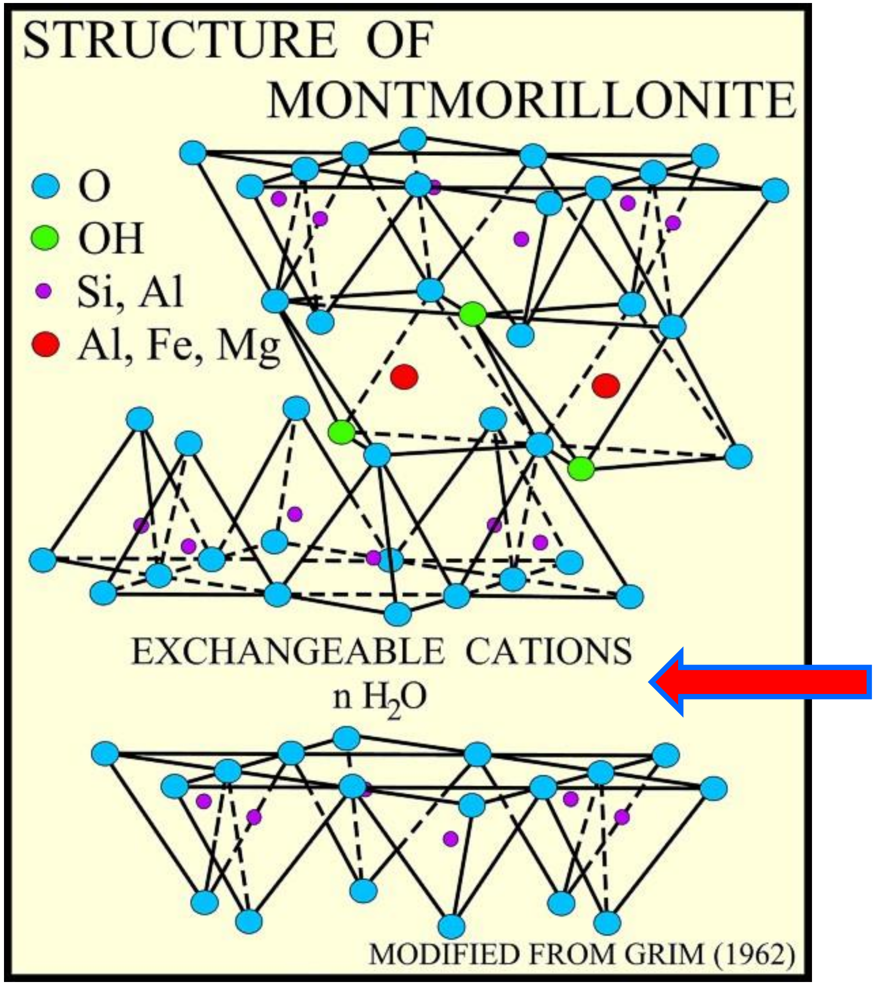
The montmorillonite-type group (2:1)



1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

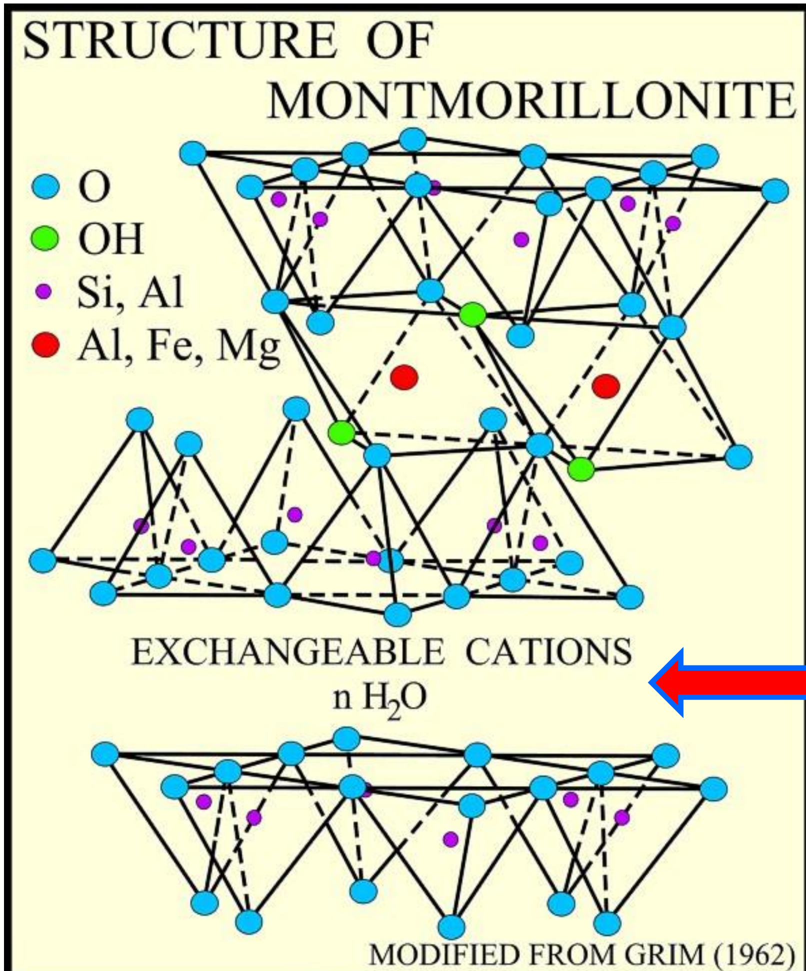
The montmorillonite-type group (2:1)



1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The montmorillonite-type group (2:1)



Montmorillonite
layer charge balance

$6\ O^{2-}$......................-12
$4\ Si^{4+}$, Al^{3+}............+16

$4\ O^{2-}$, $2\ OH^{-}$ ....-10
Al^{3+}, Mg^{2+}, Fe^{2+}, Li^{+}...vary
$4\ O^{2-}$, $2\ OH^{-}$..........-10

$6\ O^{2-}$.....................-12
$4\ Si^{4+}$, Al^{3+}...........+16

Charge Net.......usually between
- 0.6-0.25

Q^3: Clay Minerals (phyllosilicates)

The montmorillonite-type group (2:1)

→ It is generally accepted that the **unit layers in the montmorillonites** are superposed in a completely **random manner** due to the **relatively weak bonding between the layers**.

→ Because of the great variety of substitutions possible, the unit cell dimensions vary from type to type, but are approximately: **a= 5.3 Å**, **b= 9.2 Å**, **b = 97°**, **the value of c being variable**.

→ The unit layers can be forced apart by water and other polar liquids, causing the **basal spacing** (the perpendicular distance between equivalent planes) **to vary from about 10 to 15 Å for water**.

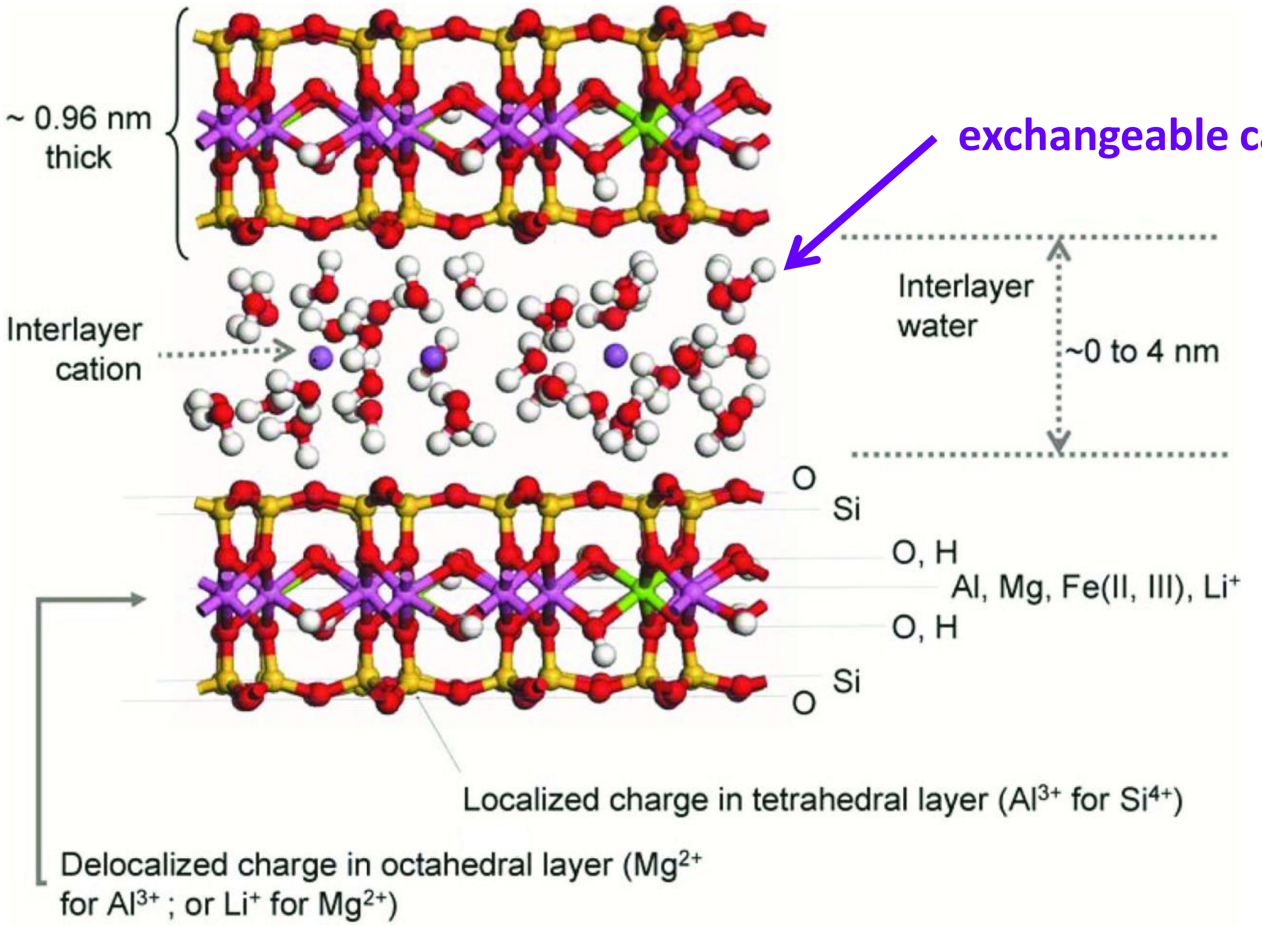
→ The structural formula is **$Al_2Si_4O_{10}(OH)_2$**.

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The montmorillonite-type group (2:1)

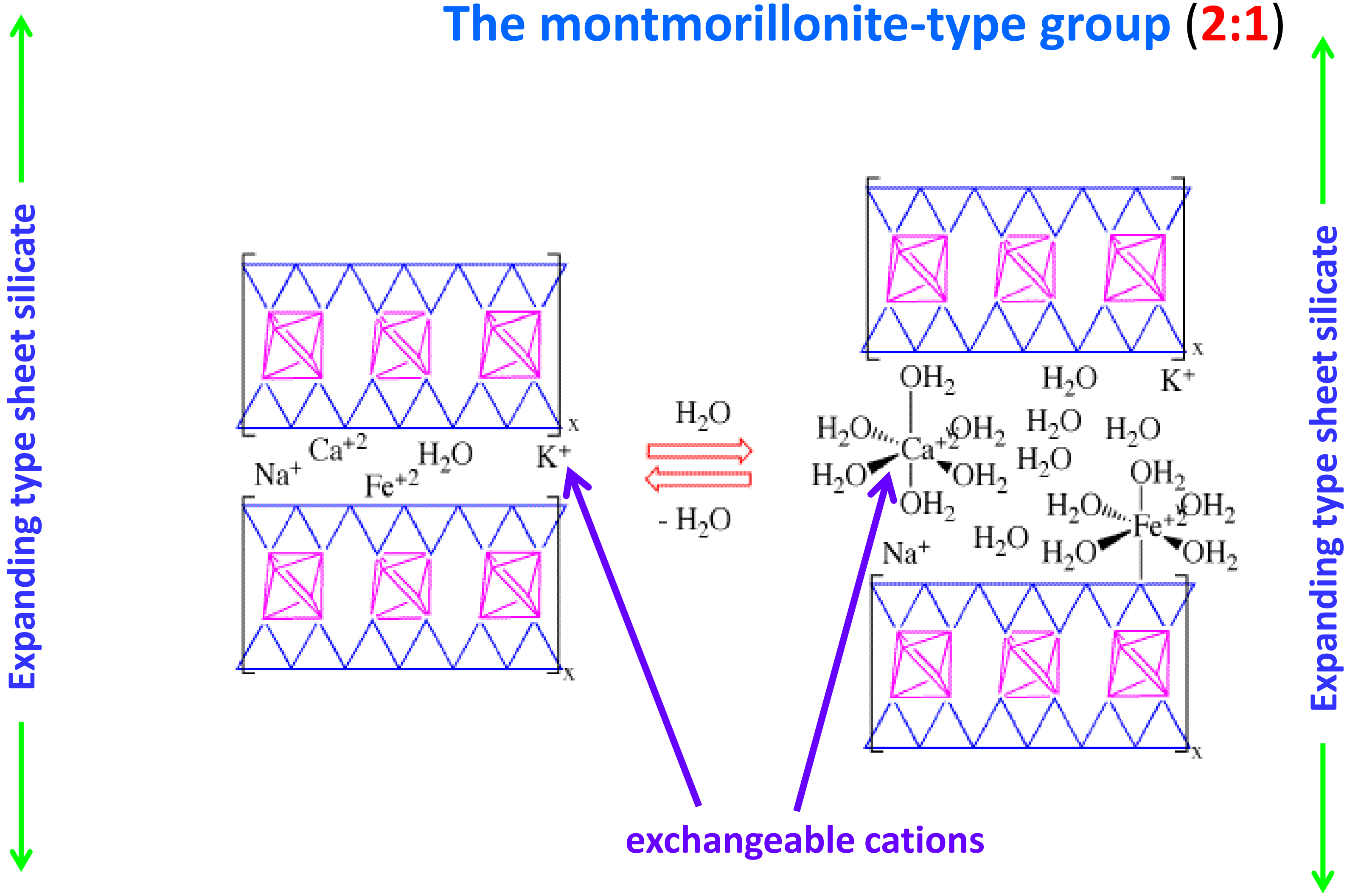
Expanding type sheet silicate



exchangeable cations

Q^3: Clay Minerals (phyllosilicates)

The montmorillonite-type group (2:1)

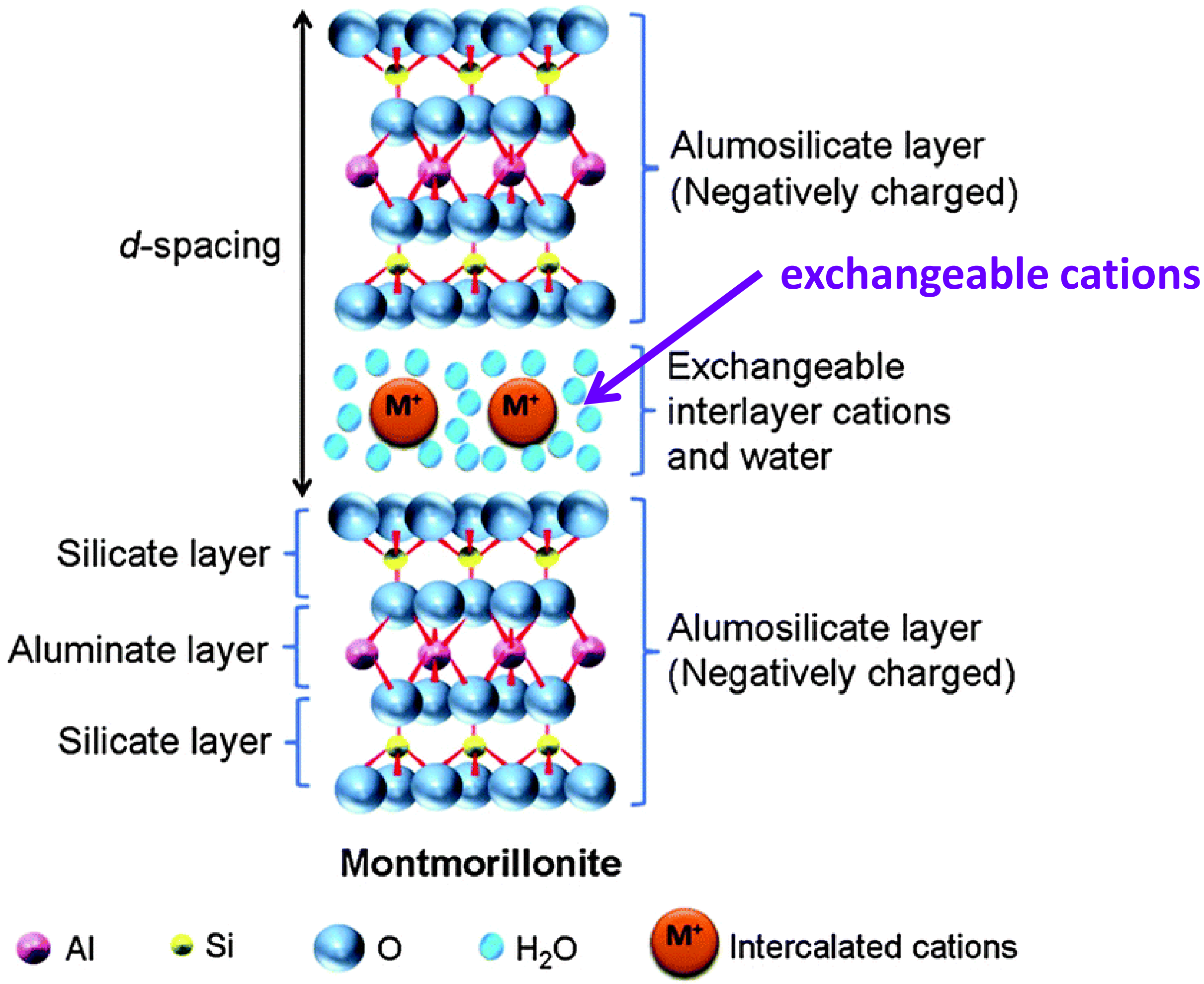


1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

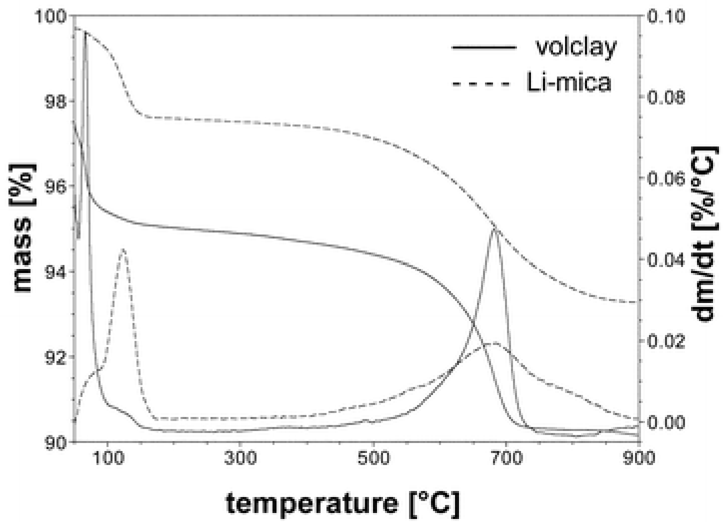
The montmorillonite-type group (2:1)

Expanding type sheet silicate



Q[3]: Clay Minerals (phyllosilicates)

The montmorillonite-type group (2:1)



DOI: 10.1039/B302331A

→ The **montmorillonite** all have in common a **large endotherm** at about **150ºC**, corresponding to the evolution of inter-layer water and water associated with exchangeable cations. The peaks varies in size and shape according to the nature of the cations and the lattice substitutions.

→ The **main endotherm**, corresponding to the **thermal decomposition of the mineral**, occurs at about **700ºC** and there is a **final exotherm** at about **1000ºC** as for kaolinite.

→ **Multiple low-temperature peaks** have also been reported around **150 to 200ºC**, for montmorillonites saturated with various cations, corresponding to partly hydration of the surface and partly to hydration of the cations.

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The serpentine-type group (2:1)

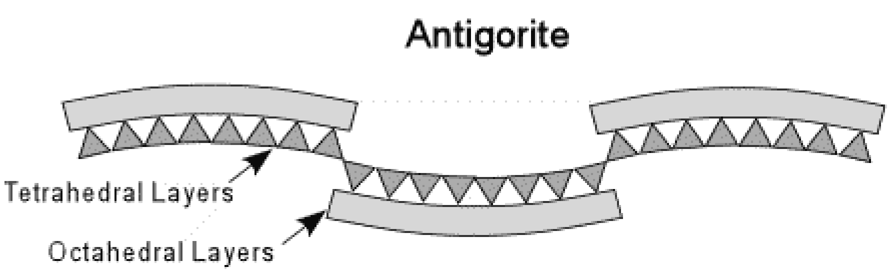
→ The **serpentine group** of minerals have a structure consisting of a **silica sheet** condensed with a **brucite sheet**, with the unit formula $Mg_3Si_2O_5(OH)_4$. This group is clearly **trioctahedral**, this being possible because three atoms of divalent magnesium carry only the same charge as two atoms of trivalent aluminium.

→ The best known minerals of this group are **antigorite** and **chrysotile**, but these latter are not generally classed as clay minerals.

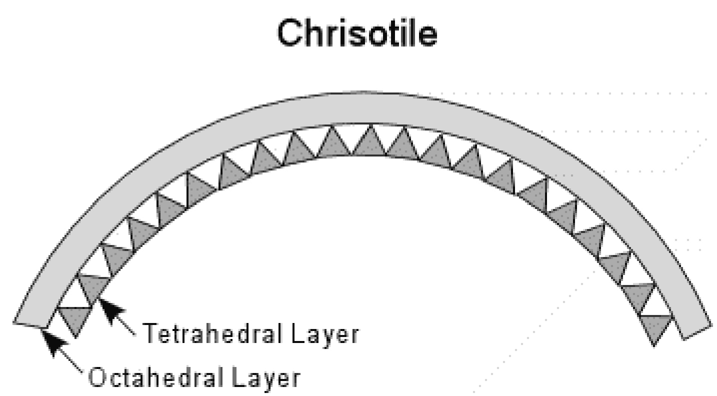
Q^3: Clay Minerals (phyllosilicates)

The serpentine-type group (2:1)

→ The **serpentine group** of minerals has the formula - $Mg_3Si_2O_5(OH)_4$. Three varieties of serpentine are known. Antigorite and **Lizardite** are usually massive and fine grained, while **Chrisotile** is fibrous. As discussed above, the imperfect fit of the octahedral layers and the tetrahedral layers causes the crystal structure to have to bend.



http://www.tulane.edu/~sanelson/eens211/phyllosilicates.htm



Q^3: Clay Minerals (phyllosilicates)

The mica-type group (2:1)

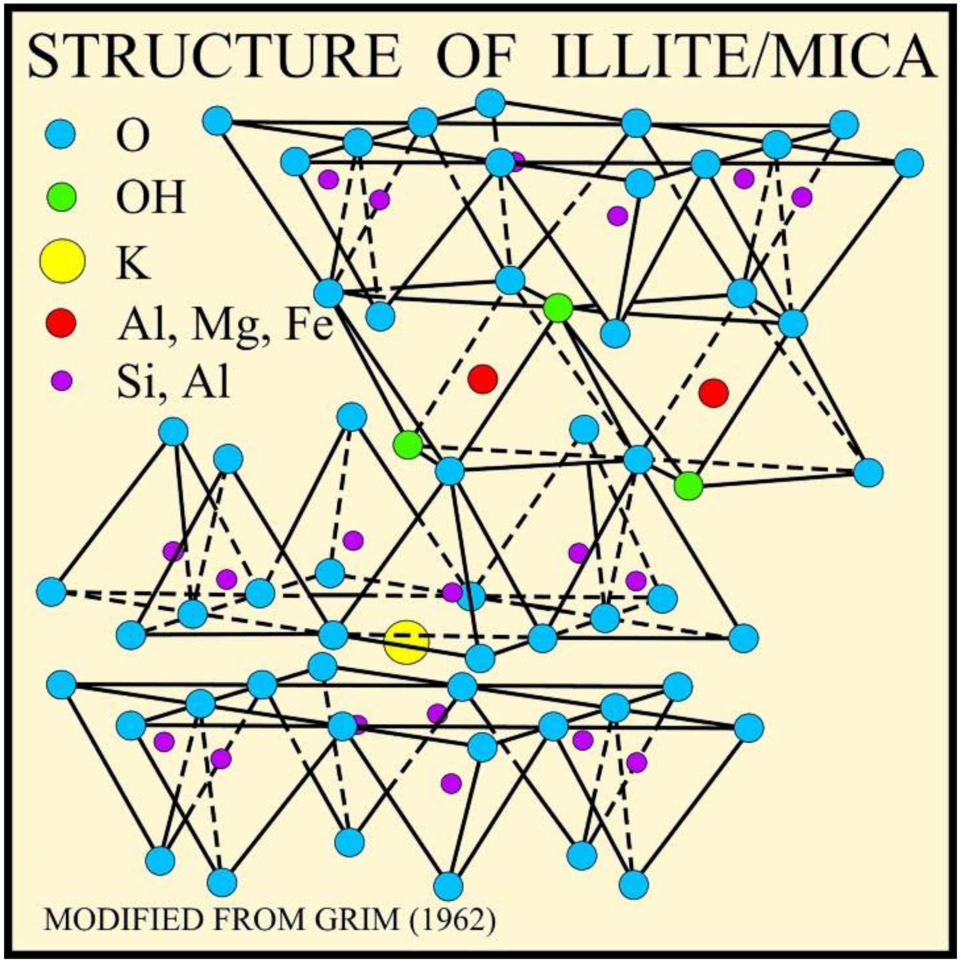
→ In **montmorillonite** the degree of substitution rarely exceeds one-third of an atom per unit formula in any one layer. Image that, starting with **pyrophyllite** $Al_2Si_4O_{10}(OH)_2$, we substitute one whole atom of Al for a Si atom in the tetrahedral layer, to form the negatively charged unit $Al_2(Si_3Al)O_{10}(OH)_9^{22-}$. Let the charge deficiency now be balanced by one atom of potassium, and we arrive at potash mica or muscovite, $K.Al_2(Si_3Al)O_{10}(OH)_2$, or as it frequently written $KAl_3Si_3O_{10}(OH)_2$.

→ The essential big difference between this structure and a montmorillonite is that in the **mica** there is a comparatively big charge, concentrated in one layer, so that the balancing cation, K, is very strongly held and therefore not exchangeable.

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The mica-type group (2:1)



Layer charge balance

....

....

......

......

Charge Net

1.5 Ceramic raw materials

Q^3: Clay Minerals (phyllosilicates)

The chlorite-type group (2:1)

http://www.realmagick.com/chlorite/

→ **Chlorite** is another group of phyllosilicates minerals. Although chlorite is complex in that the amount of Al that can substitute Mg and Si is variable, it may depicted as consisting of a brucite-like layer (with some Al) sandwiched between tetrahedral layers that are similar to phlogopite.

1.5 Ceramic raw materials

Summary

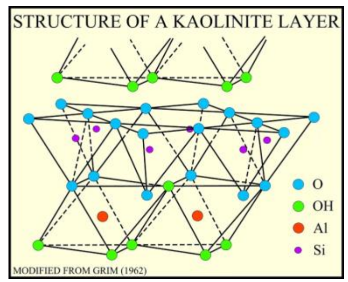
Q^3: Clay Minerals (phyllosilicates)

→ If we start with the **gibbsite** and **brucite** structures, and **replace 2 of the OH ions with O**, where the Oxygens are now the apical Oxygens of the SiO2 tetrahedral sheets, then we get:

dioctahedral layer, Al^{+3} (**trioctahedral layer**, Mg^{+2})

1:1

→ Kaolinite

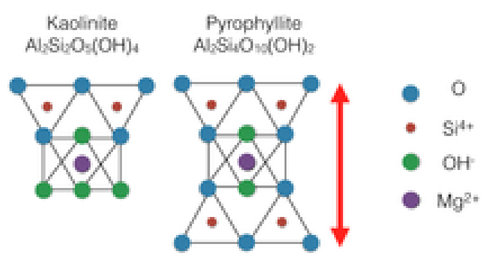


→ Lizardite

→ If we now **replace another 2 of the OH ions with O**, and these O become the apical Oxygens for another tetrahedral layer, the this builds up:

2:1

→ Pyrophyllite



→ Talc

1.5 Ceramic raw materials

Summary

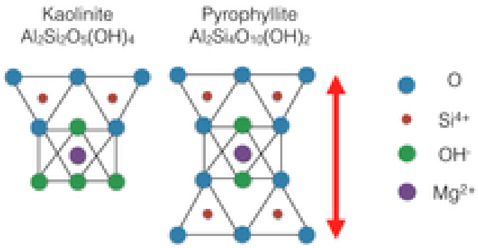
Q³: Clay Minerals (phyllosilicates)

dioctahedral layer, Al^{+3} (trioctahedral layer, Mg^{+2})

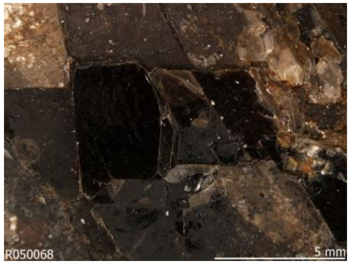
→ If in the pyrophyllite or talc minerals, an Al^{+3} is substituted for every 4th Si^{+4} in the tetrahedral layer, this causes an excess -1 charge in each T-O-T layer. To satisfy the charge, K^{+1} or Na^{+1} can be bonded between 2 T-O-T sheets in 12-fold coordination.

2:1

→ **Muscovite**



→ **Phlogopite**



→ Replacing 2 more Si^{+4} ions with Al^{+3} ions in the tetrahedral layer results in an excess -2 charge on a T-O-T layer, which is satisfied by replacing the K^{+1} with Ca^{+2}.

→ **Margarite**

2:1

→ **Clintonite**

1.5 Ceramic raw materials

Summary

Q^3: Clay Minerals (phyllosilicates)

Expanding type sheet silicate

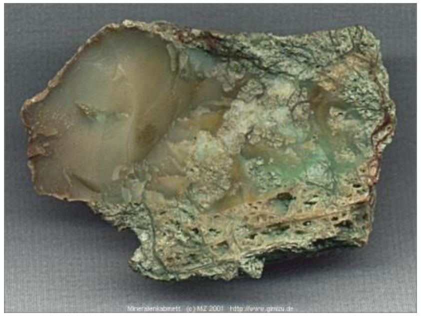
→ **Halloysite** is an **expanding type sheet silicates;** as the water is incorporated into the structure the mineral increases its volume.

→ Another important sheet silicate structure is that of **vermiculite**. This is similar to the talc structure, discussed above, with layers of water molecules occurring between each T-O-T layer.

→ Similarly, insertion of layers of water molecules between the T-O-T sheets of pyrophyllite produces the structure of **smectite** clays. The vermiculite and smectite groups are therefore **expanding type sheet silicates** and as the water is incorporated into the structure the mineral increases its volume. http://fpsc.wisc.edu/growguide/covering_seeds.shtm

Halloysite

smectite



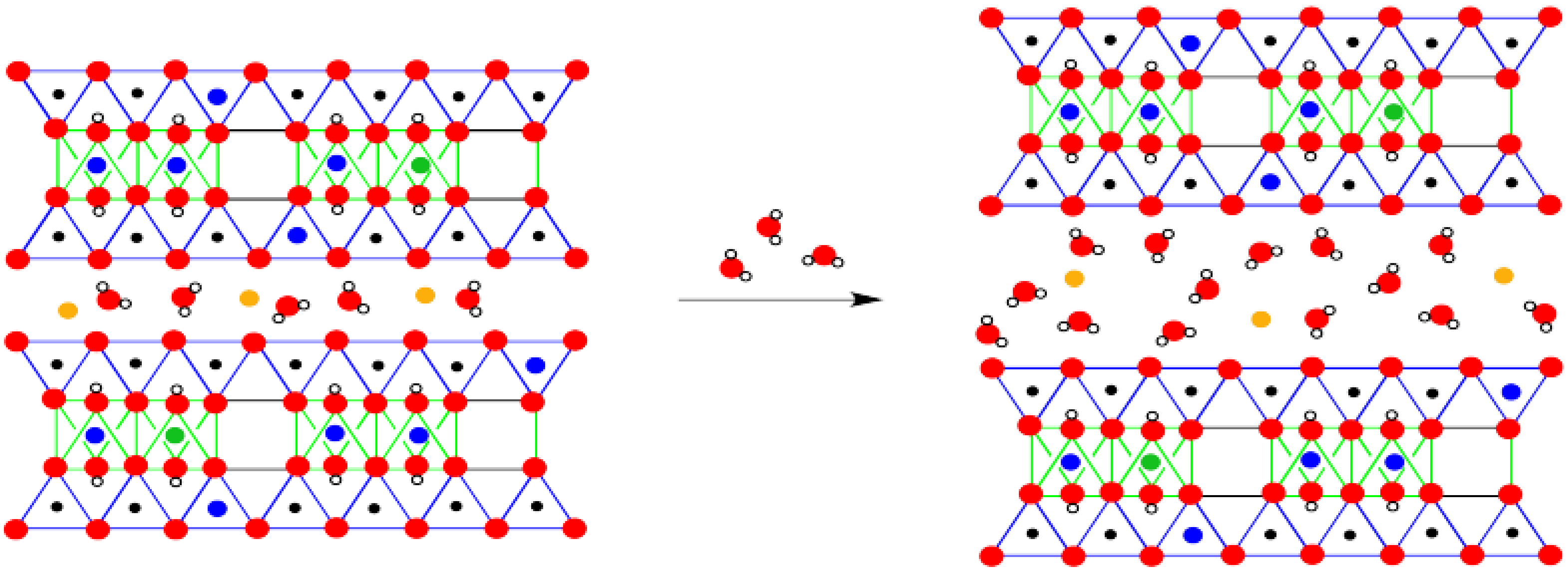
http://www.gimizu.de

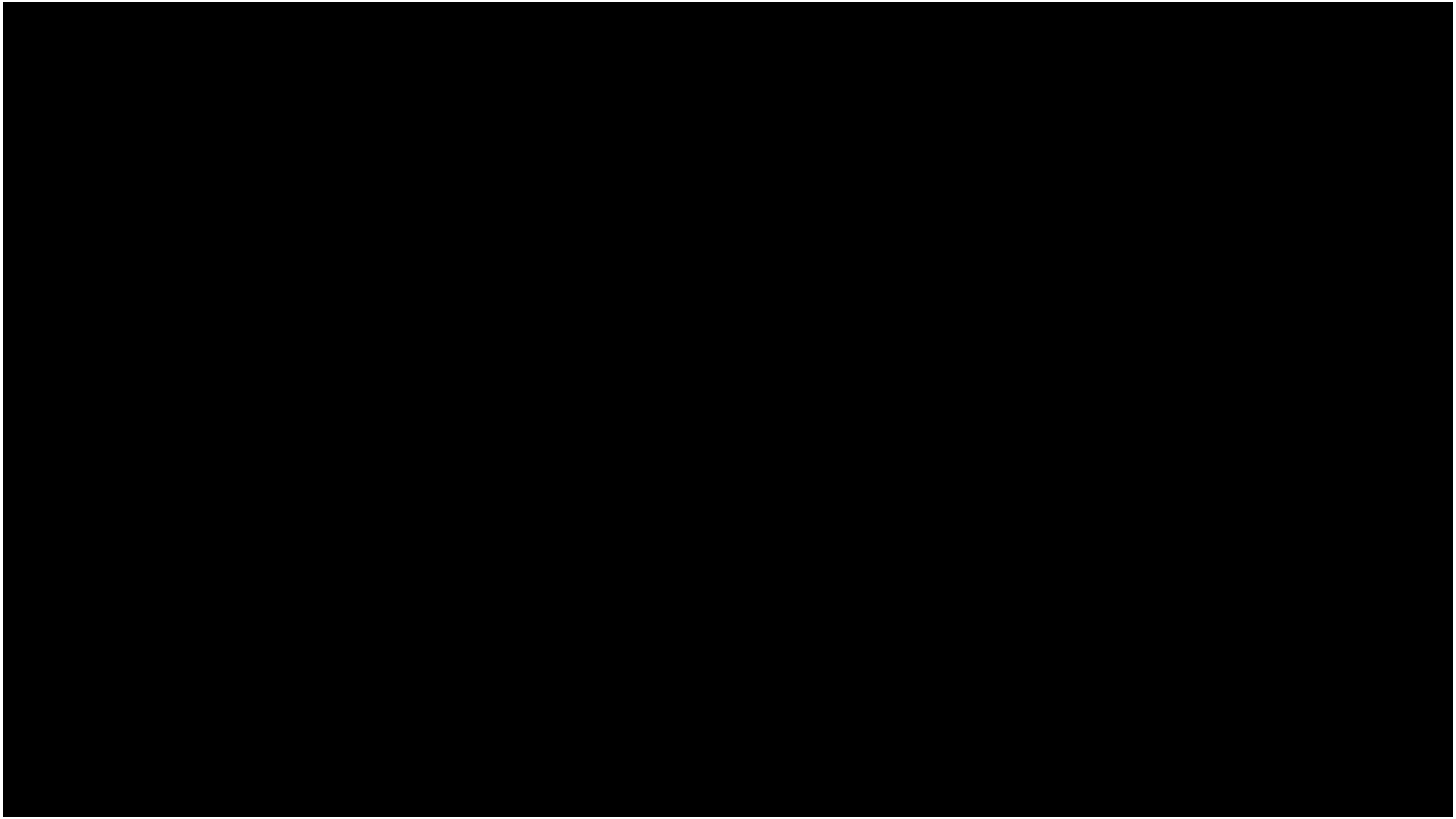
vermiculite

Q^3: Clay Minerals (phyllosilicates)

Expanding type sheet silicate

Expanding type sheet silicate





https://www.youtube.com/watch?v=cKapahIjses

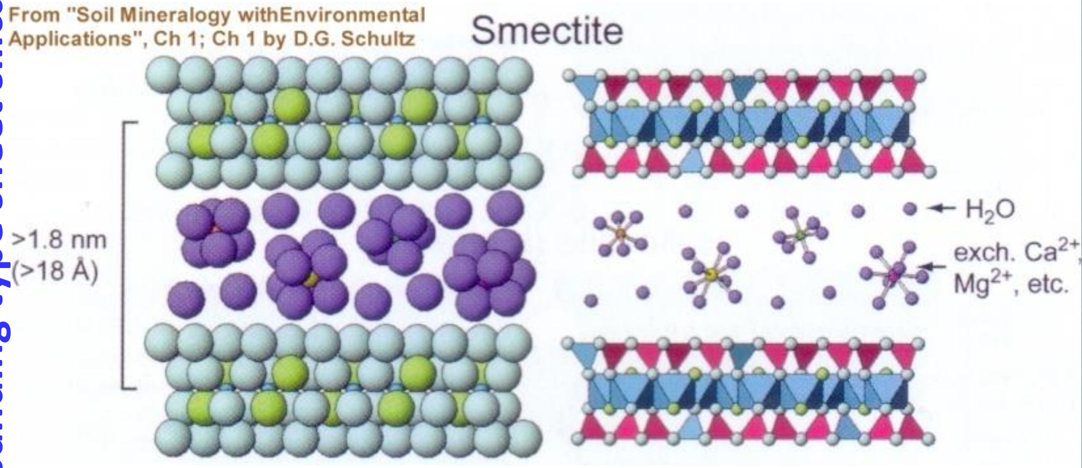
1.5 Ceramic raw materials

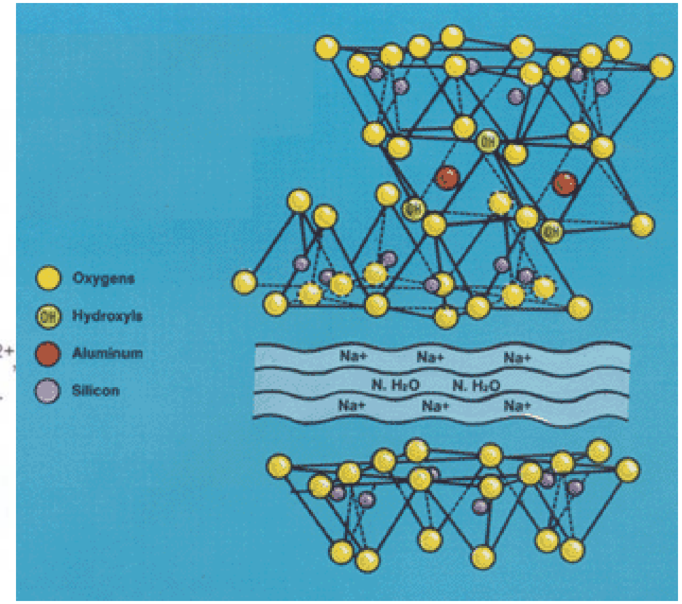
Summary

Q^3: Clay Minerals (phyllosilicates)

Expanding type sheet silicate

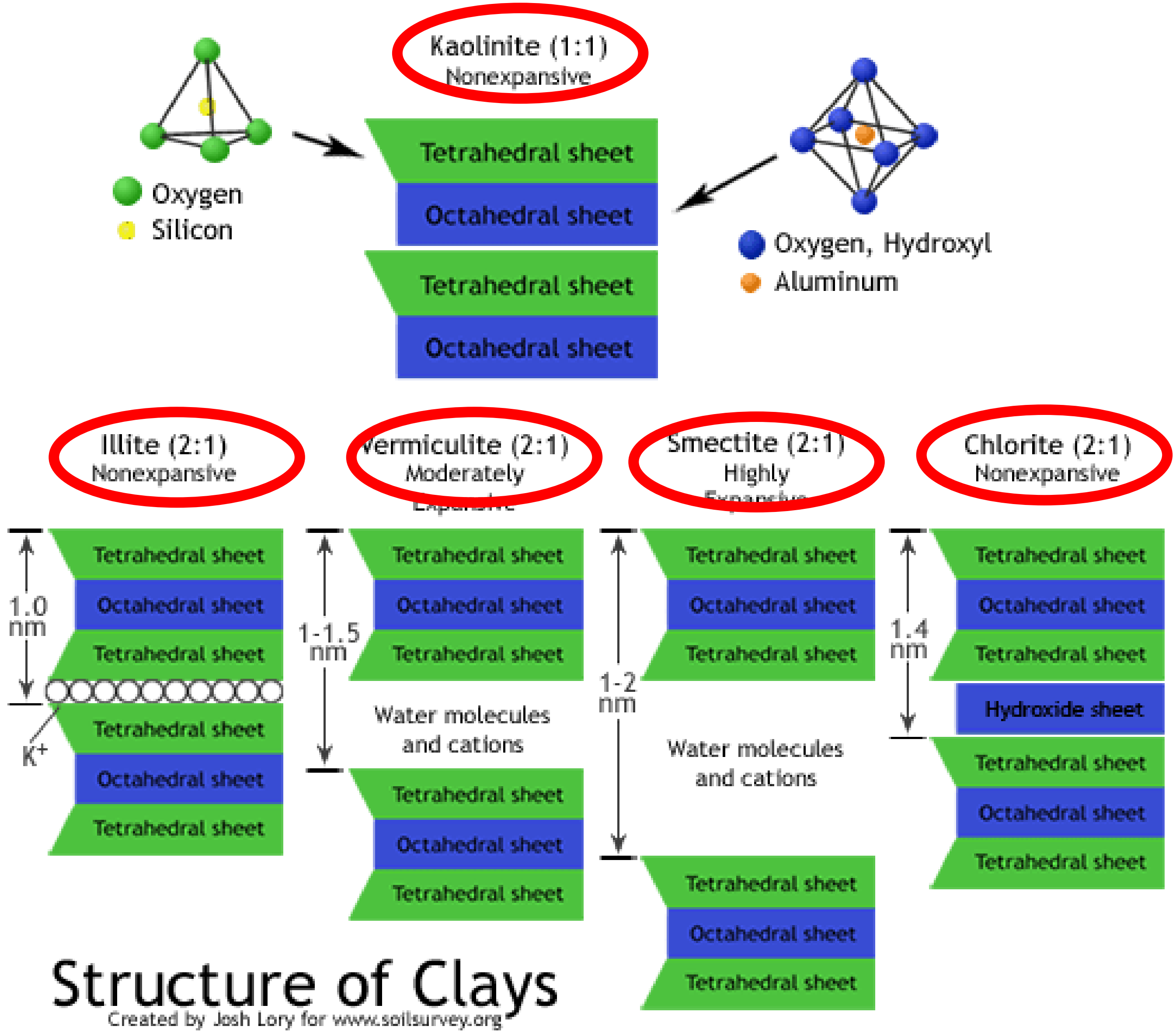
Expanding type sheet silicate





Expanding type sheet silicate

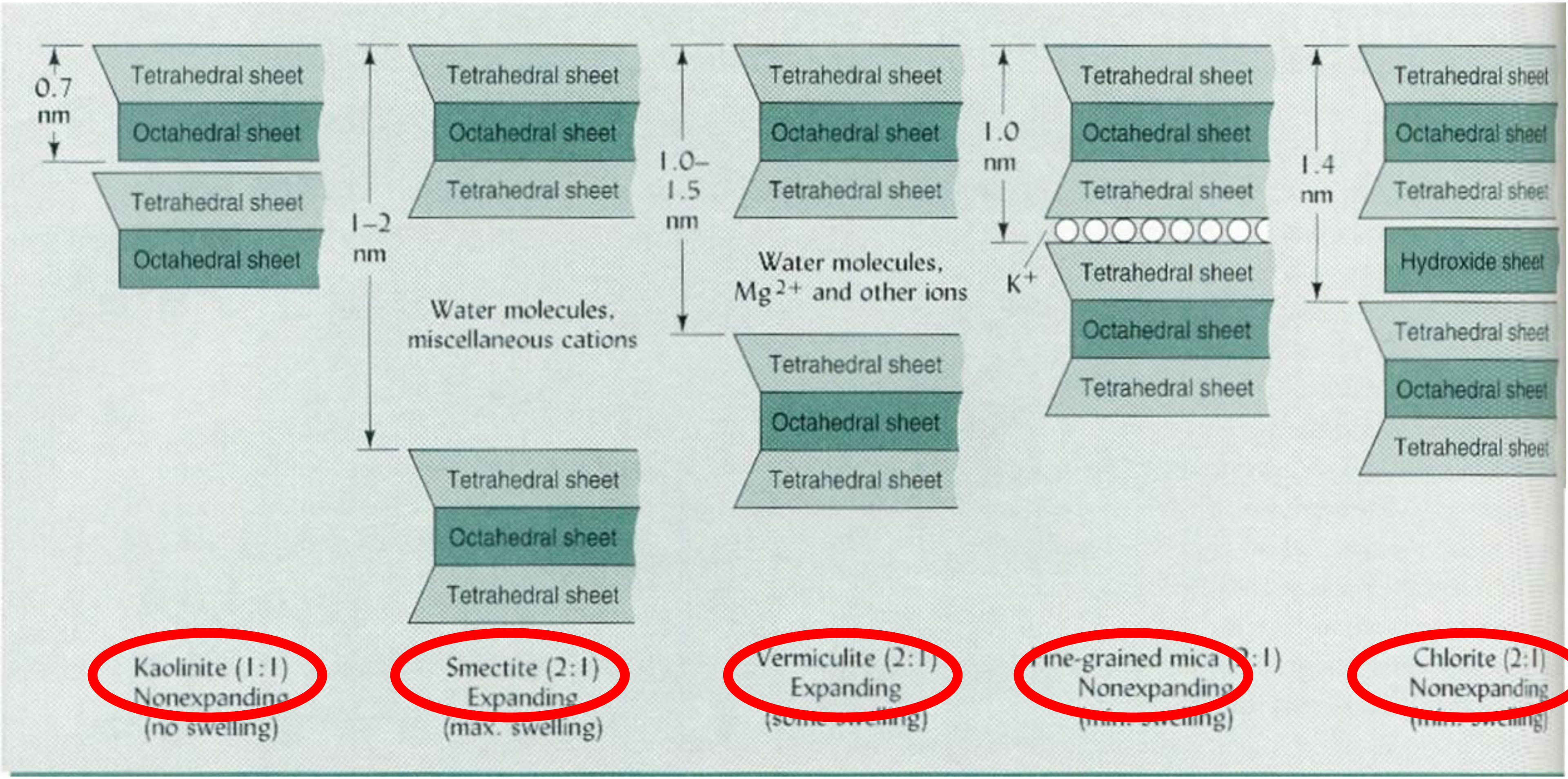
Q^3: Clay Minerals (phyllosilicates)



1.5 Ceramic raw materials

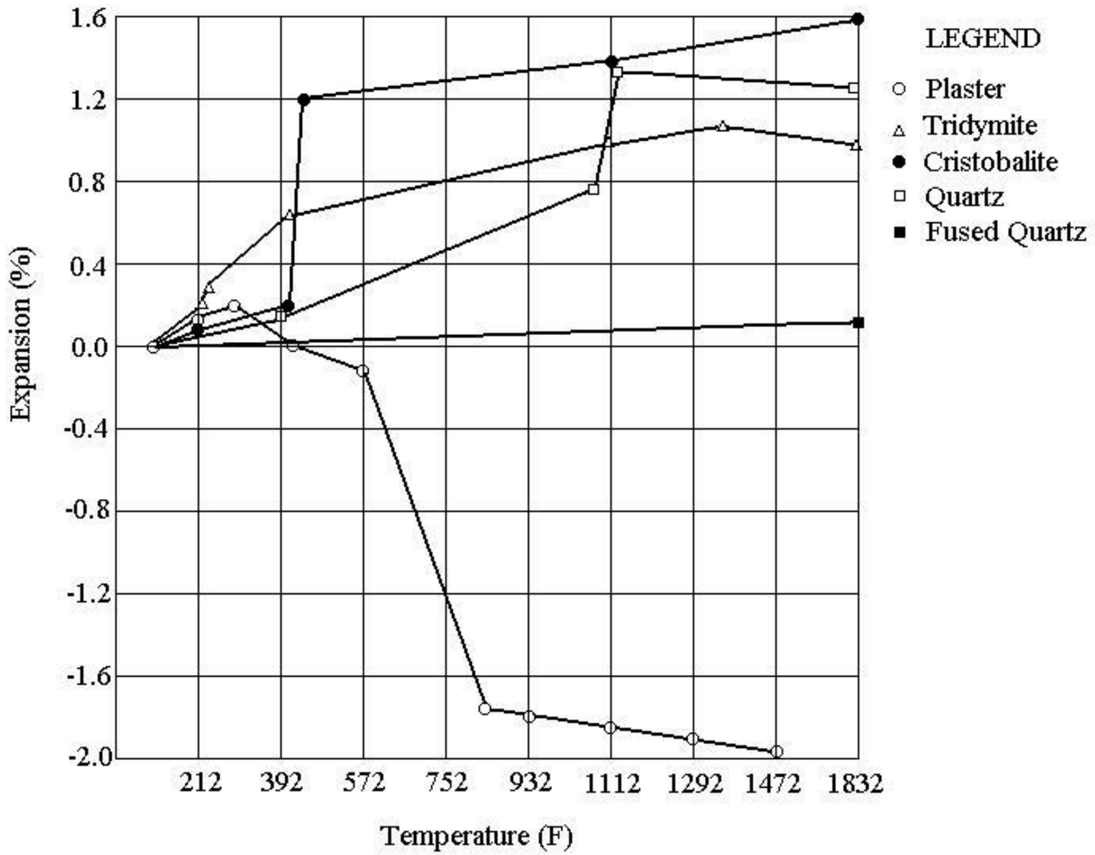
Summary

Q³: Clay Minerals (phyllosilicates)



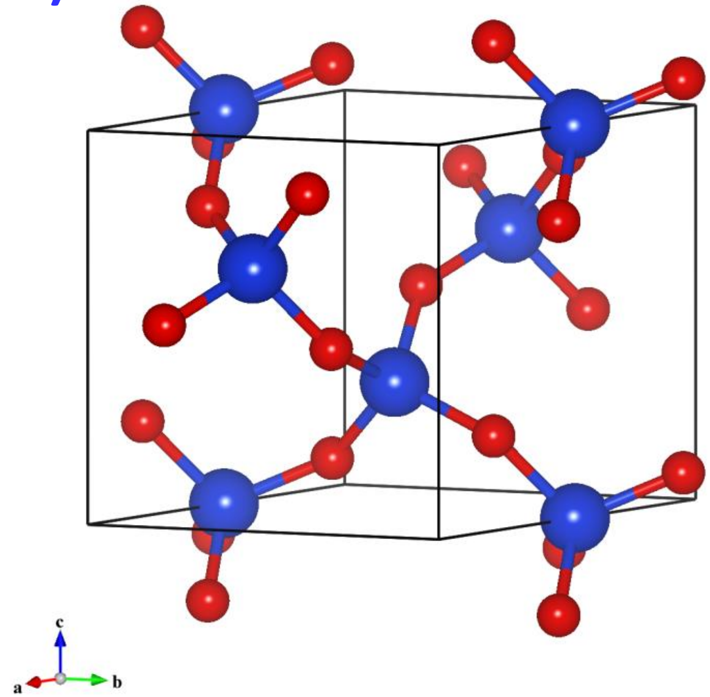
1.5 Ceramic raw materials

Q^4: Quartzites and Sands (tectosilicates)



1.5 Ceramic raw materials

Q^4: Quartz (tectosilicates)

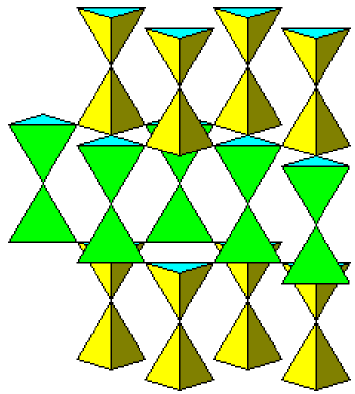


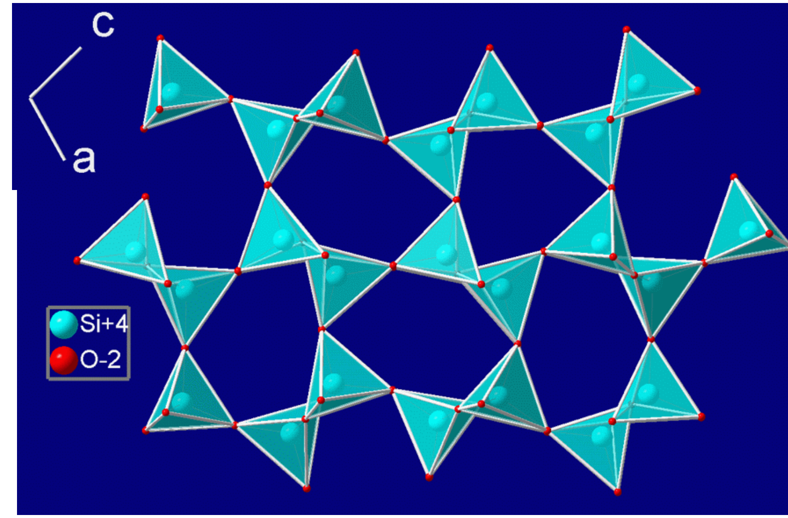
→ In **quartz**, the best-known crystalline form of silica, the Si-O-Si bonds joining neighbouring tetrahedra do not form a straight line but are bent round to give spiral chains.

→ Starting with any Si^{4+} ion, passing through silicon and oxygen alternately, spiral chains (**Si_3O_3**) can be traced throughout the structure, all in the same direction.

→ The entire structure is built up by the linking of many spiral chains through common silicon oxides.

Q^4: Tridymite (tectosilicates)





→ In **tridymite** the silica tetrahedra are linked to form rings, each containing six oxygen and six silicon ions.

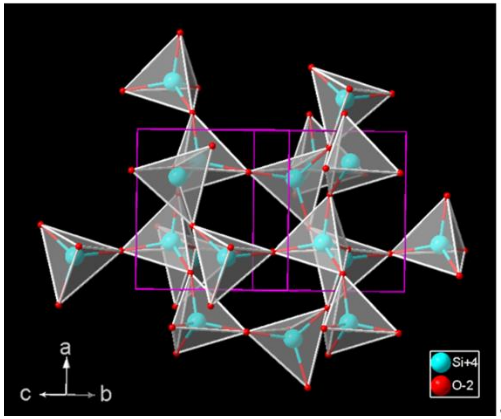
→ These **Si_6O_6** rings are joined to form planes throughout the structures, each plane being linked to a neighbouring one by bridging oxygen ions.

→ In **tridymite** has hexagonal close packing (*hc*) structure (of oxygens) i.e., in two linked silicon-oxygen tetrahedra, the three basal oxygens of the upper tetrahedron fall directly below the corresponding oxygens in the base of the lower tetrahedron.

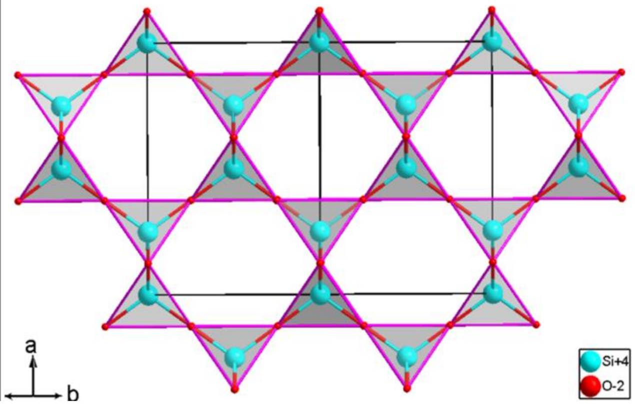
1.5 Ceramic raw materials

Q^4: Cristobalite (tectosilicates)

α-cristobalite



β-cristobalite



→ In **cristobalite** the silica tetrahedra are linked to form rings, each containing six oxygen and six silicon ions.

→ These **Si_6O_6** rings are joined to form planes throughout the structures, each plane being linked to a neighbouring one by bridging oxygen ions.

→ However, in **cristobalite** the *hc* network are much more distorted than in tridymite.

Felsdpats

Feldspar

- most common mineral

1.5 Ceramic raw materials

Q^4: Feldspat (tectosilicates)

Feldspar is a common raw material used in glassmaking, ceramics, and to some extent as a filler and extender in paint, plastics, and rubber. In glassmaking, alumina from feldspar improves product hardness, durability, and resistance to chemical corrosion.

In **ceramics**, **the alkalis in feldspar** (calcium oxide, potassium oxide and sodium oxide) act as a **flux**, l**owering the melting temperature** of a mixture. Fluxes melt at an early stage in the firing/sintering process, forming a **glassy matrix that bonds the other components of the system together**.

1.4 Ceramic ternary diagram

Stoneware / Grés

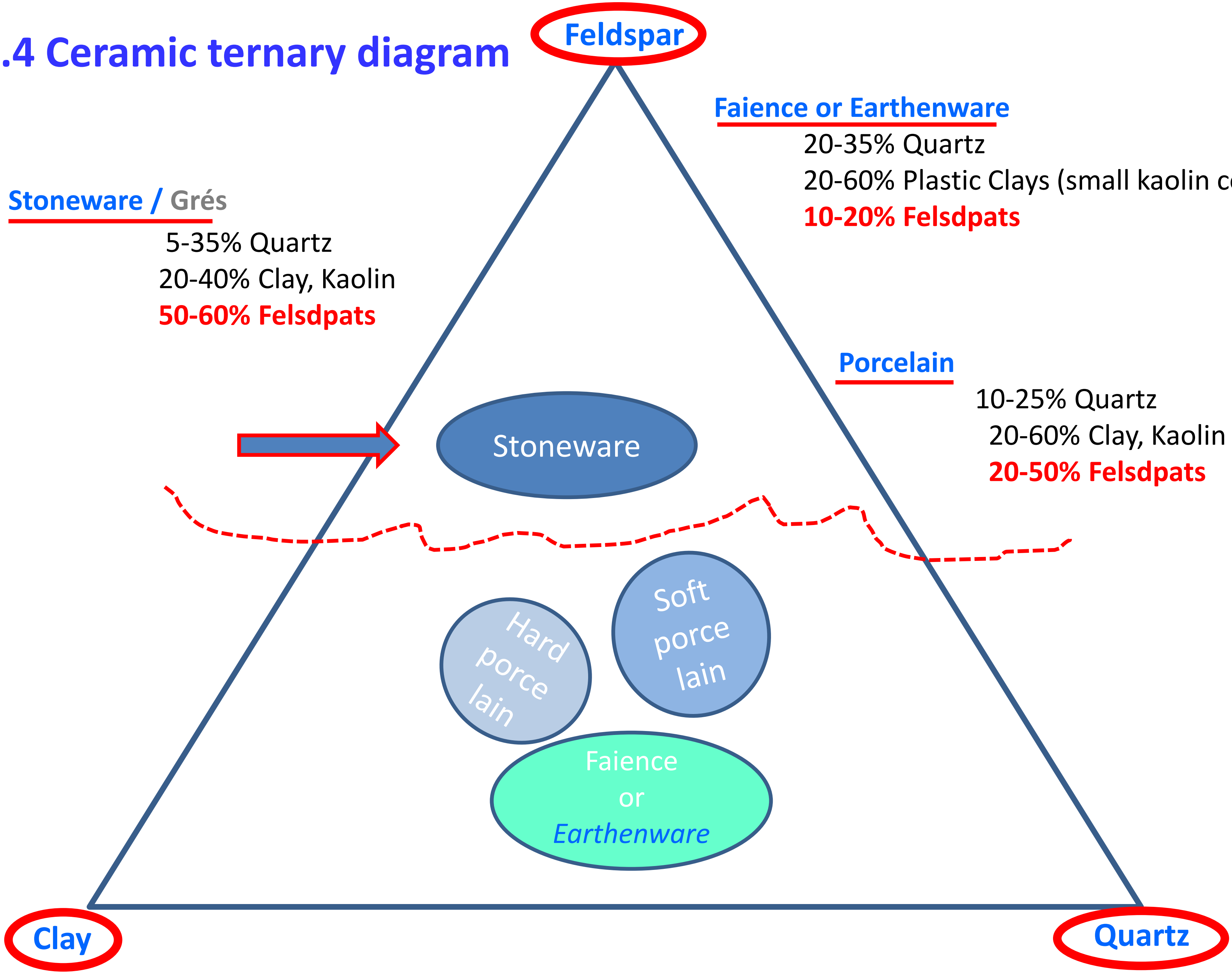
5-35% Quartz
20-40% Clay, Kaolin
50-60% Felsdpats

Faience or Earthenware

20-35% Quartz
20-60% Plastic Clays (small kaolin content)
10-20% Felsdpats

Porcelain

10-25% Quartz
20-60% Clay, Kaolin
20-50% Felsdpats



1.5 Ceramic raw materials

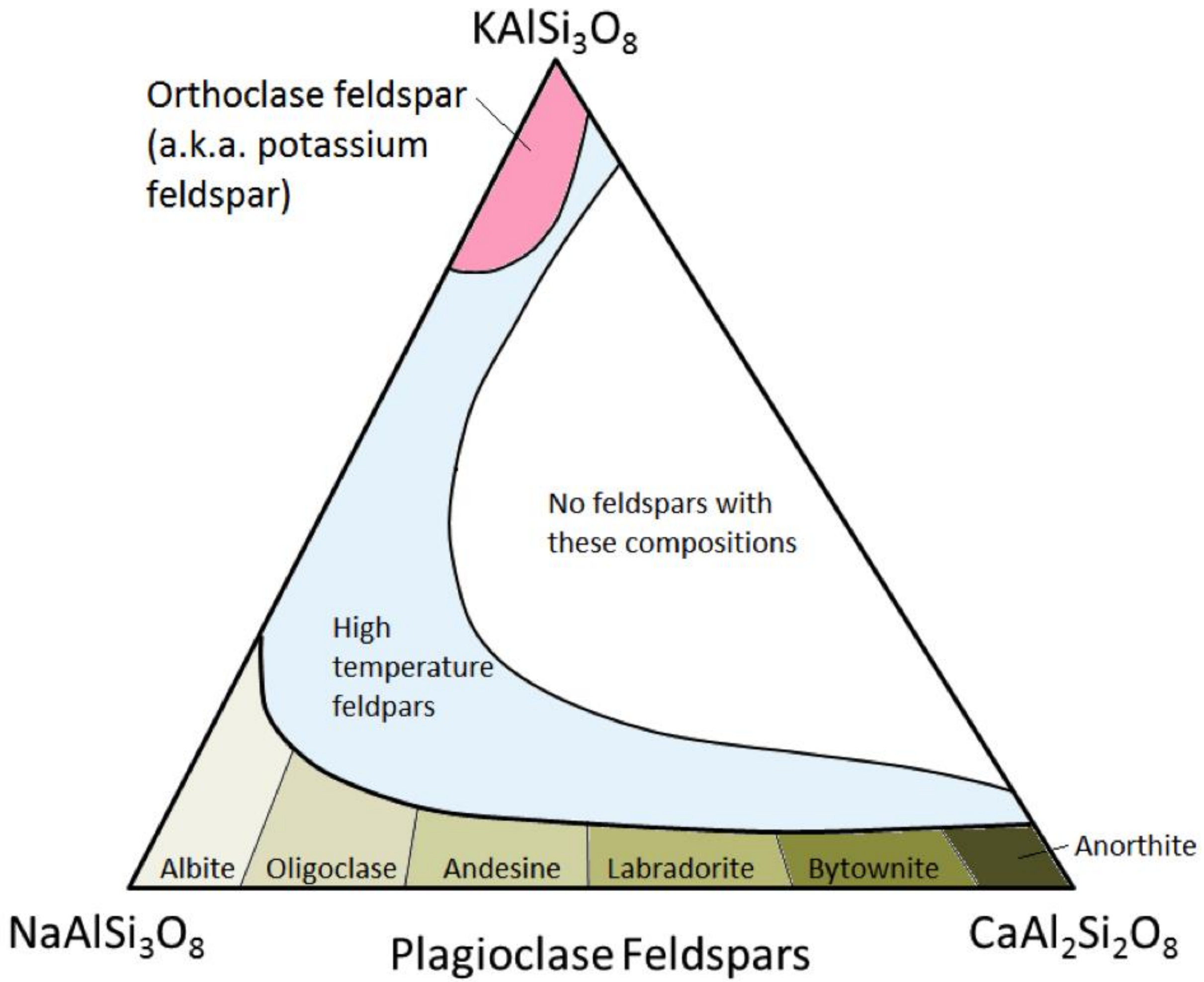
Q^4: Feldspat (tectosilicates)

If in **tectosilicates** the **SiO_2** tetrahedra silicon atoms are replaced by aluminium ions, electrical neutrality is re-established by incorporation of alkali or alkaline earth ions on interstitials, resulting a **feldspar**.

Microcline	$K[AlSi_3O_8]$	**triclinic**
Sanidine	$K[AlSi_3O_8]$	**monoclinic**
Albite	$Na[AlSi_3O_8]$	**triclinic**
Analbite	$Na[AlSi_3O_8]$	**triclinic**
Monalbite	$Na[AlSi_3O_8]$	**monoclinic**
Anorthite	$Ca[Al_2Si_2O_8]$	**triclinic**
Celsian	$Ba[Al_2Si_2O_8]$	**monoclinic**

1.5 Ceramic raw materials

Q[4]: Feldspat (tectosilicates)



http://opentextbc.ca/geology/chapter/2-4-silicate-minerals/

Other oxides

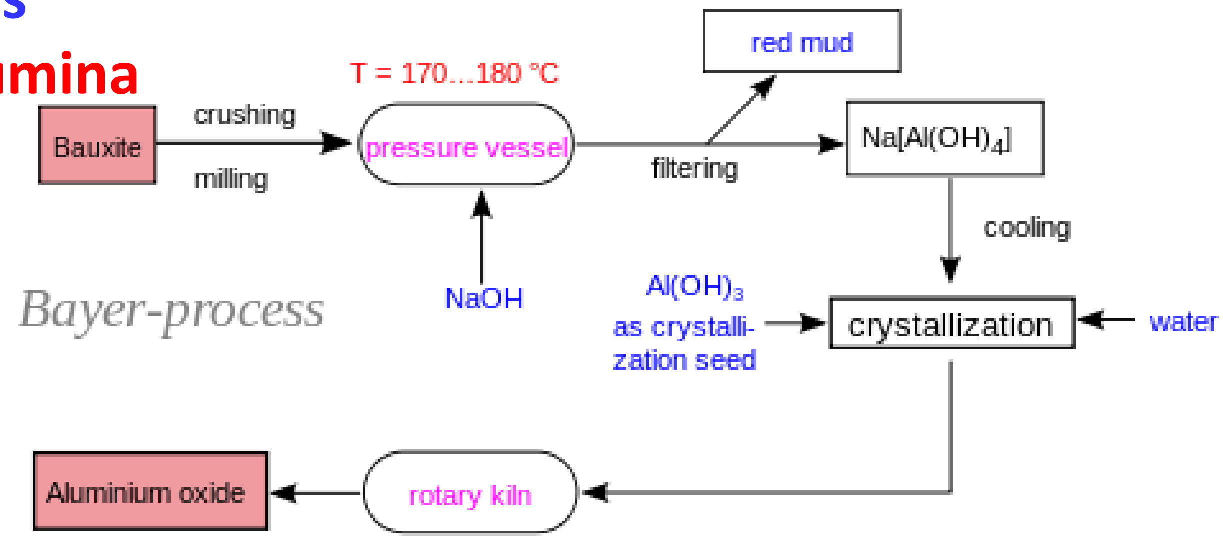
1.5 Ceramic raw materials

Other oxides

Oxide	Density (g/cm3)	Melting Point (ºC)	Resistivity 225ºC	(Ω.cm) 1000ºC
BeO	3.01	2570	10^{14}	10^{8}
MgO	3.57	2840	10^{14}	10^{7}
CaO	3.32	2580	10^{14}	10^{6}
Al_2O_3	3.99	2050	10^{14}	10^{8}
Y_2O_3	4.50	2450	------	-----
ZrO_2	5.56 Mon. 6.10 Tetr.	2680	10^{11}	10
HfO_2	9.68 Mon. 10,0 Tetr.	2900	-----	-----

1.5 Ceramic raw materials

Alumina



Bauxite is a mixture of different aluminum hydroxides, contaminated with iron hydroxides, silicates and titanium oxides. First the raw materials are grinded to a grain size of < 1 mm. Then they are processed with sodium hydroxide in an autoclave at a pressure of 40 bars and a temperature of about 250ºC. A sodium solution is formed dissolving the alumina hydrates as aluminates. Iron oxide, titanium oxide and SiO_2 remain undissolved. This so-called red-mud (red coloration caused by iron hydroxide) can be separated by filtration from the sodium aluminate.

Aluminium hydroxide seed crystals are now dispersed in the aluminate solution and aluminum hydroxide again crystallizes and can be separated by filtration from the sodium hydroxide.

This aluminum hydroxide is transformed into aluminum oxide by a thermal treatment in a rotaty klin.

1.5 Ceramic raw materials

Zirconia

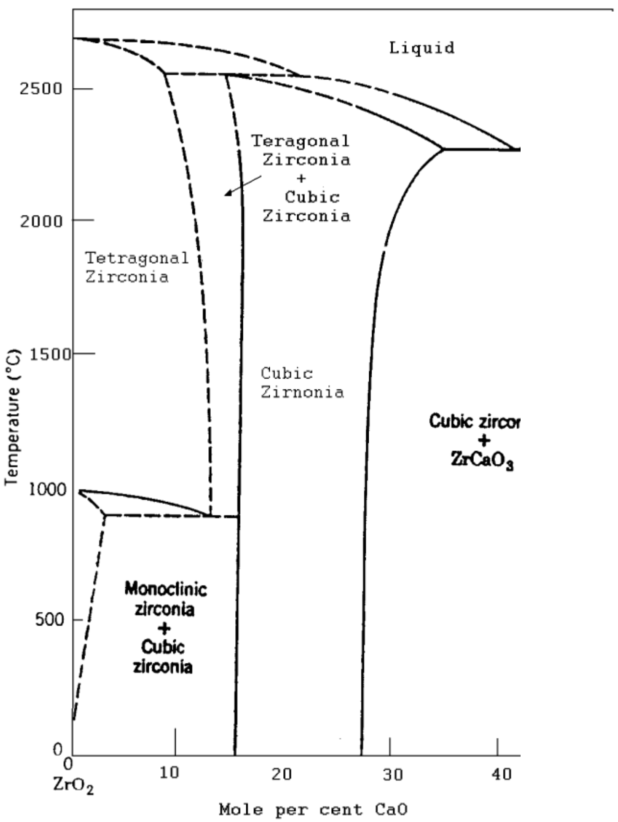
Zirconia is another interesting oxide. ZrO_2 shows particularly problematic properties. Depending on T, it suffers allotropic transformations, partly causing big volume changes. At slightly above 1000ºC the low T form changes to high T phase. This may occur during sintering! Normally this occurs at slightly lower temperatures, and a hysteresis loop is shown.

The enormous volume changes cause stresses and cracks, and this is the reason why **components cannot be made of pure ZrO_2**.

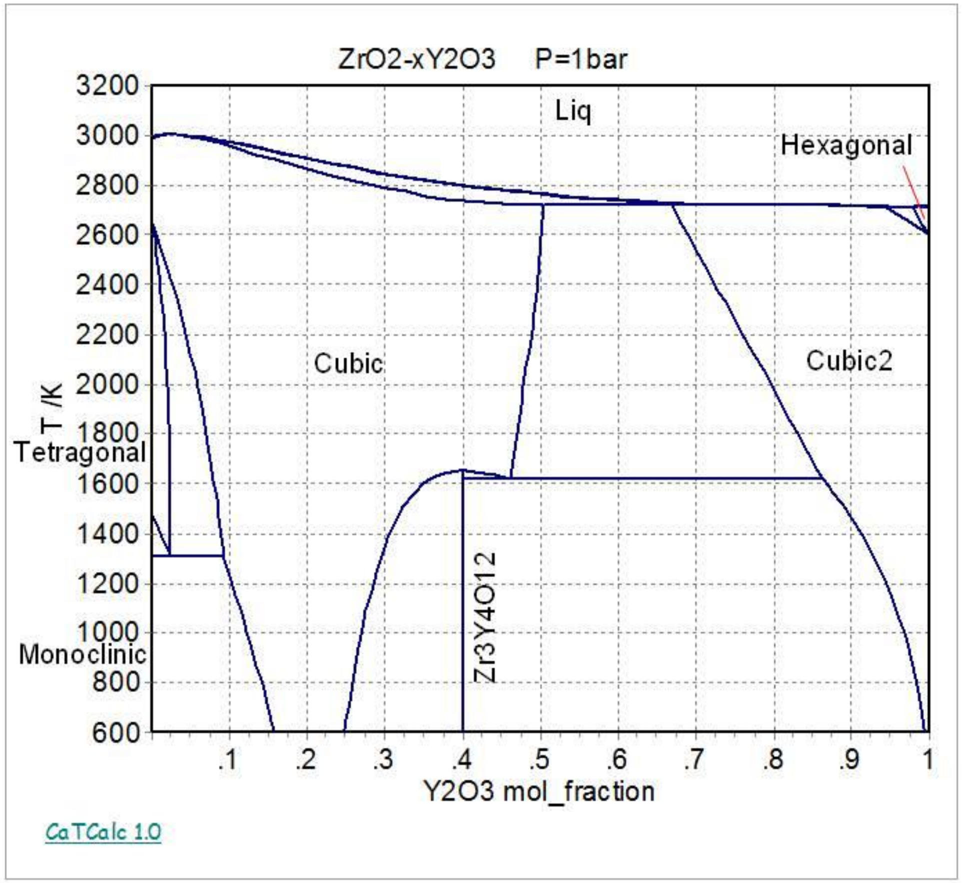
This phase transformation can be prevented if almost **20 mol% calcium or yttrea** is added, which causes a solid solution formation, avoiding the zirconia phase allotropic phase transformation.

1.5 Ceramic raw materials

Zirconia



MDT 2011



ZrO2−Y2O3 縦断面図

Organics

1.5 Ceramic raw materials

Organics

More than 95% of the ceramic materials are processed as **suspensions** either during their **preparation** or during **shaping**. In many cases the required solvent is water, but organic solvents can also be used. **Wetting agent**, **defoaming** or **conservation agents** are normally added to the suspension.

Binders increase the body's green strength often necessary for the transport of the parts after shaping to the kilns.

Binders can be modified by adding **plasticizers** or **softeners**.

Releasing and **anti-blocking agents** reduce the friction in compression molds and increase the powder consolidation.

Binders and **plasticizers** are used to increase the interval of ignition and avoid crack formation during burn out.

So, normally ceramic masses consist of ceramic powders and a **large number of organic additives**. This makes **the whole system very complex** and **the understanding of the ignition products extremely difficult**.

1.5 Ceramic raw materials

Organics

Components	Function
Ceramic powder	Matrix
Sintering aditives	Consolidation agent
Solvent	Dispersion
Deflocculant	Control of surface charge, pH value
Dispersant/surfactant	De-agglomeration
Wetting agent	Reduction of surface tension
Anti-foaming	Reduction/elimination of foaming
Conserving agents	Prevention from bacteria or *algae* development
Binder	Mechanical strength of the green body
Plasticizer	Flexibility
Softener	Flexibility
Lubricant	Reduction of attrition with matrix/molds

1.5 Ceramic raw materials

Organics

There are a large variety of organic additives depending on the shaping process. Prior to the sinter, the additives must be burn out or must be regained by condensation.

There are different binders, plasticizers, condensers and wetting agents depending on the nature of the solvent -organic solvents and water based solvents.

1.5 Ceramic raw materials

Organics

Dry Pressing	Dispersants	Polyacrylates, huminates
	Binder	Polyvinyl alcohols, tyloses, waxes
	Flow agent	Polyethylene glycols
Slip casting	Dispersants	Polyacrylates, fish oil
	Binder	Polyvinyl alchohols
		Polysaccharides, polyvinyl butyrals
		Water, trichlor, ethylene, ethanol
Tape casting	Dispersants	Oleates, polyacrylates, fish oil
		Phosphoric acid ester
	Binder	Polyvinyl butyrals, polyvinyl alcohols
		Acrylic resin, plastic dispersions
	Softener	Phtalates, polyethylene glycols
		Phosphoric acid ester
	Dispersion agents	Toluol, trichloroethylene, methanol
		Ethanol, methyl isobutyl ketone, water

1.5 Ceramic raw materials

Organics

Injection moulding	Dispersants	Oleates, polyacrylates
	Binder	Polyethylene, polystyrene, waxes
	Flow agent	Polyethylene glycols
	Porosity inducing agents	Caster oil
Extrusion	Dispersants	Polyacrylates
	Binder	Polyvinyl alcohols, tyloses
	Flow agents	Polyethylene glycols, glycerine

1.5 Ceramic raw materials

Organics

To understand the coupling behavior of organic additives on surface of oxide ceramic particles, we may observe the surface of alumina particle.

Ceramic powders normally have a **high specific surface area** with a **negative surface charges** , due to unsaturated valences at their surfaces because of incomplete coordination atoms.

When this charged surface gets in contact with water the surface becomes **hydrated**. When in contact to air humidity their surfaces also hydrate.

The number of the developing –OH groups at the surface depends on the number of the oxygen atoms at the surface, and this in turn depends on the crystal structure.

With regard to alumina the oxygen ions are saturated with H at a **pH ~9**, this means that at this pH value the particles are electrically neutral (**isoelectric point**).

Further reading

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- **Ceramics and Glasses**. V4 **Engineered Materials Handbook**. ASM International. The Materials Information Society (1991)
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- **Handbook of Advanced Ceramics**. S. Somiya, N. Claussen, K. Uchino, M. Kaneno, F. Aldinger, R. M. Spriggs, K. Koumoto. Academic Press (2003)
- **Engineering Ceramics**, M. Bengisu (Ed.) Springer (2001)
- **Structure and Properties of Ceramics**. V80, A. Koller (Ed.), Elsevier Science (1994)
- **Argilas. O que são e para que servem**. C. F. Gomes, Fundação Calouste Gulbenkian

1.5 Ceramic raw materials

And now let's see how industry prepare ceramic raw materials!