Clay Minerals
and
Soil Structure

Contents-

1. Clay Minerals

1.1 Origin of Clay Minerals

“The contact of rocks and water produces clays, either at or near the surface of the earth” (from Velde, 1995).

Rock +Water → Clay

For example,

The CO_2 gas can dissolve in water and form **carbonic acid**, which will become hydrogen ions ***H^+*** and ***bicarbonate ions***, and make water slightly ***acidic.***

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow \mathbf{H^+} + \mathbf{HCO_3^-}$$

The acidic water will react with the rock surfaces and tend to dissolve the ***K*** ion and silica from the ***feldspar.*** Finally, the feldspar is transformed into ***kaolinite.***

Feldspar + hydrogen ions + water → **clay (kaolinite)** + cations, dissolved silica

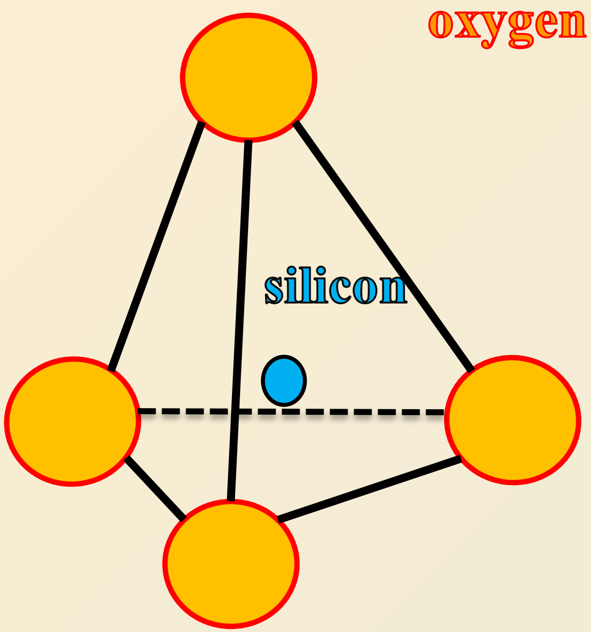
$$2KAlSi_3O_8 + 2H^+ + H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 4SiO_2$$

- The alternation of **feldspar into kaolinite** is very common in the decomposed granite.
- The clay minerals are common in the **filling materials of joints and faults** (fault gouge, seam) in the rock mass.

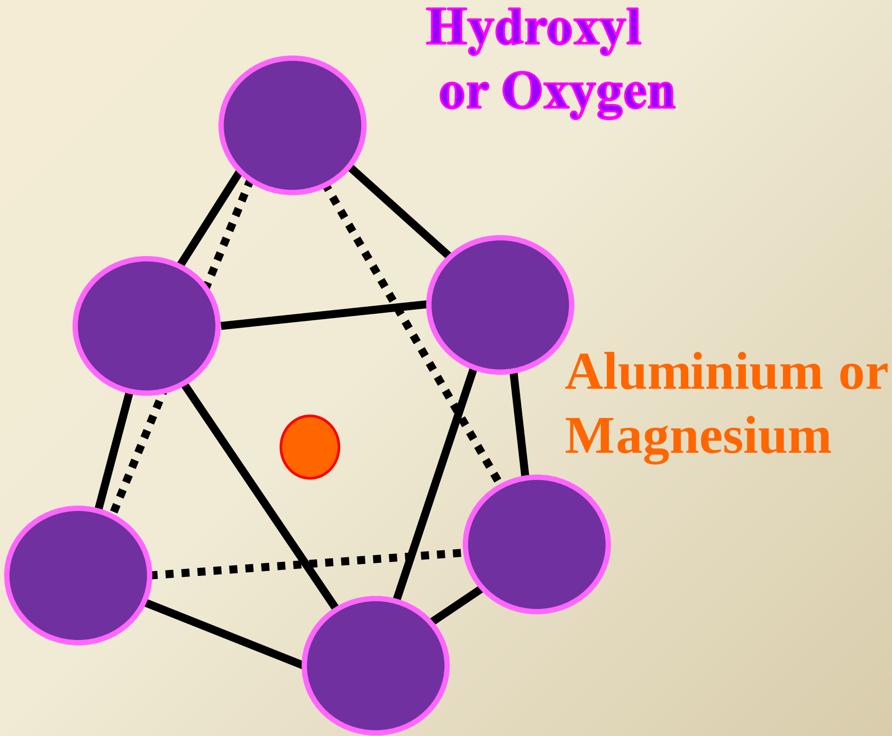
Weak plane!

1.2 Basic Structural Units

Clay minerals are made of two distinct **structural units**.



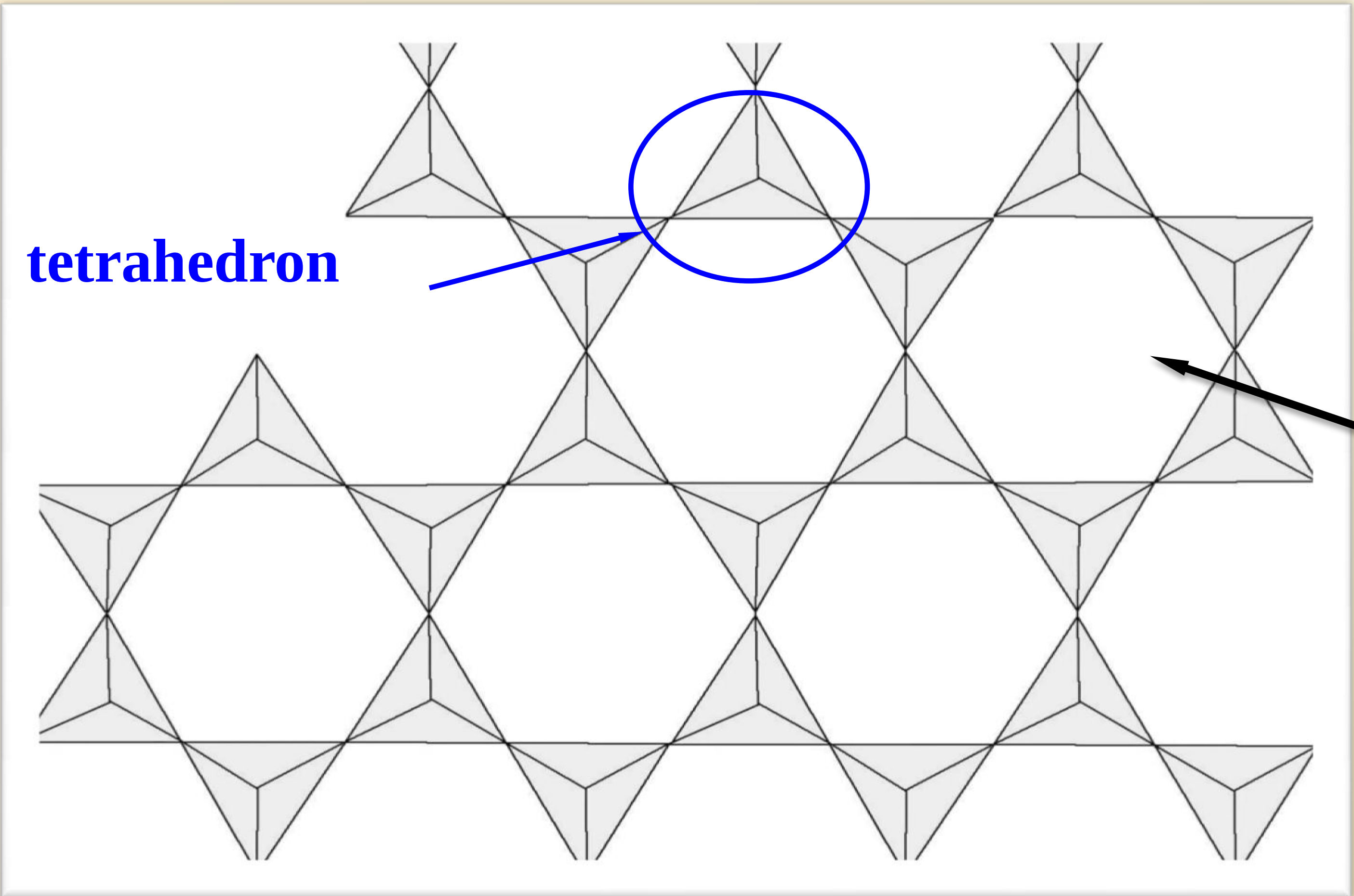
Silicon tetrahedron



Aluminium Octahedron

Tetrahedral Sheet

Several tetrahedrons joined together form a **tetrahedral sheet**.

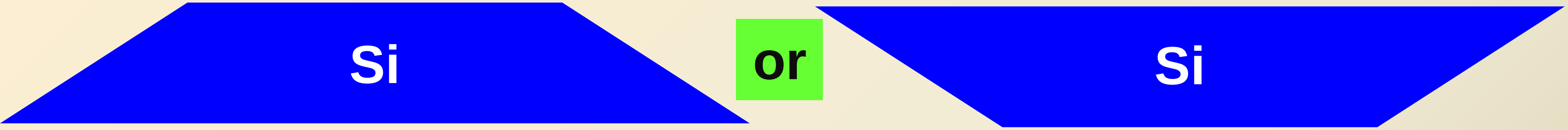


tetrahedron

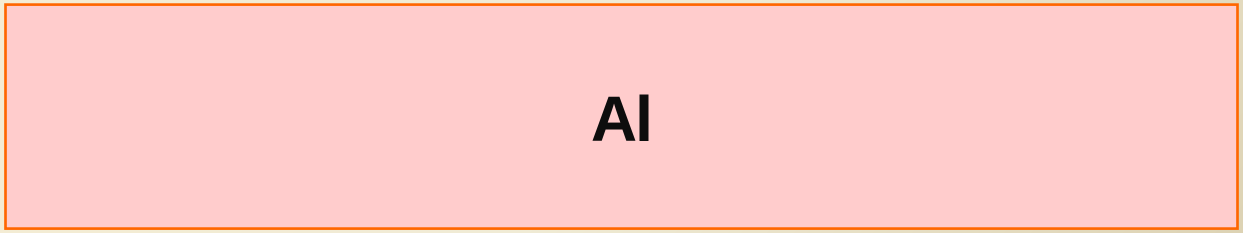
hexagonal hole

Tetrahedral & Octahedral Sheets

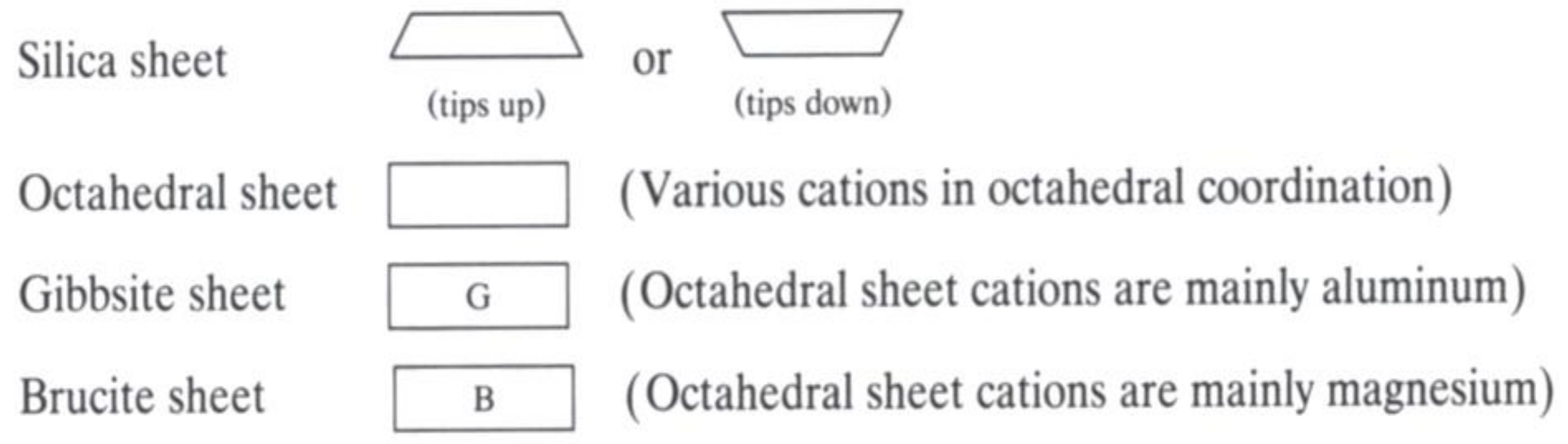
For simplicity, silica **tetrahedral sheet** by:



and alumina **octahedral sheet** by:



Basic Unit-Summary



Silica sheet (tips up) or (tips down)

Octahedral sheet (Various cations in octahedral coordination)

Gibbsite sheet G (Octahedral sheet cations are mainly aluminum)

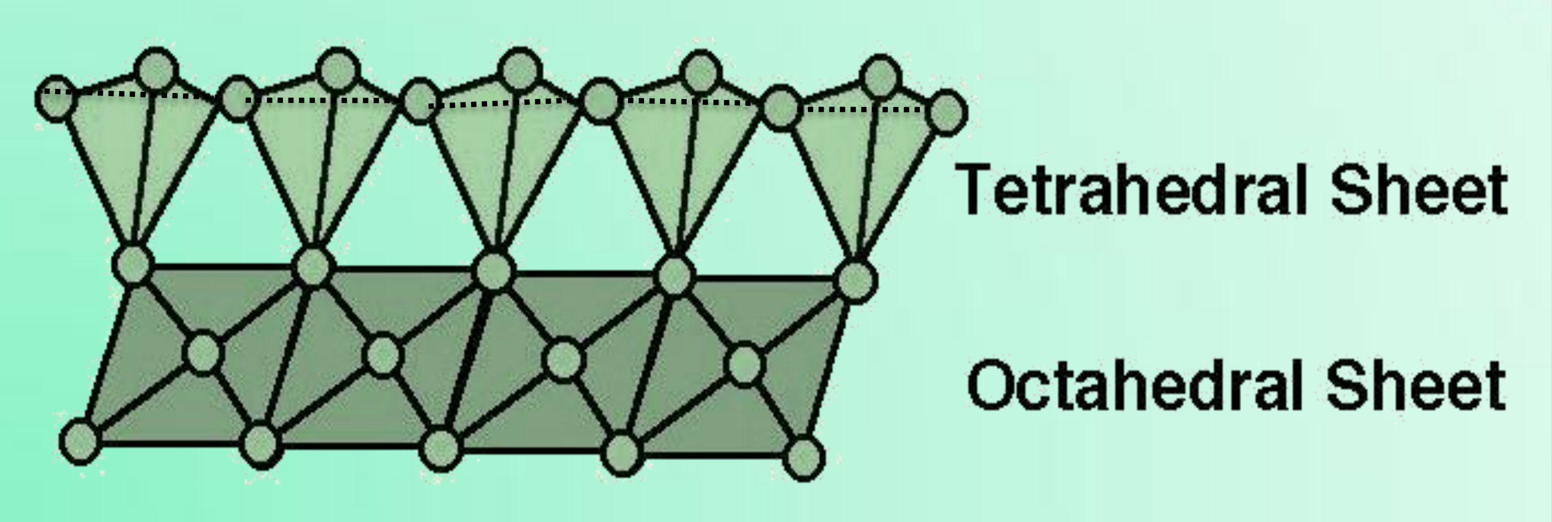
Brucite sheet B (Octahedral sheet cations are mainly magnesium)

Mitchell, 1993

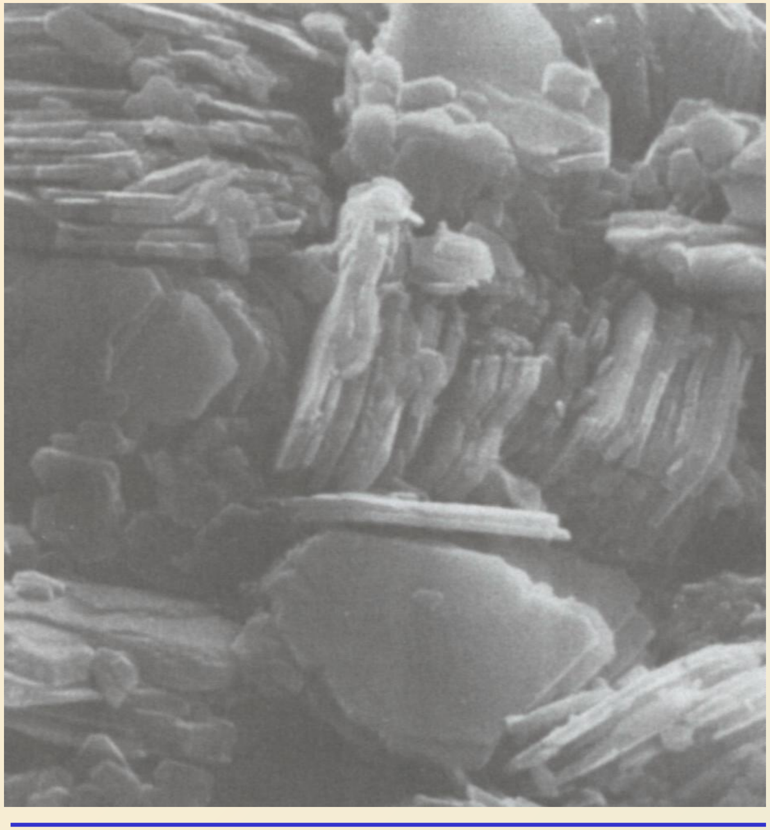
1.3 Different Clay Minerals

Different combinations of ***tetrahedral*** and ***octahedral*** sheets form different **clay minerals**:

Clay Mineral (e.g., kaolinite, halloysite):

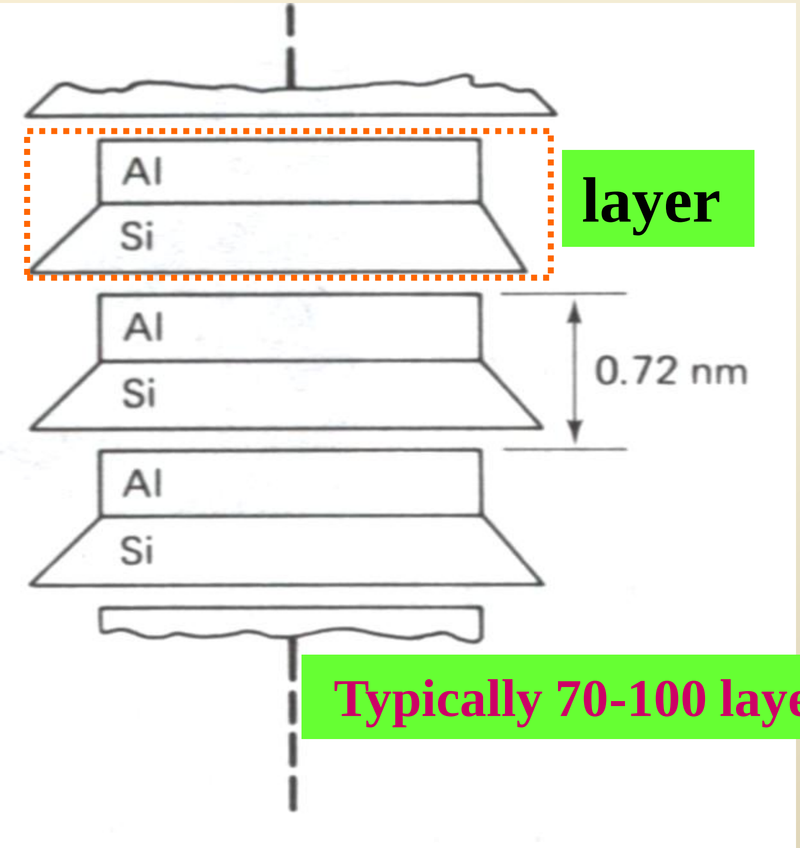


Minerals-Kaolinite



(Mitchell, 1993)

Basal spacing is 7.2 Å

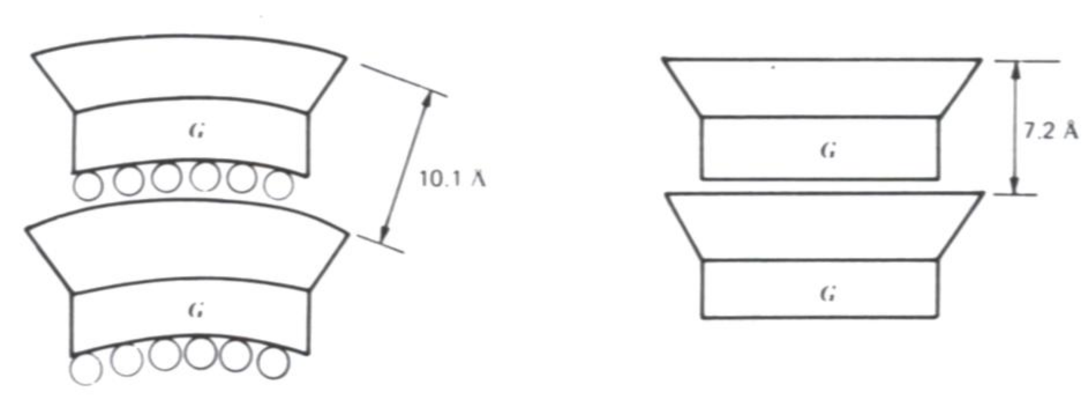


layer

Typically 70-100 layers

- $Si_4Al_4O_{10}(OH)_8$. **Platy shape**
- The bonding between layers are **van der Waals forces and hydrogen bonds** (strong bonding).
- There is no interlayer swelling
- Width: 0.1~ 4µm, Thickness: 0.05~2 µm

Minerals-Halloysite



2 μm (Mitchell, 1993)

- $Si_4Al_4O_{10}(OH)_8\cdot 4H_2O$
- A single layer of water between unit layers.
- The basal spacing is 10.1 Å for hydrated halloysite and 7.2 Å for dehydrated halloysite.
- If the temperature is **over 50 °C or the relative humidity is lower than 50%, the** hydrated halloysite will lose its interlayer water (Irfan, 1966). Note that this process is **irreversible** **and will affect the results of soil classifications (GSD and Atterberg limits) and compaction tests.**
- There is no interlayer swelling.
- Tubular shape while it is hydrated.

Å=Angstrom=10^{-10}m

Kaolinite

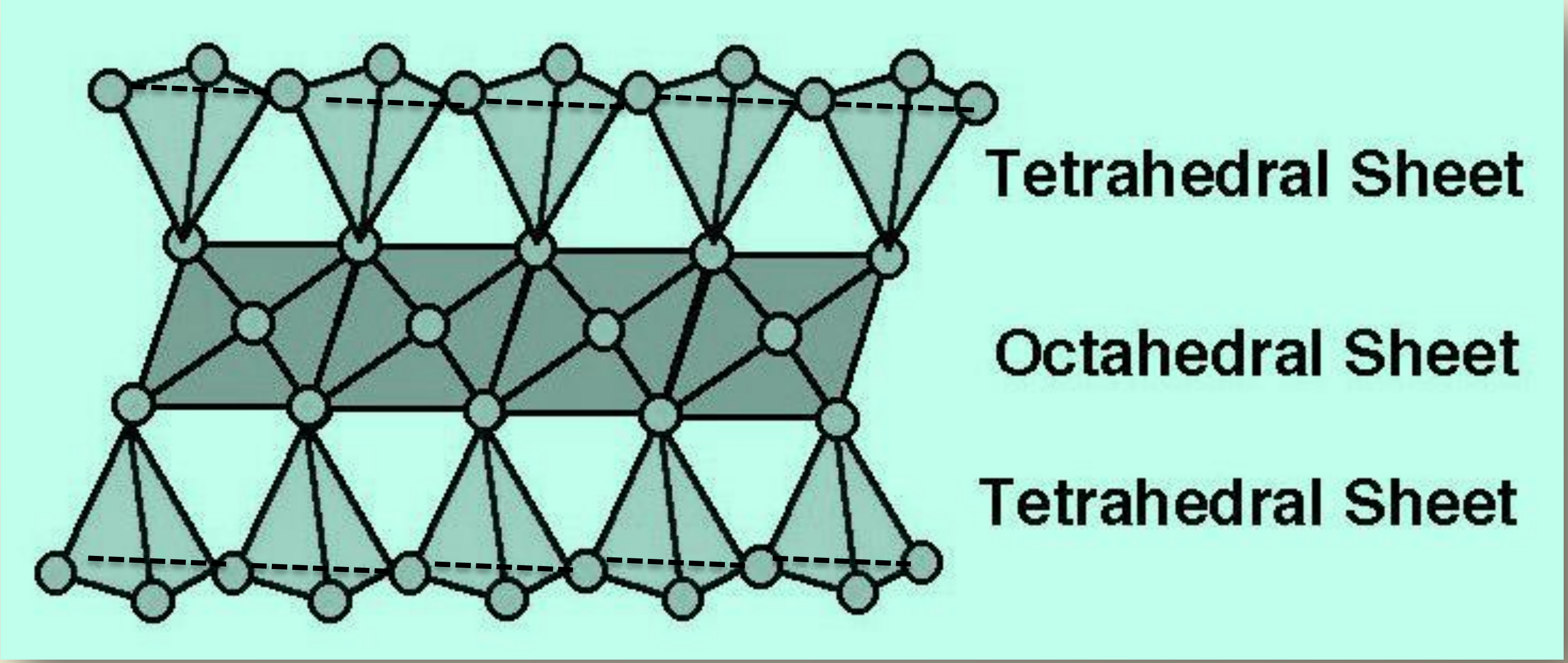
- **used in paints, paper and in pottery and pharmaceutical industries**

- $(OH)_8Al_4Si_4O_{10}$

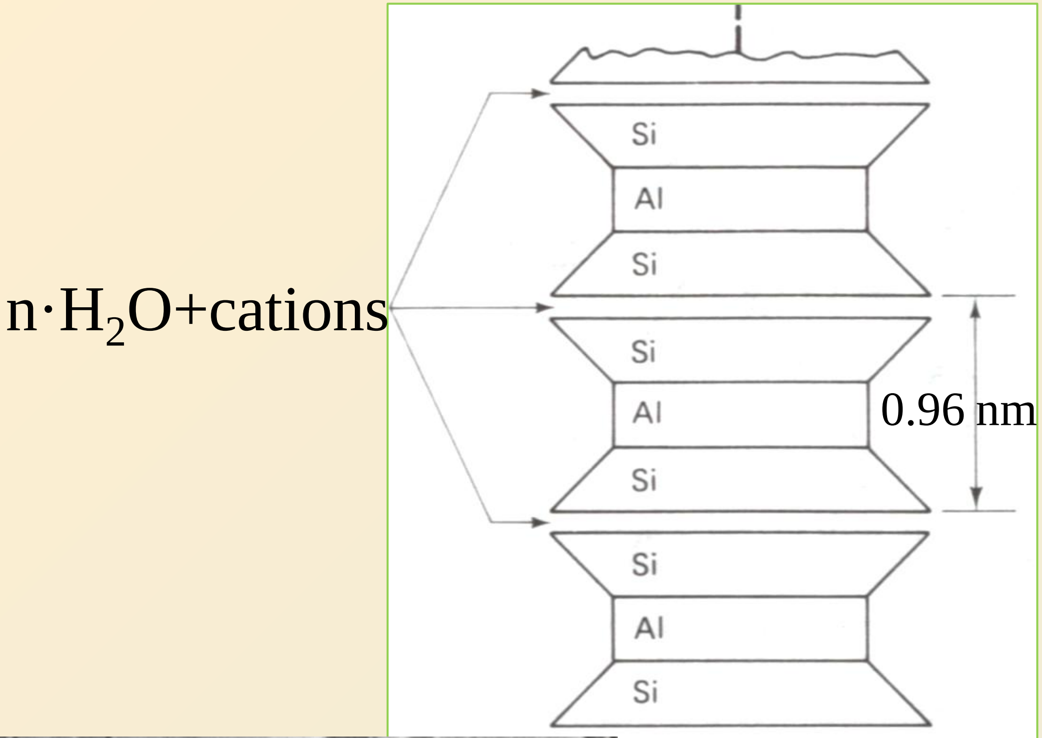
Halloysite

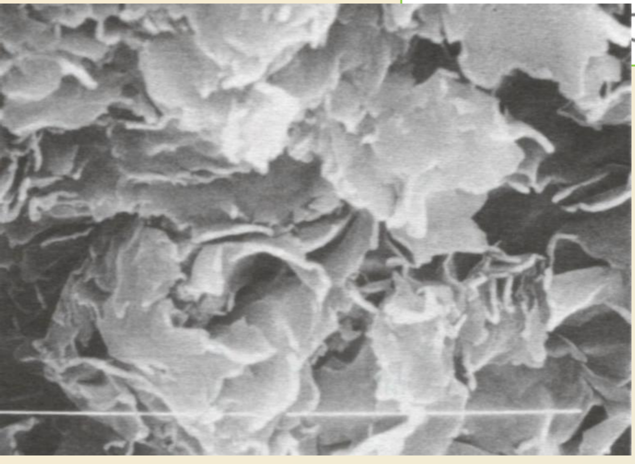
- kaolinite family; hydrated and tubular structure
- $(OH)_8Al_4Si_4O_{10}.4H_2O$

Clay Mineral (e.g., montmorillonite, illite)



Minerals-Montmorillonite





(Holtz and Kovacs, 1981)

- $Si_8Al_4O_{20}(OH)_4\cdot nH_2O$ (Theoretical unsubstituted). **Film-like shape**.
- There is extensive isomorphous substitution for silicon and aluminum by other cations, which results in charge deficiencies of clay particles.
- $n\cdot H_2O$ and cations exist between unit layers, and the basal spacing is from 9.6 Å to ∞ (after swelling).
- The interlayer bonding is by van der Waals forces and by cations which balance charge deficiencies (weak bonding).
- There exists interlayer swelling, which is very important to engineering practice **(expansive clay).**
- Width: 1 or 2 µm, Thickness: 10 Å~1/100 width

Montmorillonite

- A highly **reactive** (expansive) clay

swells on contact with water

- $(OH)_4Al_4Si_8O_{20}.nH_2O$

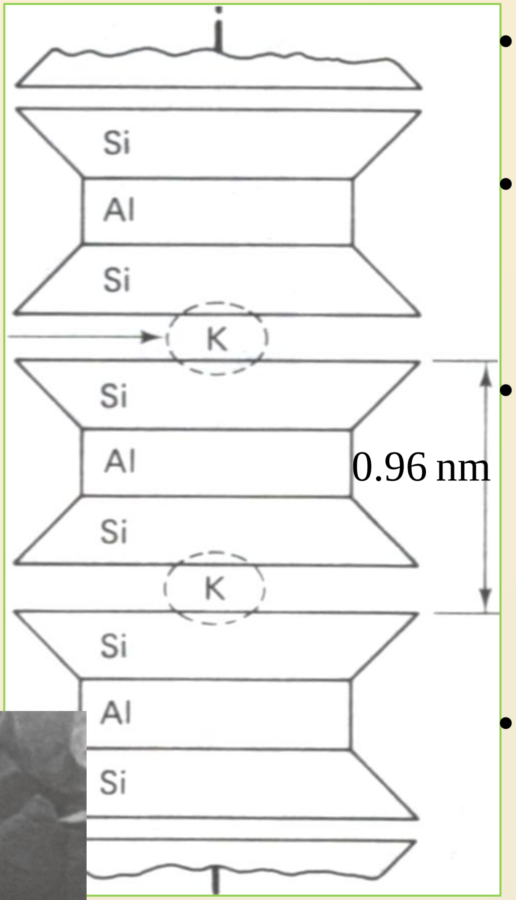
high affinity to water

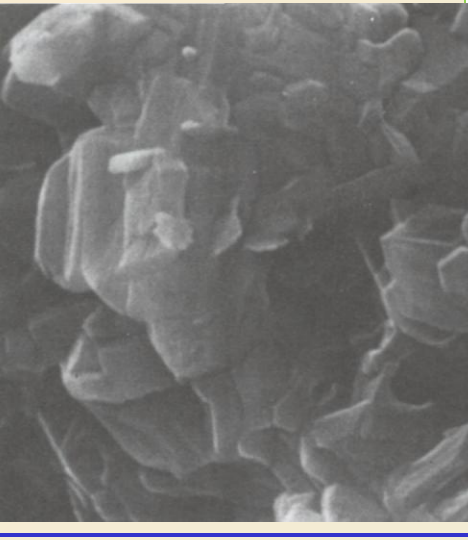
Bentonite

- **montmorillonite family**
- **used as drilling mud, in slurry trench walls, stopping leaks**

Minerals-Illite (mica-like minerals)

potassium **K**

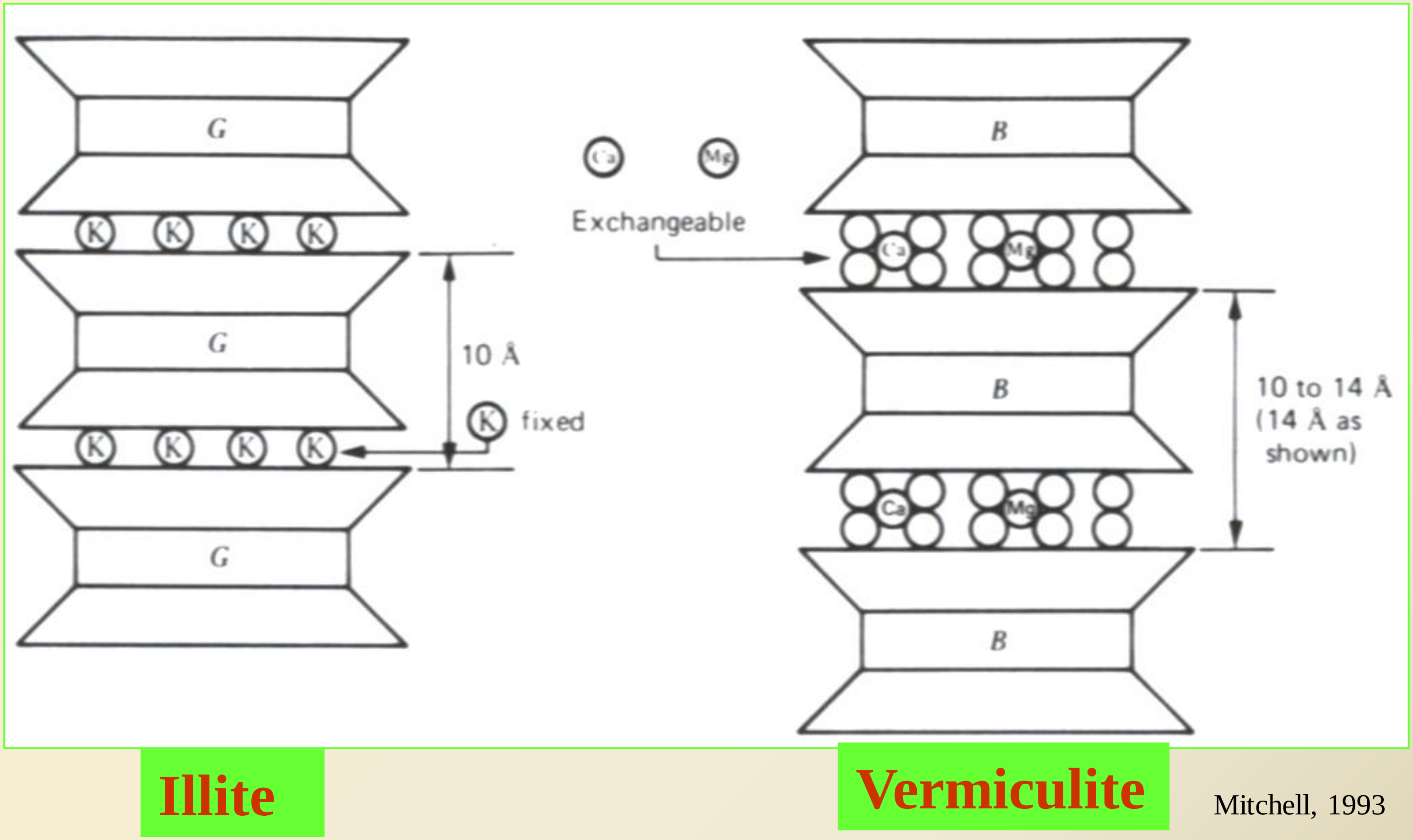



7.5 μm

(Mitchell, 1993)

- $Si_8(Al,Mg,\ Fe)_{4\sim6}O_{20}(OH)_4 \cdot (K,H_2O)_2$. **Flaky shape.**
- The basic structure is very similar to the mica, so it is sometimes referred to as **hydrous mica**. **Illite is the chief constituent in many shales.**
- Some of the Si^{4+} in the tetrahedral sheet are replaced by the Al^{3+}, and some of the Al^{3+} in the octahedral sheet are substituted by the Mg^{2+} or Fe^{3+}. Those are the origins of charge deficiencies.
- The charge deficiency is balanced by the **potassium ion** between layers. Note that the potassium atom can exactly fit into the hexagonal hole in the tetrahedral sheet and form a strong interlayer bonding.
- The **basal spacing** is fixed at 10 Å in the presence of polar liquids (**no interlayer swelling**).
- Width: 0.1~ several μm, Thickness: ~ 30 Å

Minerals-Vermiculite (micalike minerals)

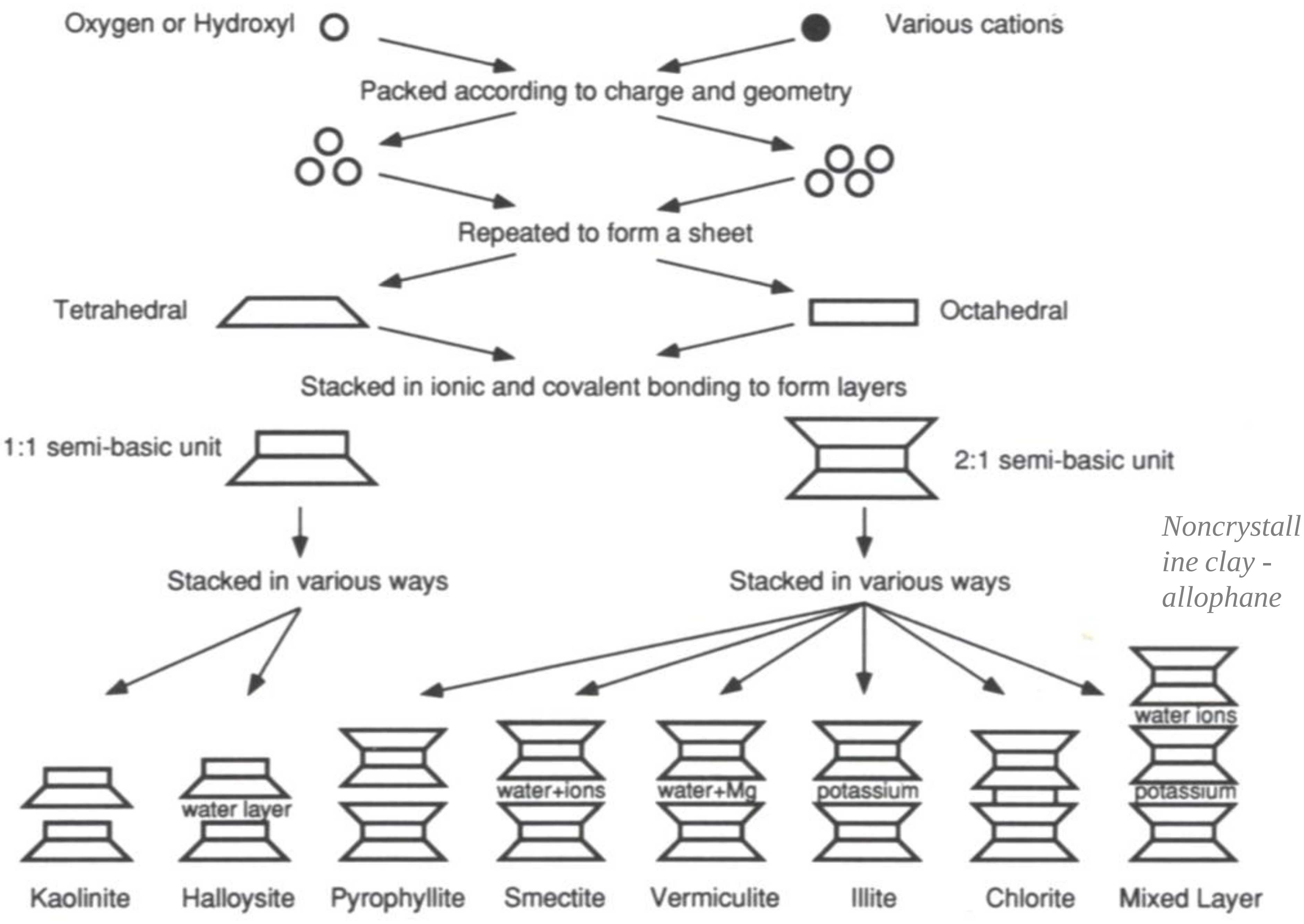


Mitchell, 1993

- The octahedral sheet is **brucite.**
- The basal spacing is from 10 Å to 14 Å.
- It contains exchangeable cations such as Ca^{2+} and Mg^{2+} and **two layers of water within interlayers.**
- **It can be an excellent insulation material after dehydrated.**

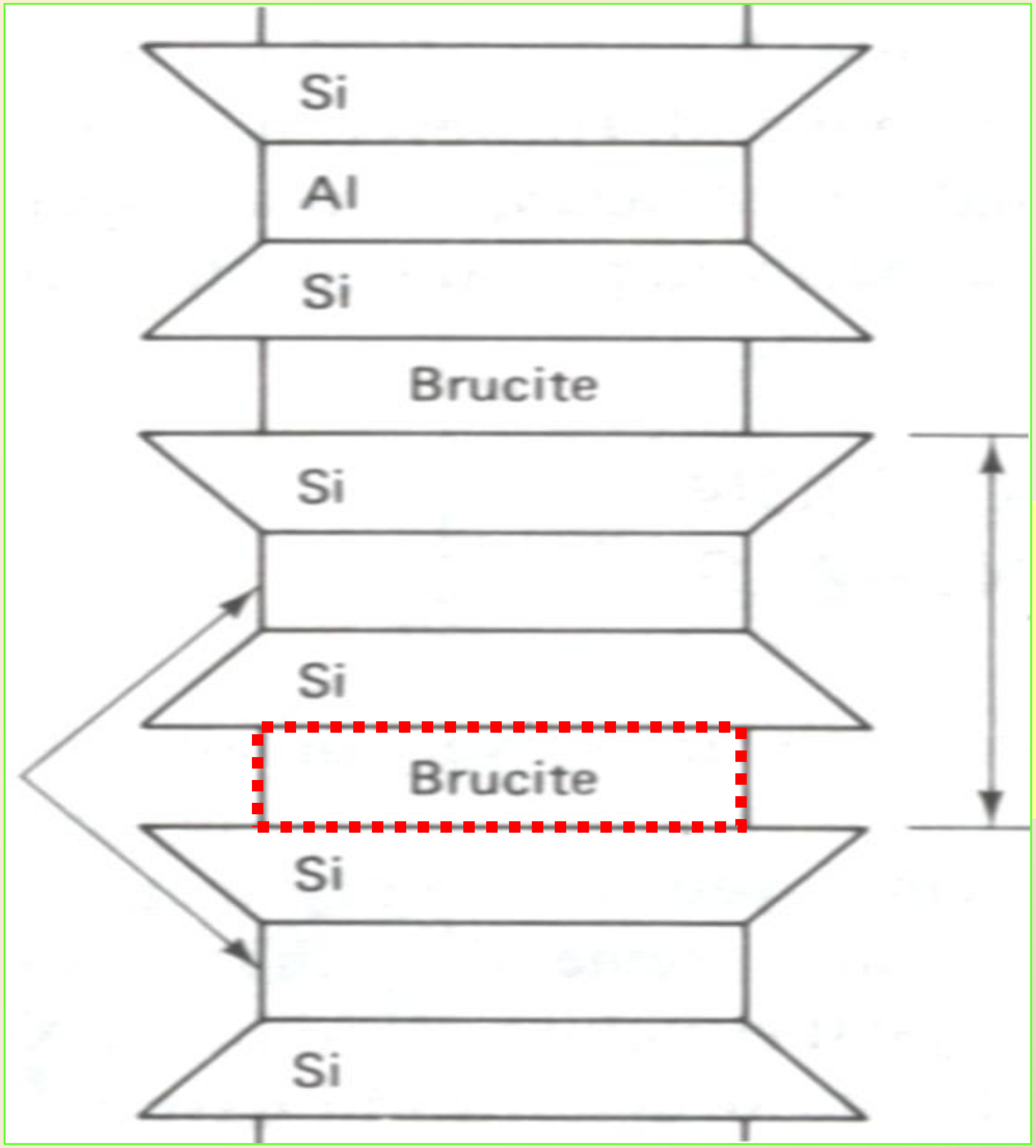
1.4 Synthesis

Mitchell, 1993



Noncrystalline clay - allophane

Minerals-Chlorite



Gibbsite

or

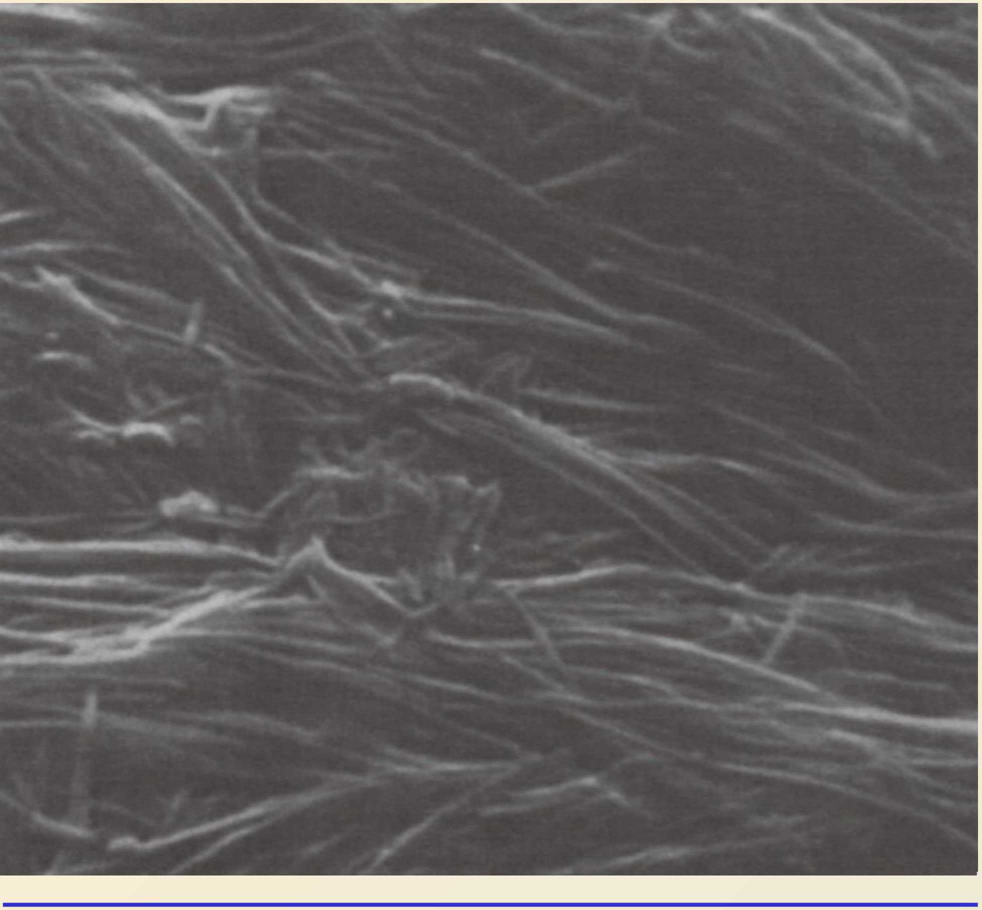
brucite

The basal spacing

is fixed at 14 Å.

Chain Structure Clay Minerals

Attapulgite



(Mitchell, 1993)

- They have lathlike or **threadlike morphologies**. chain structure (no sheets); **needle-like appearance**
- The particle diameters are from 50 to 100 Å and the length is up to 4 to 5 μm.
- **Attapulgite is useful as a *drilling mud in saline environment due to its high stability*.**

Mixed Layer Clays

- Different types of clay minerals have similar structures (*tetrahedral and octahedral sheets*) so that interstratification of layers of different clay minerals can be observed.

- In general, the mixed layer clays are composed of ***interstratification of*** **expanded water-bearing layers** and **non-water-bearing layers.** **Montmorillonite-illite** is most common, and **chlorite-vermiculite** and **chlorite-montmorillonite** are often found.

(Mitchell, 1993)

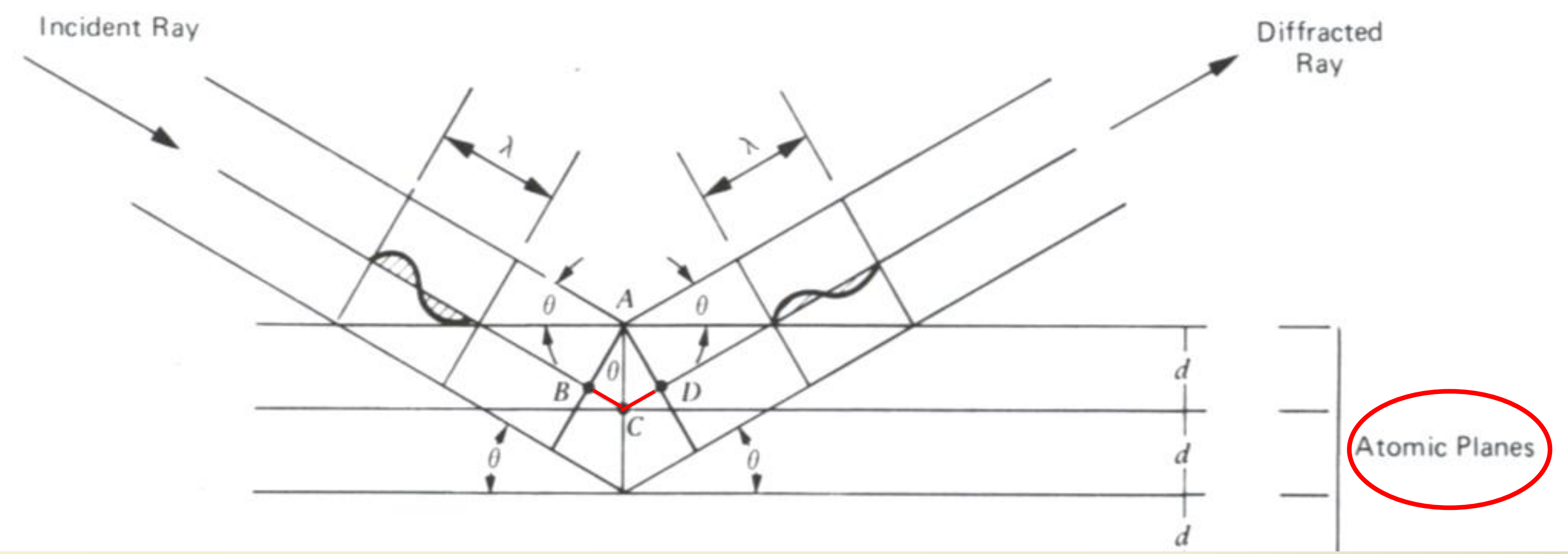
Noncrystalline Clay Materials

Allophane

Allophane is X-ray amorphous (Formless) and has no definite composition or shape. It is composed of hollow, irregular spherical particles with diameters of 3.5 to 5.0 nm.

2. Identification of Clay Minerals

2.1 X-ray diffraction



Mitchell, 1993

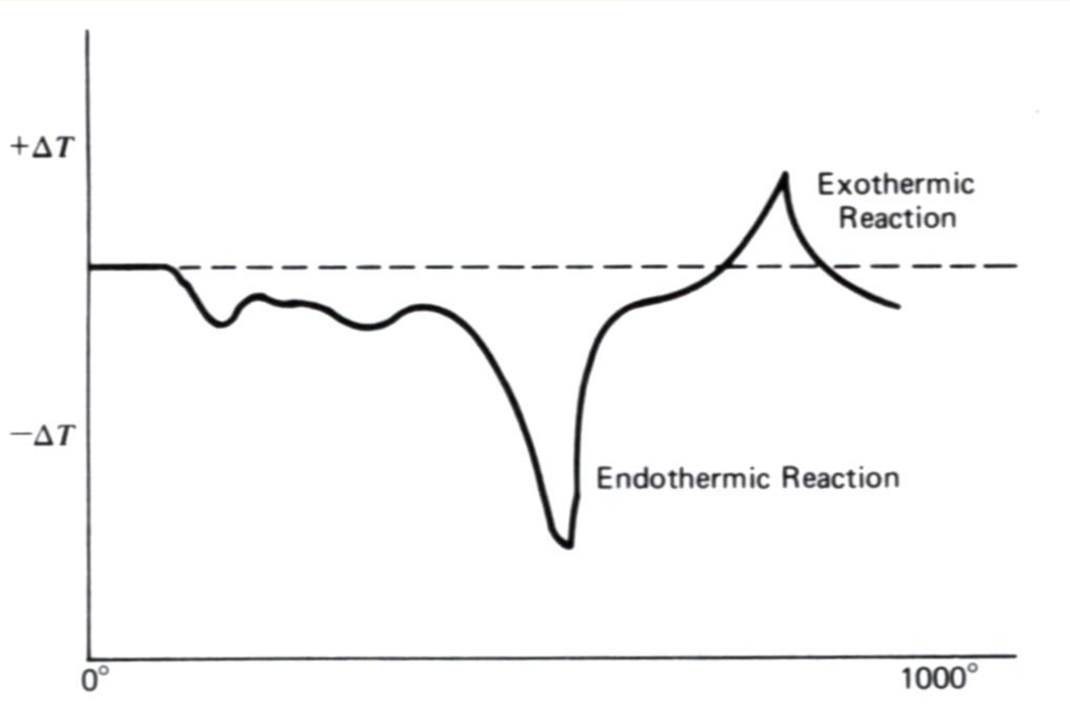
- The distance of atomic planes ***d*** can be determined based on the Bragg's equation.

  $BC+CD = n\lambda$, $n\lambda = 2d\cdot\sin\theta$, $d = n\lambda/2 \sin\theta$

  where n is an integer and λ is the wavelength.

- **Different clay minerals have various basal spacing** (atomic planes). For example, the basing spacing of kaolinite is 7.2 Å.

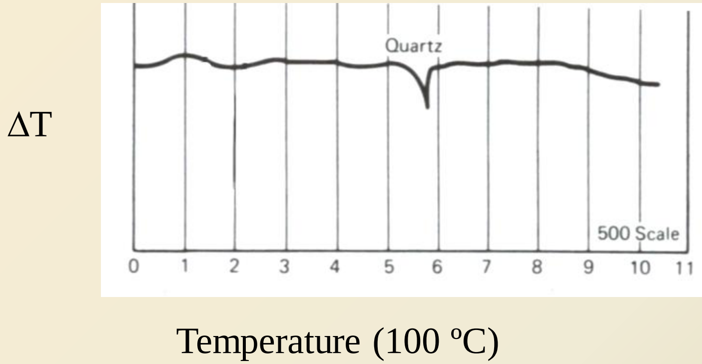
2.2 Differential Thermal Analysis (DTA)



- Differential thermal analysis (DTA) consists of simultaneously heating a test sample and a **thermally inert** substance at constant rate (usually about 10 ºC/min) to **over 1000 ºC** and continuously measuring differences in temperature and the inert material ΔT.

For example:

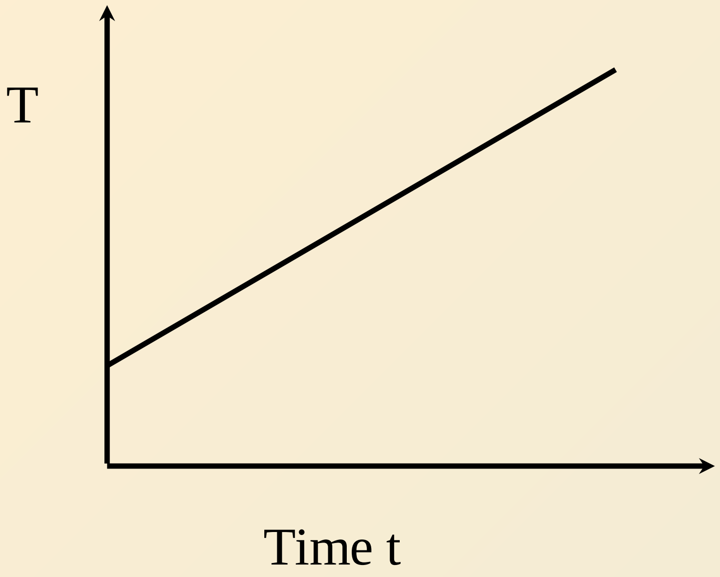
Quartz changes from the α to β form at 573 ºC and an endothermic peak can be observed.



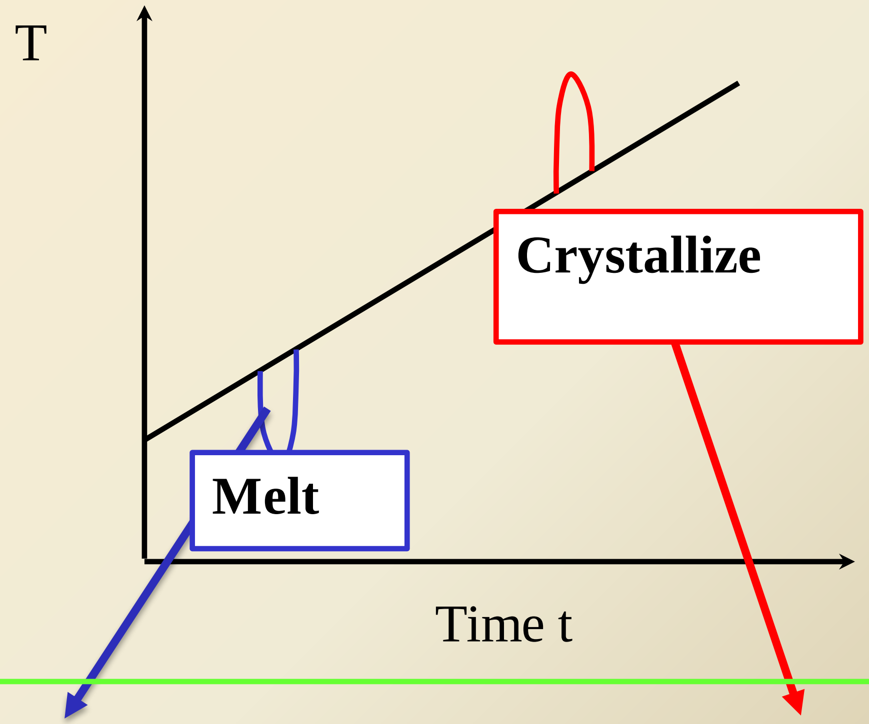
- **Endothermic** (take up heat) or **exothermic** (liberate heat) reactions can take place at different heating temperatures. **The mineral types can be characterized based on those signatures shown in the left figure.**

(from Mitchell, 1993)

If the sample is thermally inert,



If the phase transition of the sample occurs,



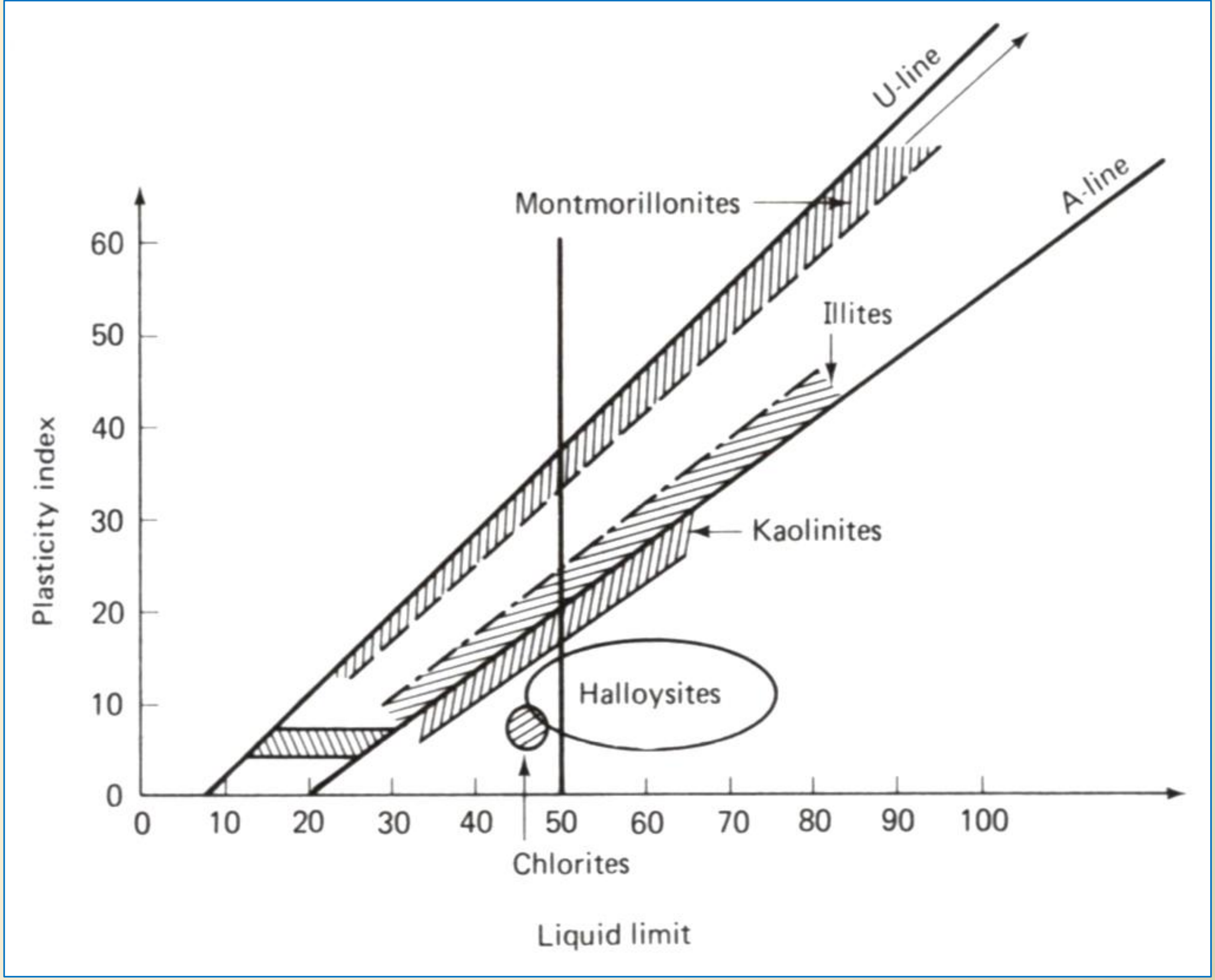
Endothermic reactions take up heat from surroundings and therefore the temperature T decreases.

Exothermic reactions liberate heat to surroundings and therefore the temperature T increases.

ΔT= the temperature of the sample – the temperature of the thermally inert substance.

2.3 Other Methods

i) Using Plasticity chart



ii) Scanning Electron Microscope

- common technique to see clay particles
- qualitative

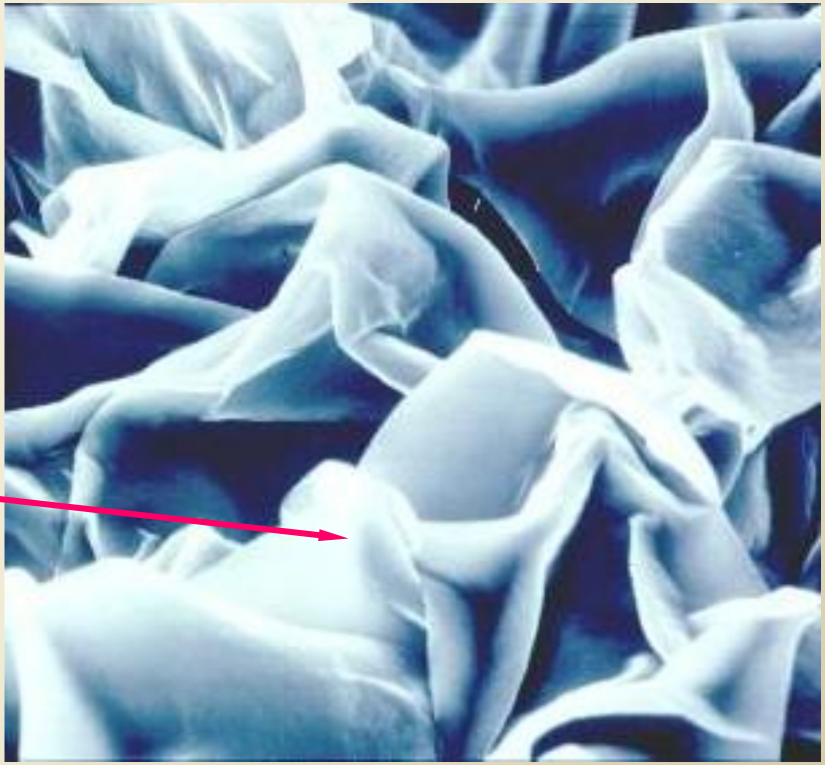


plate-like structure

iii) Specific Surface (S_s)

Definition:

$$Specific\ surface = surface / volume$$

$$Specific\ surface = surface / mass \longrightarrow \boxed{\text{Commonly used}}$$

$$\boxed{\frac{Surface\ related\ \ force}{Gravational\ \ force}}$$

Surface related forces:
van der Waals forces, capillary forces, etc.

Example:

$$1\times1\times1\,\text{cm cube},\ \rho = 2.65\text{g}/\text{cm}^3$$

$$S_s = \frac{6\cdot 1\text{cm}^2}{1\text{cm}^3\cdot 2.65\,\text{g}/\text{cm}^3} = 2.3\cdot 10^{-4}\cdot \text{m}^2/\text{g}$$

$$1\times1\times1\,\mu\text{m cube},\ \rho = 2.65\text{g}/\text{cm}^3$$

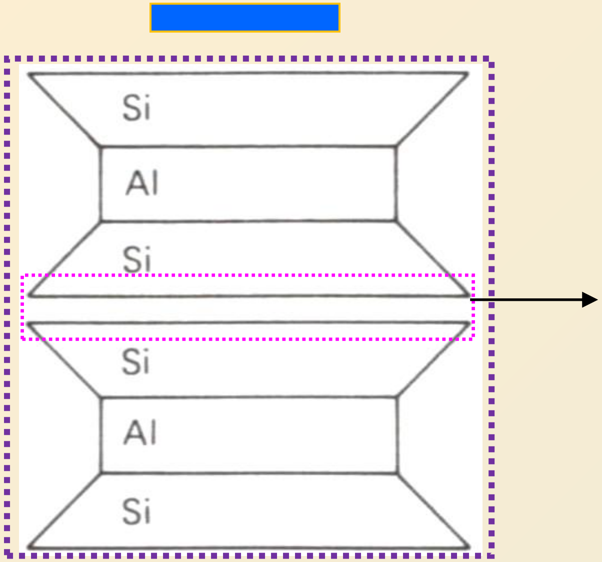
$$S_s = \frac{6\cdot 1\mu\text{m}^2}{1\mu\text{m}^3\cdot 2.65\,\text{g}/\text{cm}^3} = 2.3\cdot \text{m}^2/\text{g}$$

S_s is inversely proportional to the particle size

Note: smaller the grain, higher the specific surface

Typical Values

Montmorillonite



50-120 m^2/gm (external surface)

700-840 m^2/gm (including the interlayer surface)

Interlayer surface

Illite

65-100 m^2/gm

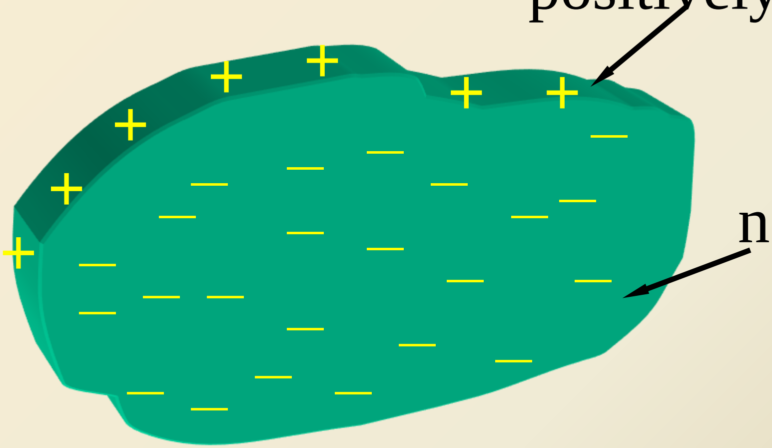
Kaolinite

10-20 m^2/gm

iv) Cation exchange capacity (cec)

(Isomorphous Substitution)

- substitution of Si^{4+} and Al^{3+} by other lower valence (Mg^{2+}) cations
- results in charge imbalance (net negative)



positively charged edges

negatively charged faces

Clay Particle with Net negative Charge

v) Potassium determination

Well-organized 10Å illite layers contain 9% ~ 10 % K_2O.

vi) Thermogravimetric analysis

It is based on changes in weight caused by loss of water or CO2 or gain in oxygen.

Sometimes, identification of clay minerals not only based on one method.

4. Interaction of Water

and

Clay Minerals

4.1 Origins of Charge Deficiencies

1. Imperfections in the crystal lattice -Isomorphous substitution.

- The cations in the octahedral or tetrahedral sheet can be replaced by different kinds of **cations** without change in crystal structure (similar physical size of cations).

  For example,

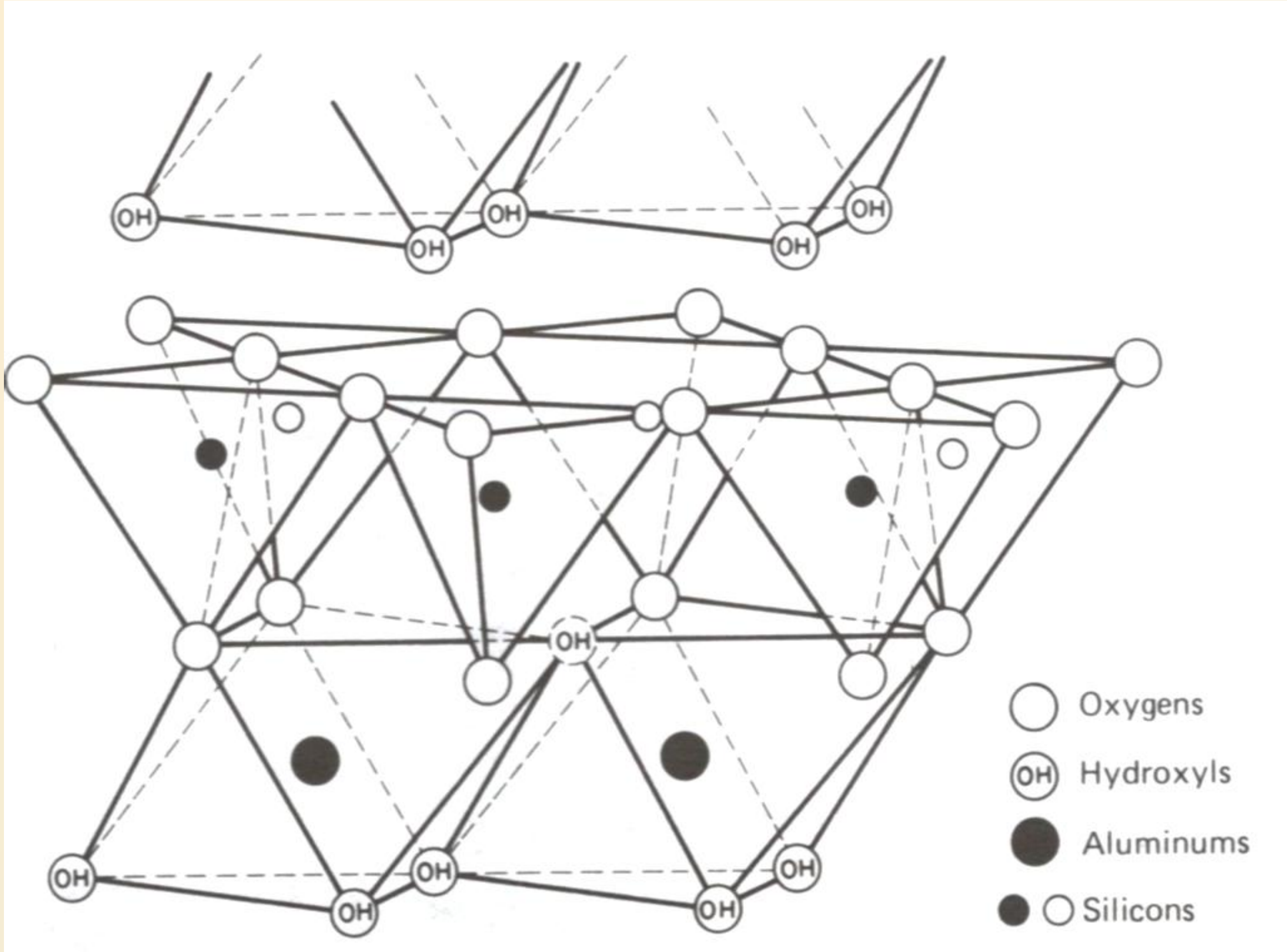
  Al^{3+} in place of Si^{4+} (Tetrahedral sheet)

  Mg^{2+} instead of Al^{3+}(Octahedral sheet)

⇒**unbalanced charges (charge deficiencies)**

- This is the main source of charge deficiencies for **montmorillonite.**
- Only minor isomorphous substitution takes place in kaolinite.

2. Imperfections in the crystal lattice-The broken edge

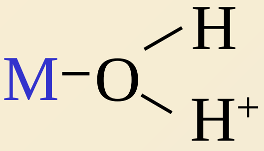


The broken edge can be positively or negatively charged.

3. Proton equilibriaum (pH-dependent charges)

$$M - OH + H^+ \leftrightarrow M - OH_2^+$$ Protonation

$$M - OH + OH^- \leftrightarrow M - O^- + H_2O$$ Deprotonation



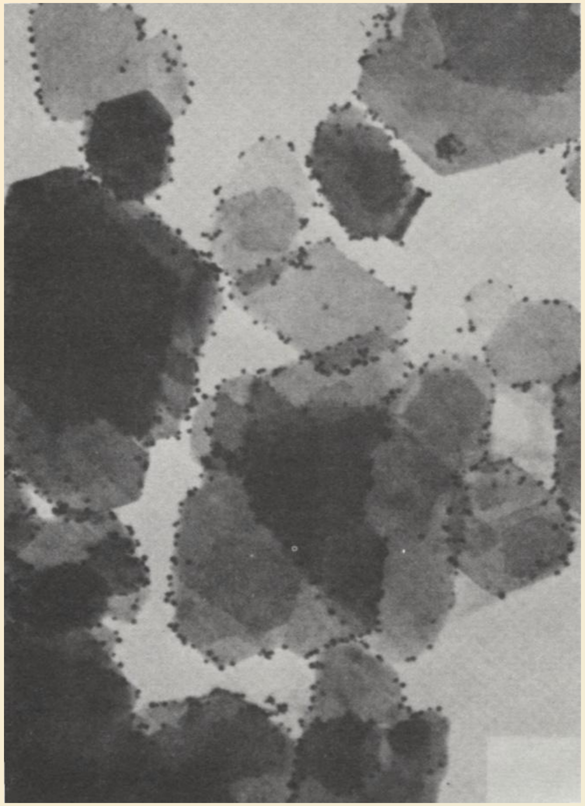
M: metal

$M-O-H$

$M-O^-$

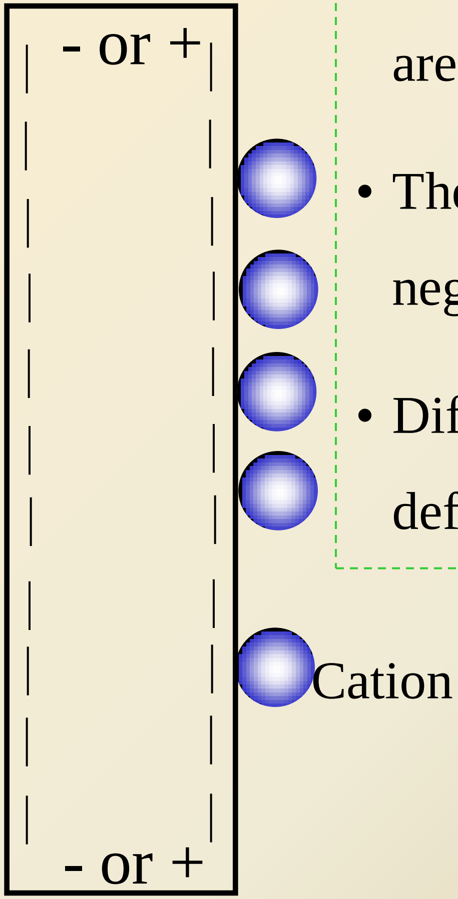
Kaolinite particles are positively charged on their edges when in a low pH environment, but negatively charged in a high pH (basic) environment.

4.2 “Charged” Clay Particles



Kaolinite and negative gold sol

(van Olphen, 1991)

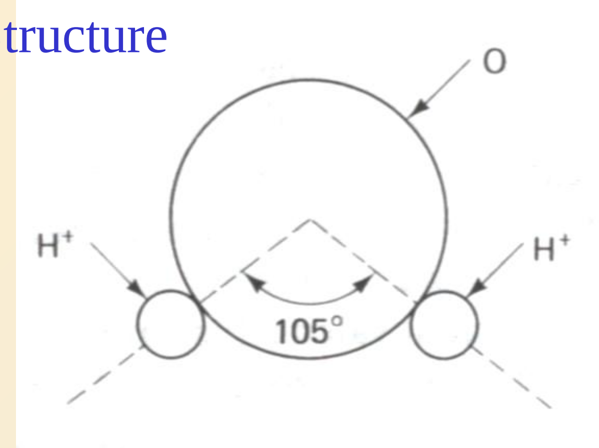


Dry condition

- **External or interlayer surfaces** are negatively charged in general.
- The edges can be positively or negatively charged.
- Different cations balance charge deficiencies.

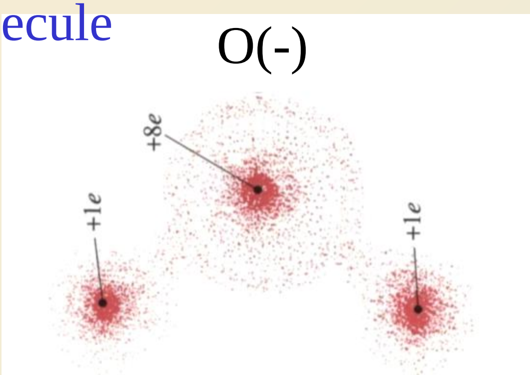
4.3 Polar Water Molecules

Structure



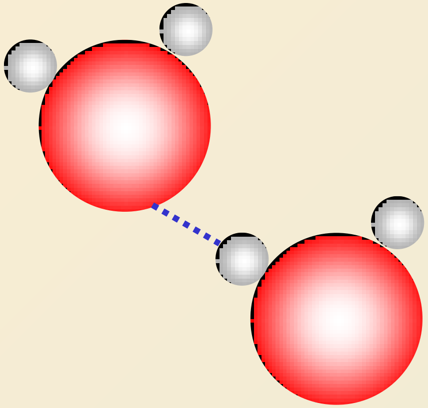
Polar molecule

O(-)

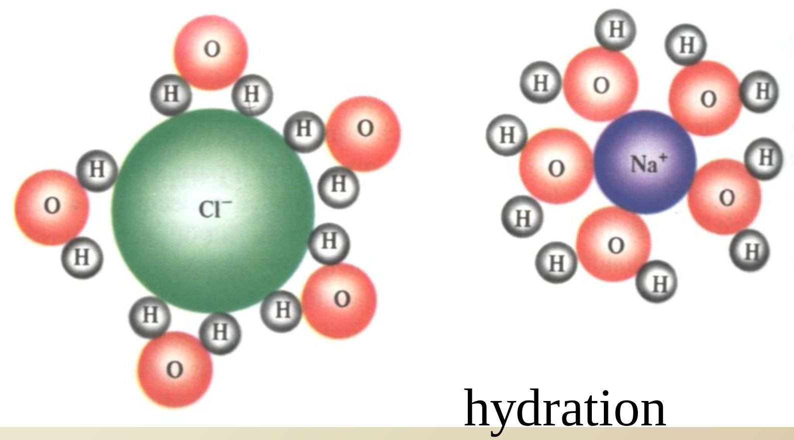


H(+) H(+)

Hydrogen bond



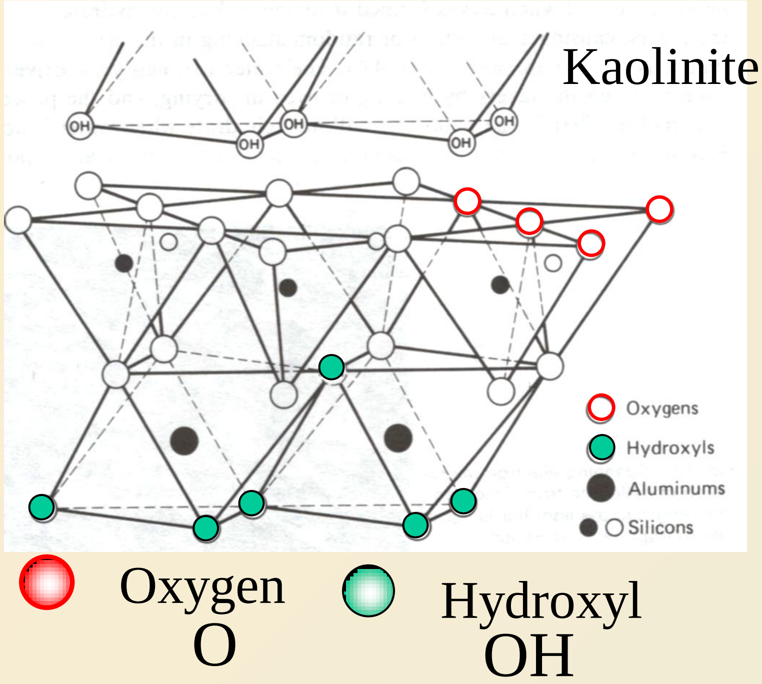
Salts in aqueous solution



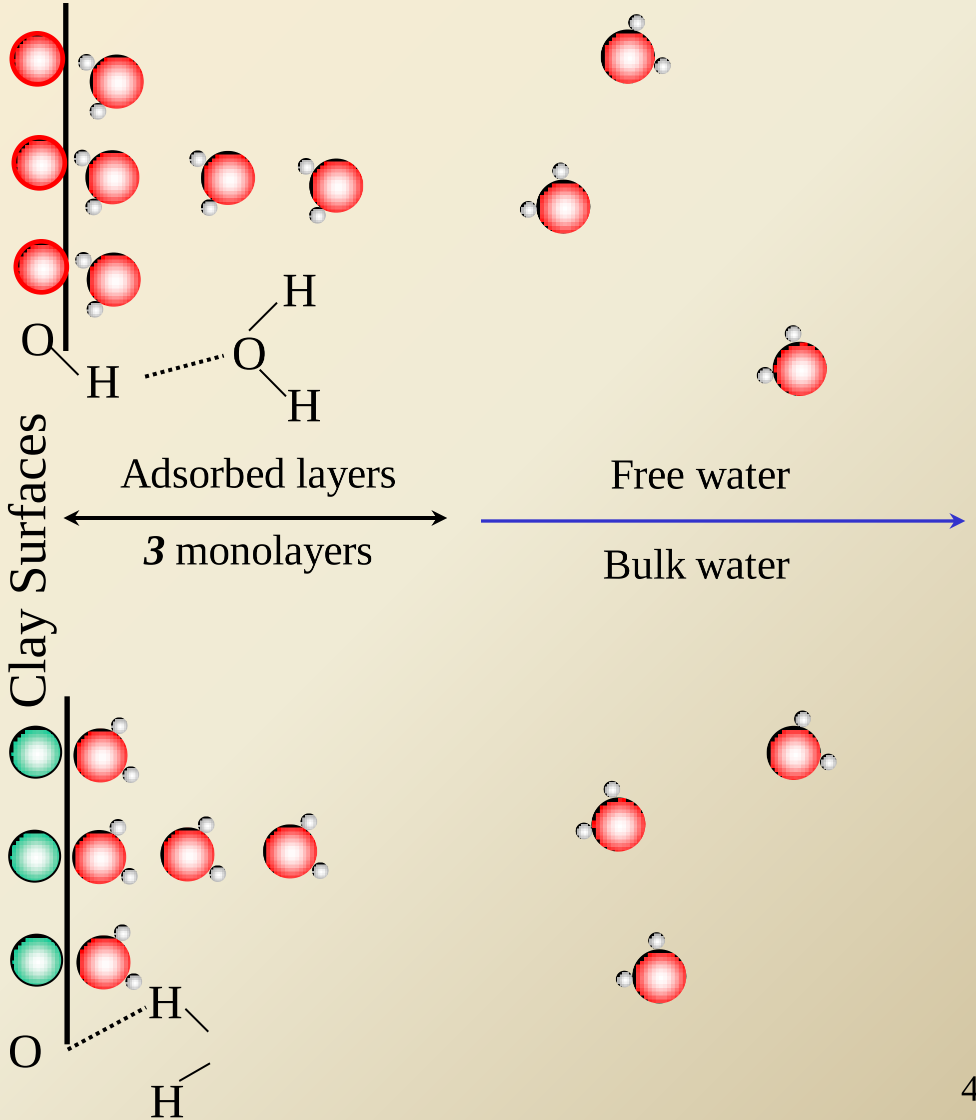
hydration

4.5 Clay-Water Interaction

1. Hydrogen bond



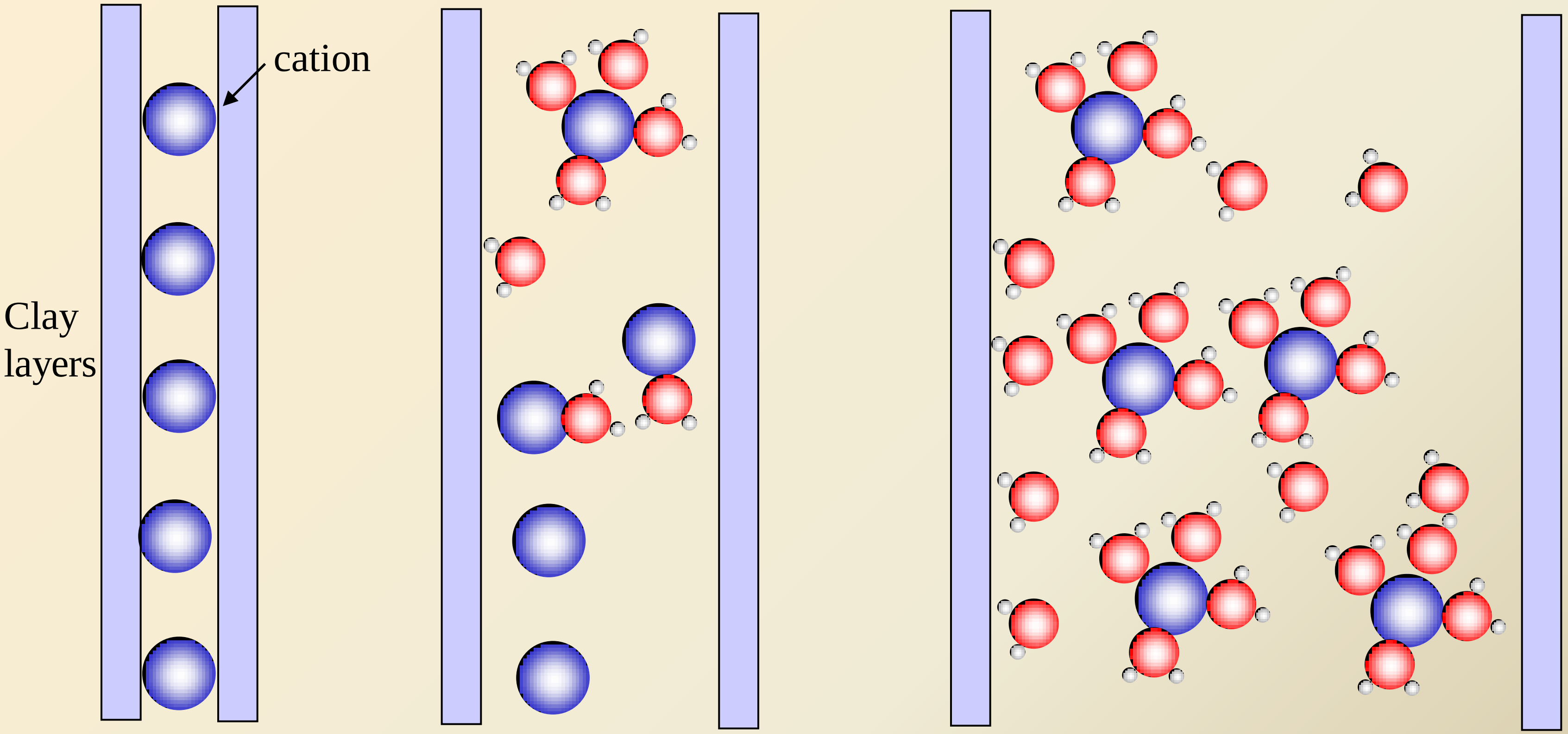
The water molecule “locked” in the adsorbed layers has different properties compared to that of the bulk water due to the strong attraction from the surface.



2. Ion hydration

Na^+ crystal radius: 0.095 nm

radius of hydrated ion: 0.358 nm



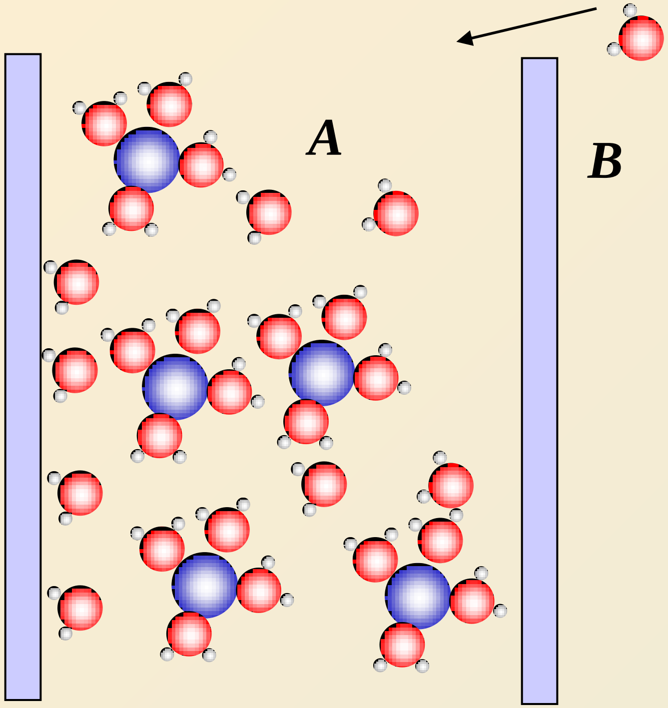
Dry condition

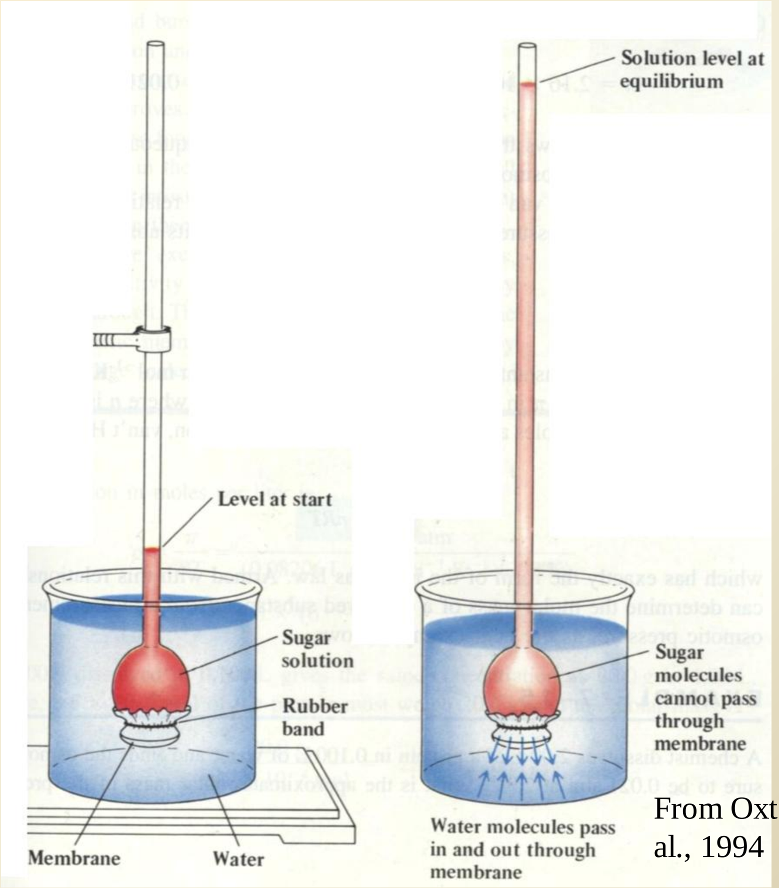
(Interlayer)

The water molecules wedge into the interlayer after adding water

The cations are fully hydrated, which results in repulsive forces and expanding clay layers (hydration energy).

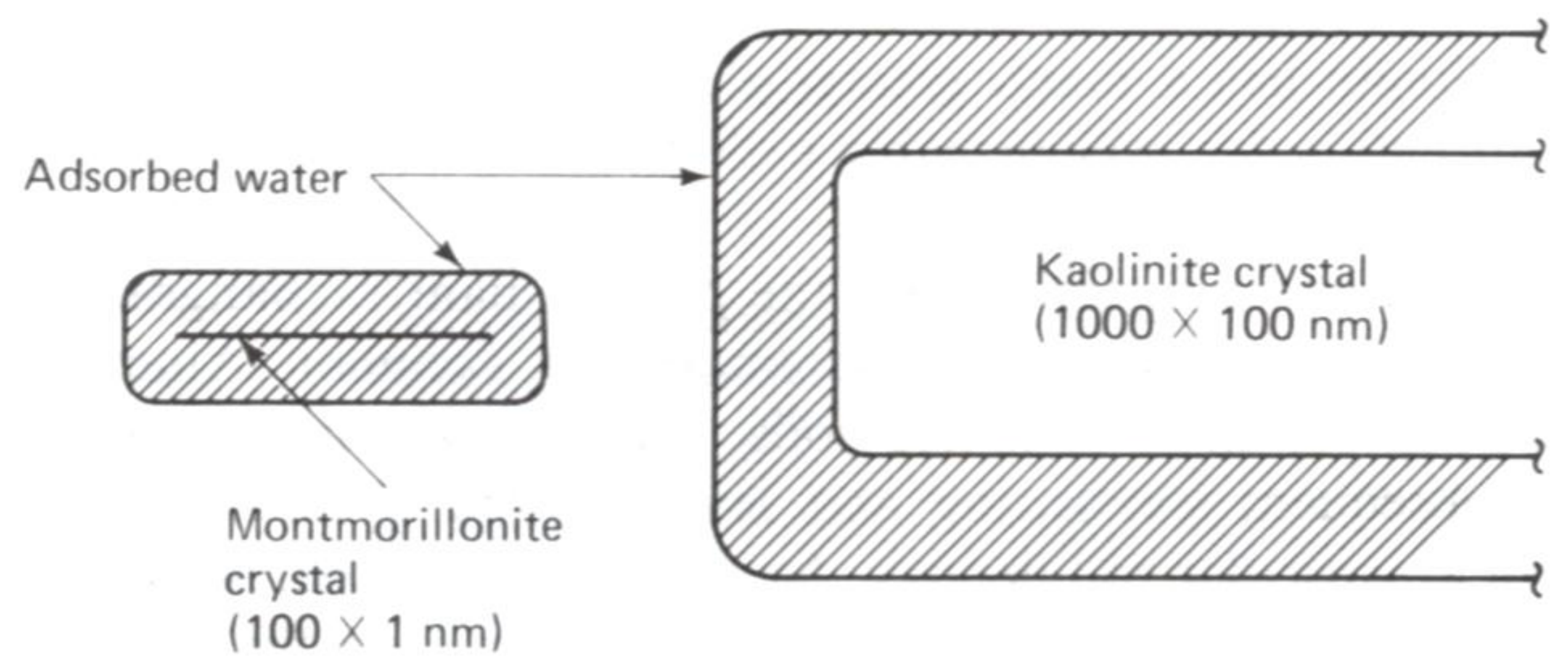
3. Osmotic pressure





From Oxtoby et al., 1994

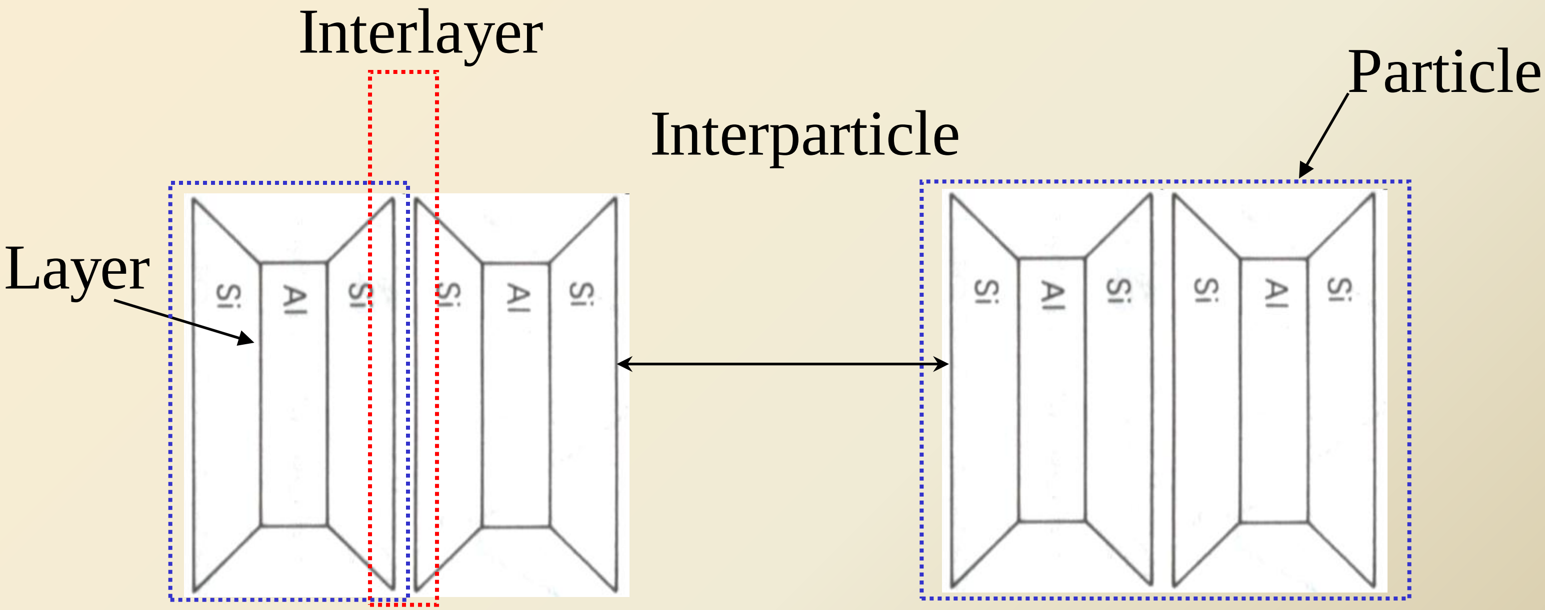
The concentration of cations is higher in the interlayers (A) compared with that in the solution (B) due to negatively charged surfaces. Because of this concentration difference, water molecules tend to diffuse toward the interlayer in an attempt to equalize concentration.



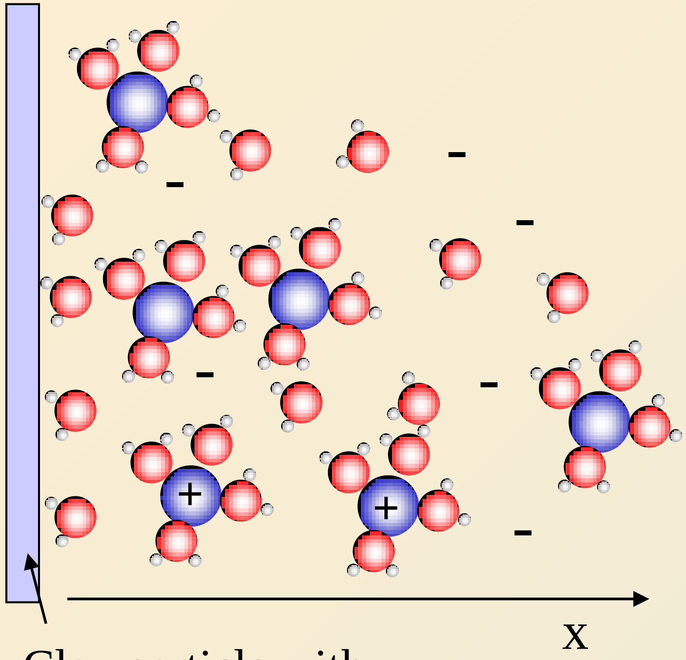
Relative sizes of adsorbed water layers on sodium montmorillonite and sodium kaolinite

Holtz and Kovacs, 1981

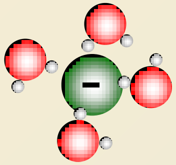
5. Interaction of Clay Particles (or Layers)

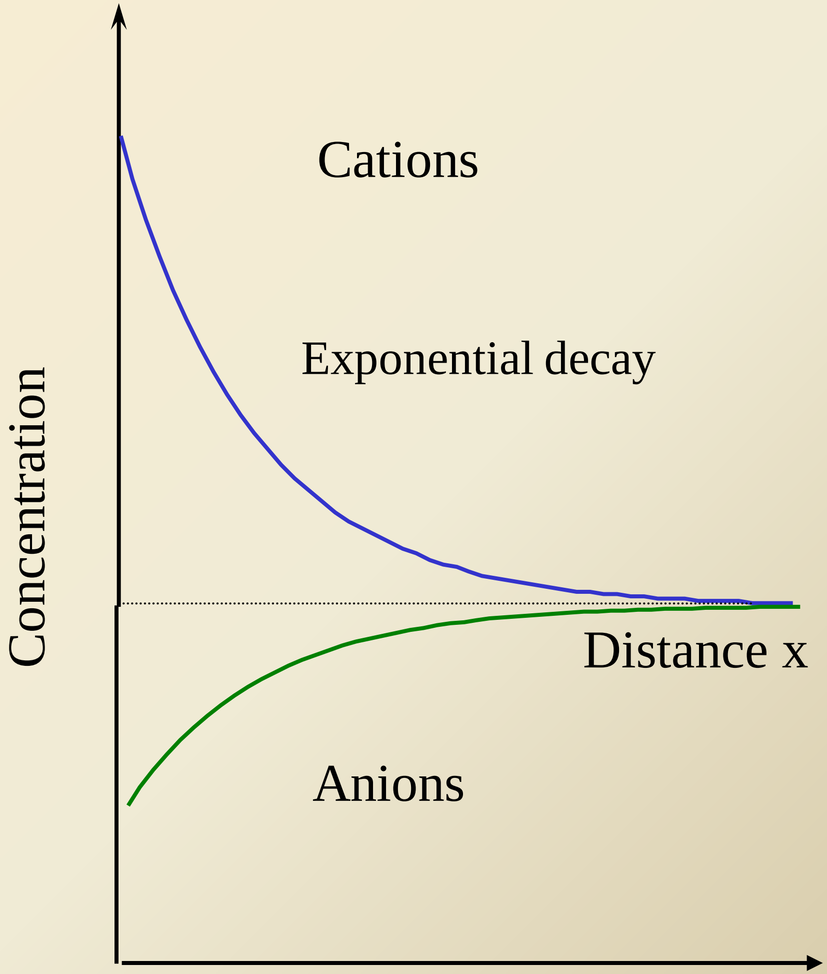


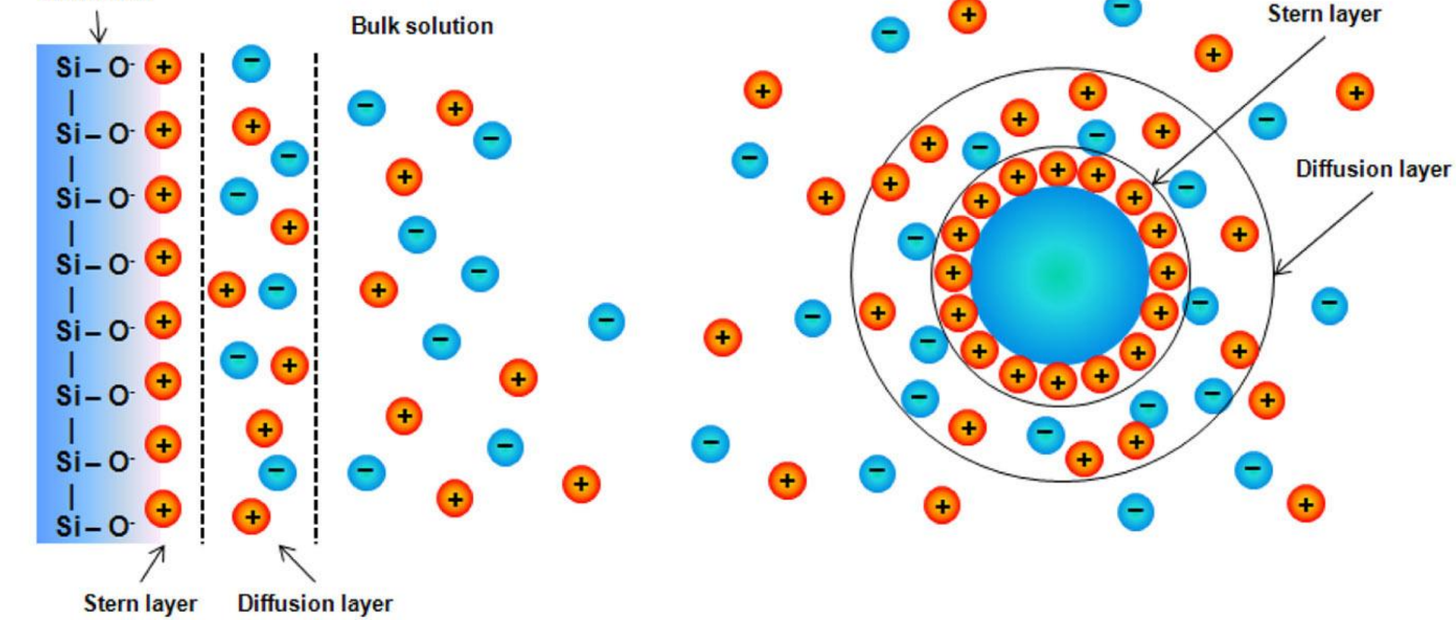
5.1 Diffuse Double Layer

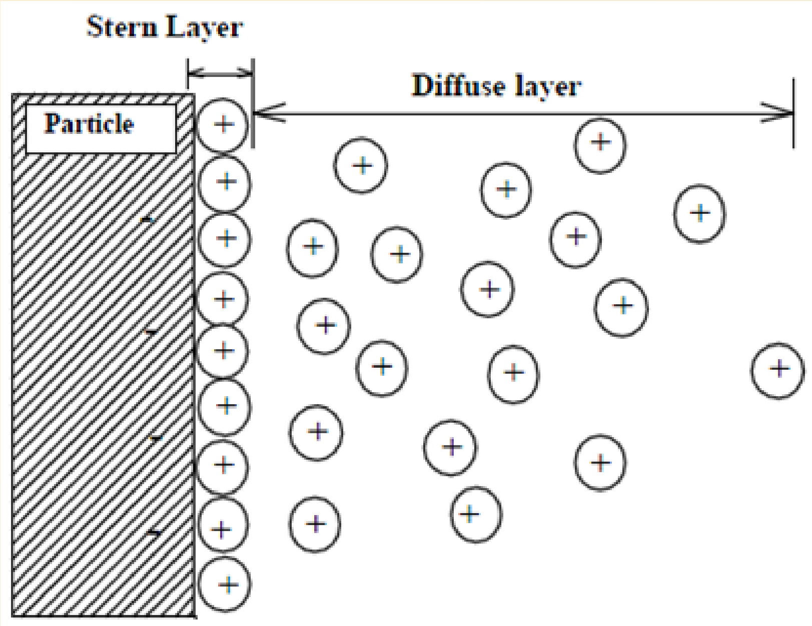


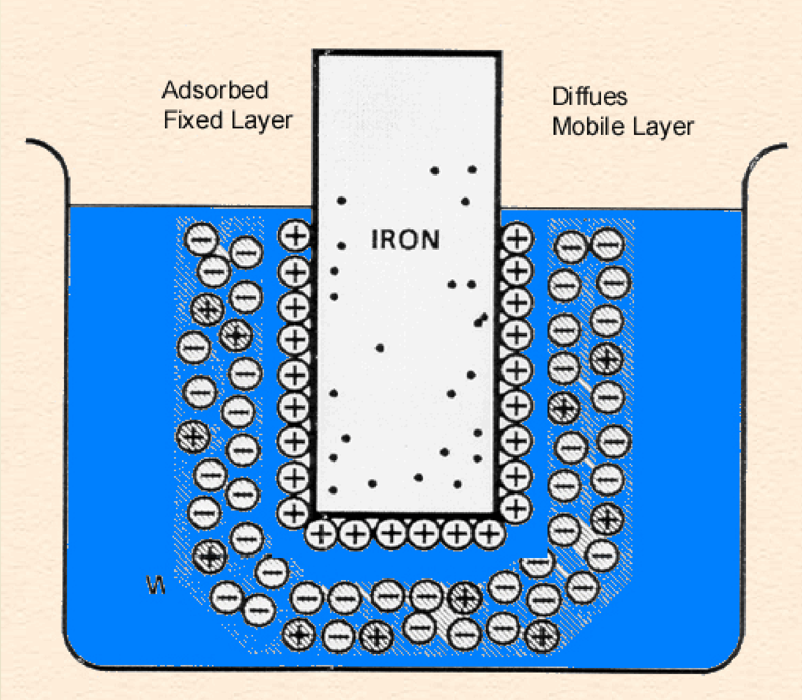
Clay particle with negatively charged surface

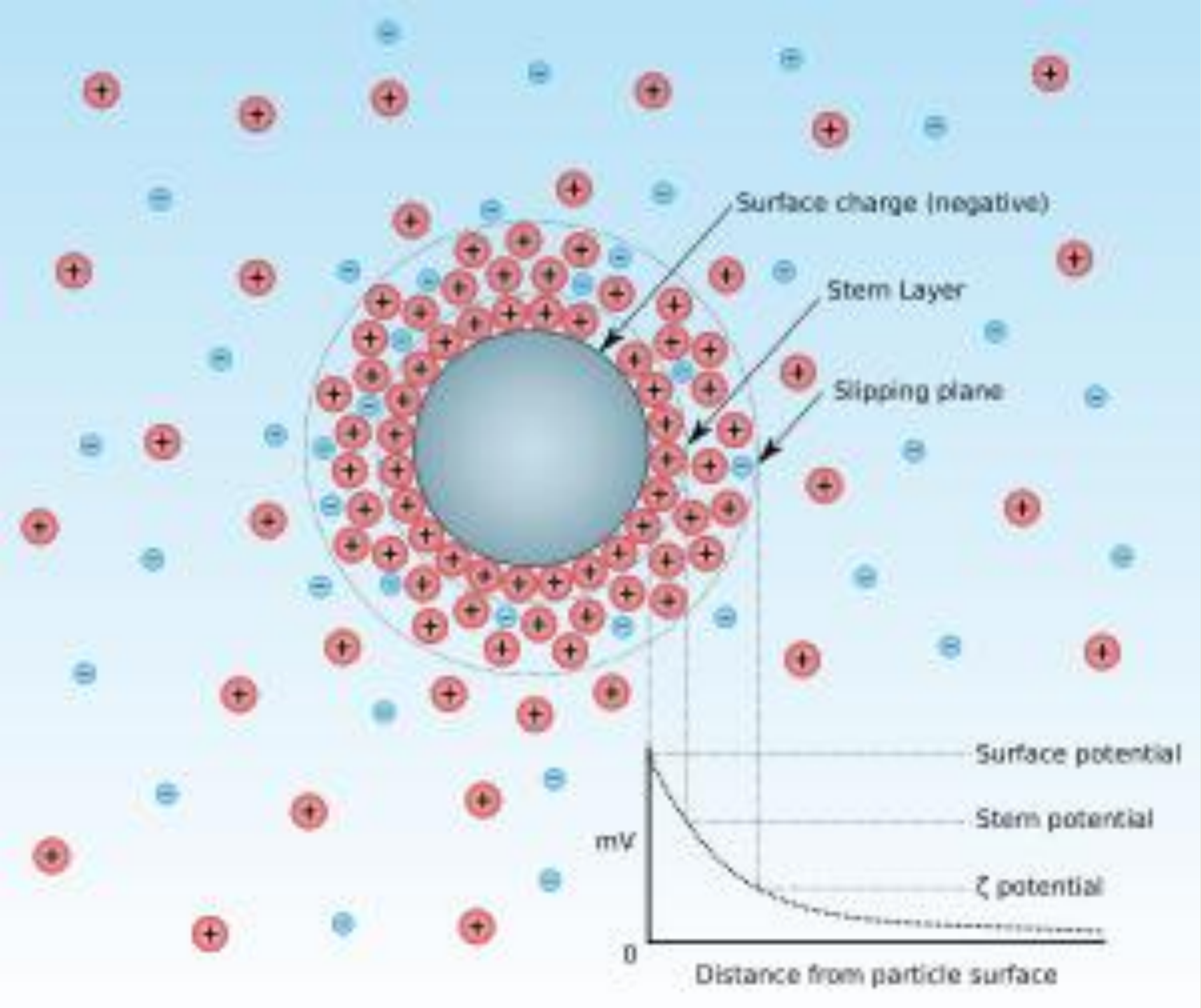




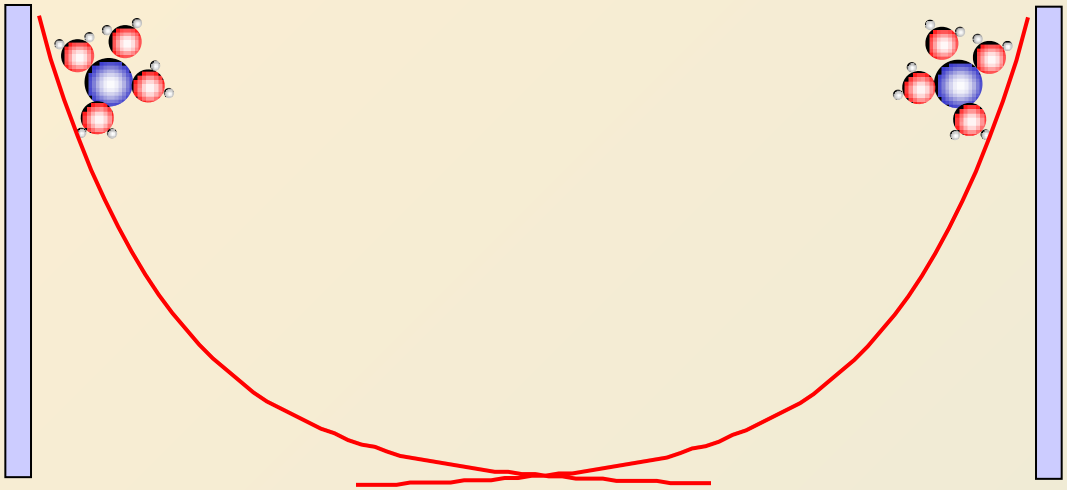

Bulk solution
Stern layer
Diffusion layer
Si – O⁻
Stern layer
Diffusion layer


Stern Layer
Diffuse layer
Particle


Adsorbed
Fixed Layer
Diffues
Mobile Layer
IRON


Surface charge (negative)
Stern Layer
Slipping plane
Surface potential
Stern potential
mV
ζ potential
0
Distance from particle surface

5.2 Interaction Forces



Net force between clay particles (**or interlayers**)

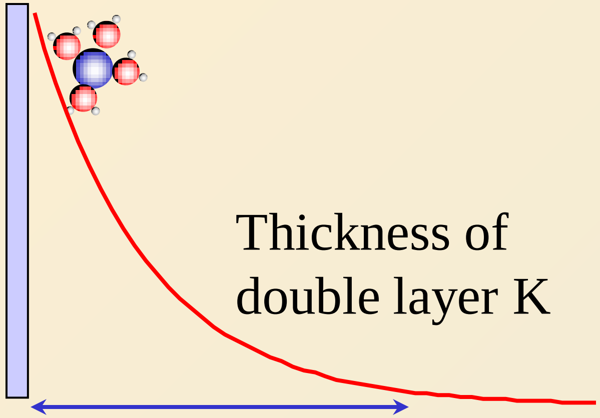
DLVO forces

= van der Waals attraction +

Double layer repulsion (overlapping of the double layer)+

Coulombian attraction (between the positive edge and negative face)

5.3 Thickness of Double Layer



Thickness of
double layer K

$$K = \left(\frac{\varepsilon_0 \kappa \cdot kT}{2 n_0 e^2 \nu^2} \right)^{1/2}$$

ε_0 : Permittivity in vacuum

κ : Relative permittivity

k : Boltzman constant

T : Temperature

n_0: Cation concentration

e : Electron charge

ν : Valence

K ↑ repulsion force ↑

---

n_0↑ K ↓ repulsion force ↓

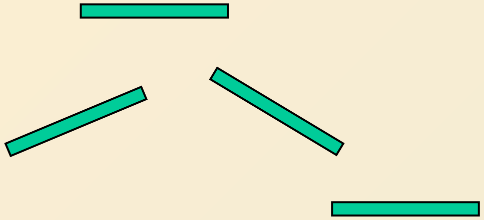
v ↑ K ↓ repulsion force ↓

T ↑ K ↑ repulsion force ↑(?)

κ decreases with increasing temperature

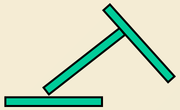
5.4 Interaction of Clay Particles

Dispersed fabric

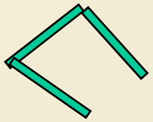


The net interparticle force between surfaces is repulsive

Flocculated fabric

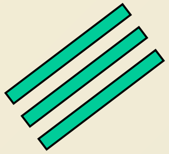


Edge-to-face (EF): positively charged edges and negatively charged surfaces (more common)

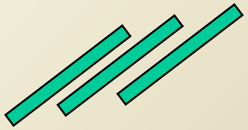


Edge-to-edge (EE)

Aggregated fabric

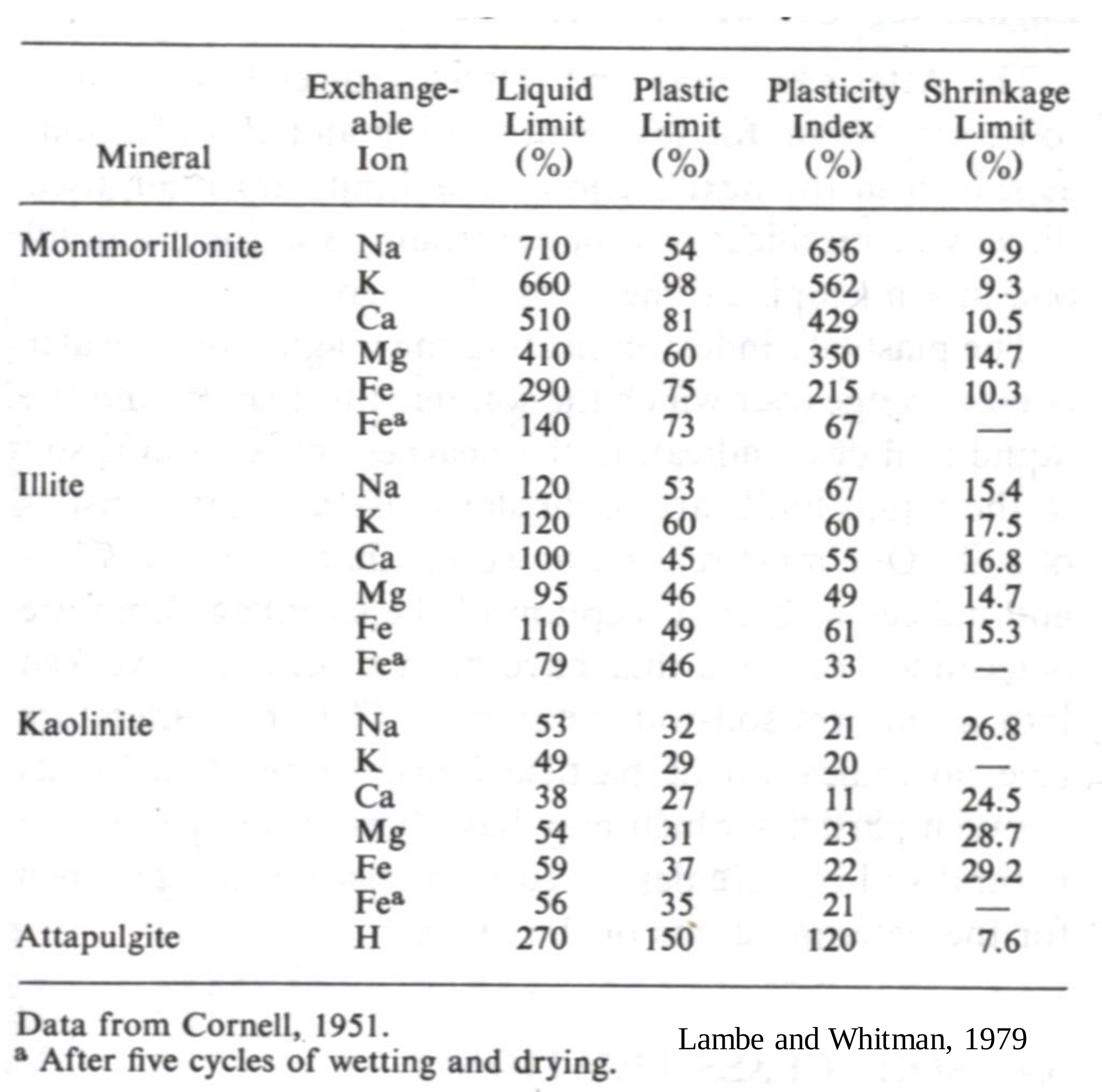


Face-to-Face (FF)



Shifted FF

5.5 Atterberg Limit of Clay Minerals



Mineral	Exchangeable Ion	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Shrinkage Limit (%)
Montmorillonite	Na	710	54	656	9.9
	K	660	98	562	9.3
	Ca	510	81	429	10.5
	Mg	410	60	350	14.7
	Fe	290	75	215	10.3
	Fe[a]	140	73	67	—
Illite	Na	120	53	67	15.4
	K	120	60	60	17.5
	Ca	100	45	55	16.8
	Mg	95	46	49	14.7
	Fe	110	49	61	15.3
	Fe[a]	79	46	33	—
Kaolinite	Na	53	32	21	26.8
	K	49	29	20	—
	Ca	38	27	11	24.5
	Mg	54	31	23	28.7
	Fe	59	37	22	29.2
	Fe[a]	56	35	21	—
Attapulgite	H	270	150	120	7.6

Data from Cornell, 1951.

[a] After five cycles of wetting and drying.

Lambe and Whitman, 1979

Na-montmorillonite

- Thicker double layer
- LL=710

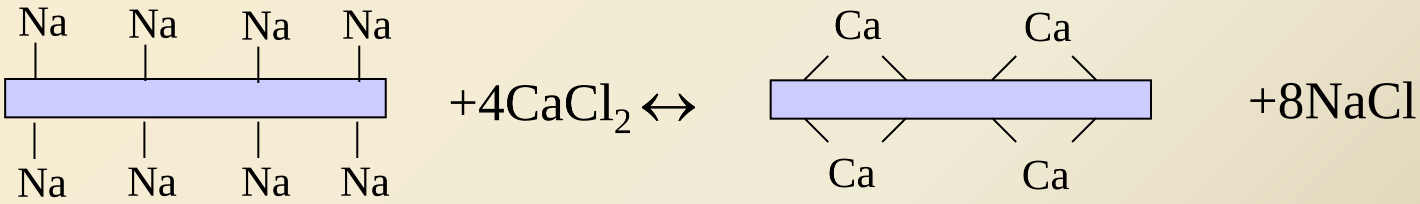
Ca-montmorillonite

- Thinner double layer
- LL=510

The thickness of double layer increases with decreasing cation valence.

5.6 Cation Replaceability

- Different types and quantities of cations are adsorbed to balance charge deficiencies in clay particles.
- The types of adsorbed cations depend on the depositional environment. For example, sodium and magnesium are dominant cations in marine clays since they are common in sea water. In general, calcium and magnesium are the predominant cations.
- The adsorbed cations are exchangeable (replaceable). For example,



(Lambe and Whitman, 1979)

5.6 Cation Replaceability (Cont.)

The ease of cation replacement depends on the

(1) Valence (primarily)

- Higher valence cations can replace cations of lower valence.

(2) Ion size

- Cations with larger non-hydrated radii or smaller hydrated radii have greater replacement power.

According to rules (1) and (2), the general order of replacement is

$Li^+ < Na^+ < K^+ < Rb^+ < Cs^+ < Mg^{2+} < Ca^{2+} < Ba^{2+} < Cu^{2+} < Al^{3+} < Fe^{3+} < Th^{4+}$

(3) Relative amount

- High concentration of Na+ can displace Al^{3+}.

Cations	**Non-hydrated radius (Å)**	**Hydrated radius (Å)**
Li^+	0.68	3.8
Na^+	0.95	3.6
K^+	1.33	3.3
Cs^+	1.69	3.3
Be^{2+}	0.31	4.6
Mg^{2+}	0.65	4.3
Ca^{2+}	0.99	4.1
Ba^{2+}	1.35	
Al^{3+}	0.5	4.8
Fe^{3+}	0.6	

(Data compiled from Israelachvili, 1991)

5.7 Cation Replaceability (Cont.)

- **Hard water softener**

Hard water contains soluble calcium and magnesium salts such as $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$. The hardness can be removed by exchanging Ca^{2+} and Mg^{2+} with sodium ions Na^+. For example,

$Na_2Z_{(s)}$ (Zeolite) $+ Ca^{2+}{}_{(aq)} \leftrightarrow CaZ_{(s)} + 2\ Na^+{}_{(aq)}$

As the ion-exchange capacity of Zeolite is saturated, the capacity can be regained by passing through a concentrated solution of NaCl.

5.7 Cation Exchange Capacity (cec)

- The quantity of exchangeable cations is termed the cation exchangeable capacity (cec) and is usually expressed as milliequivalents (meq) per 100 gram of dry clay (from Mitchell, 1993).

- One equivalent = 6.02×10^{23} electron charges or 96500 Coulombs, which is 1 Faraday.

5.8 Swelling Potential

Practically speaking, the three ingredients generally necessary for potentially damaging swelling to occur are (1) presence of montmorillonite in the soil, (2) the natural water content must be around the PL, and (3) there must be a source of water for the potentially swelling clay (Gromko, 1974, from Holtz and Kovacs, 1981)

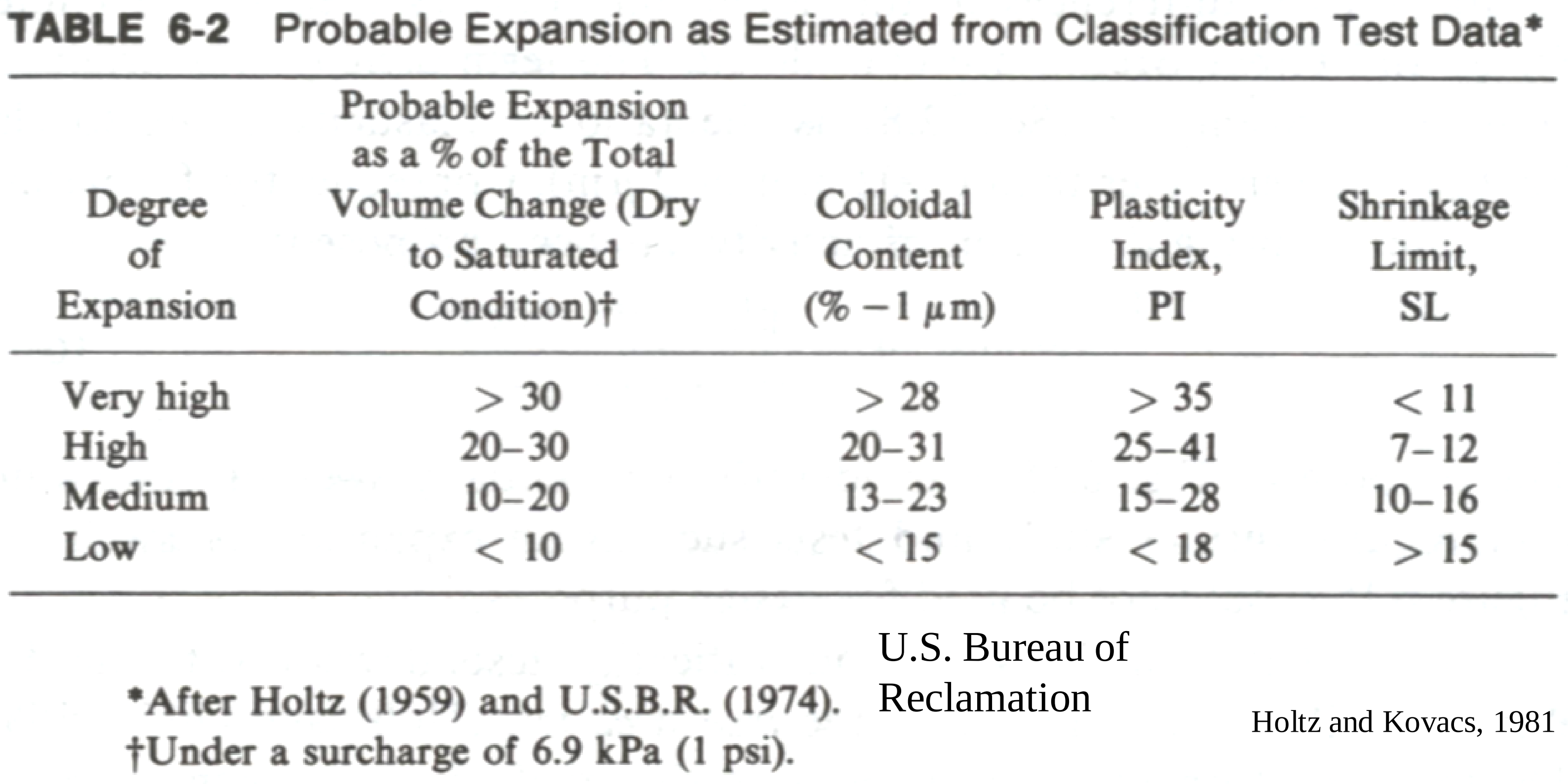


TABLE 6-2 Probable Expansion as Estimated from Classification Test Data*

Degree of Expansion	Probable Expansion as a % of the Total Volume Change (Dry to Saturated Condition)†	Colloidal Content (% −1 μm)	Plasticity Index, PI	Shrinkage Limit, SL
Very high	> 30	> 28	> 35	< 11
High	20–30	20–31	25–41	7–12
Medium	10–20	13–23	15–28	10–16
Low	< 10	< 15	< 18	> 15

*After Holtz (1959) and U.S.B.R. (1974).
†Under a surcharge of 6.9 kPa (1 psi).

U.S. Bureau of Reclamation

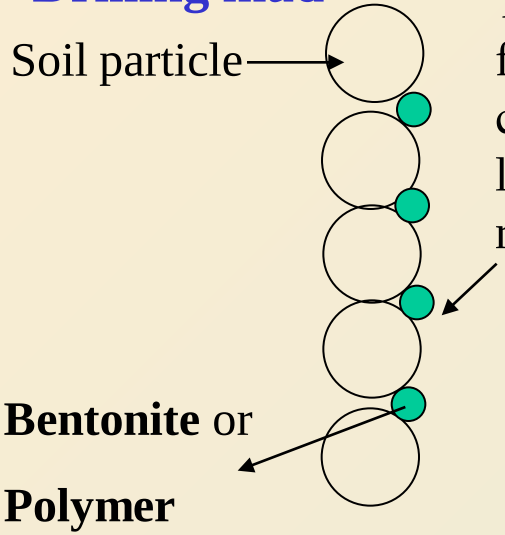
Holtz and Kovacs, 1981

5.9 Engineering Applications

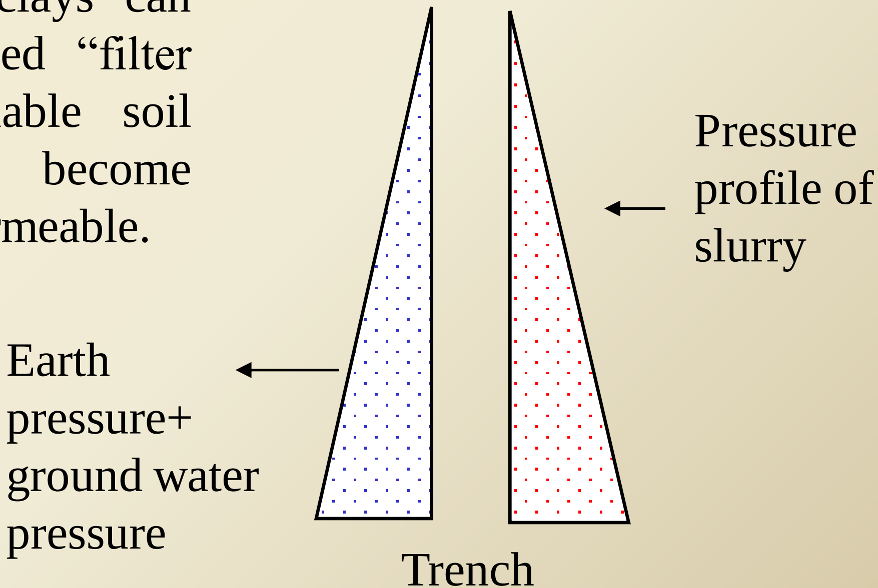
Lime treatment for the swelling clay

- The swelling clay such as Na-montmorillonite beneath the foundation is potentially harmful to the light structure. Adding lime (CaO) into such soil can effectively reduce the swelling potential due to Ca^{2+} displacing Na^{+}, and can increase the strength by dehydration of soils and cementation.

Drilling mud



The swelling clays can form a so-called “filter cake” and enable soil layers to become relatively impermeable.



Montmorillonite is the dominant clay mineral in bentonite

Xanthakos, 1991

5.9 Engineering Applications (Cont.)

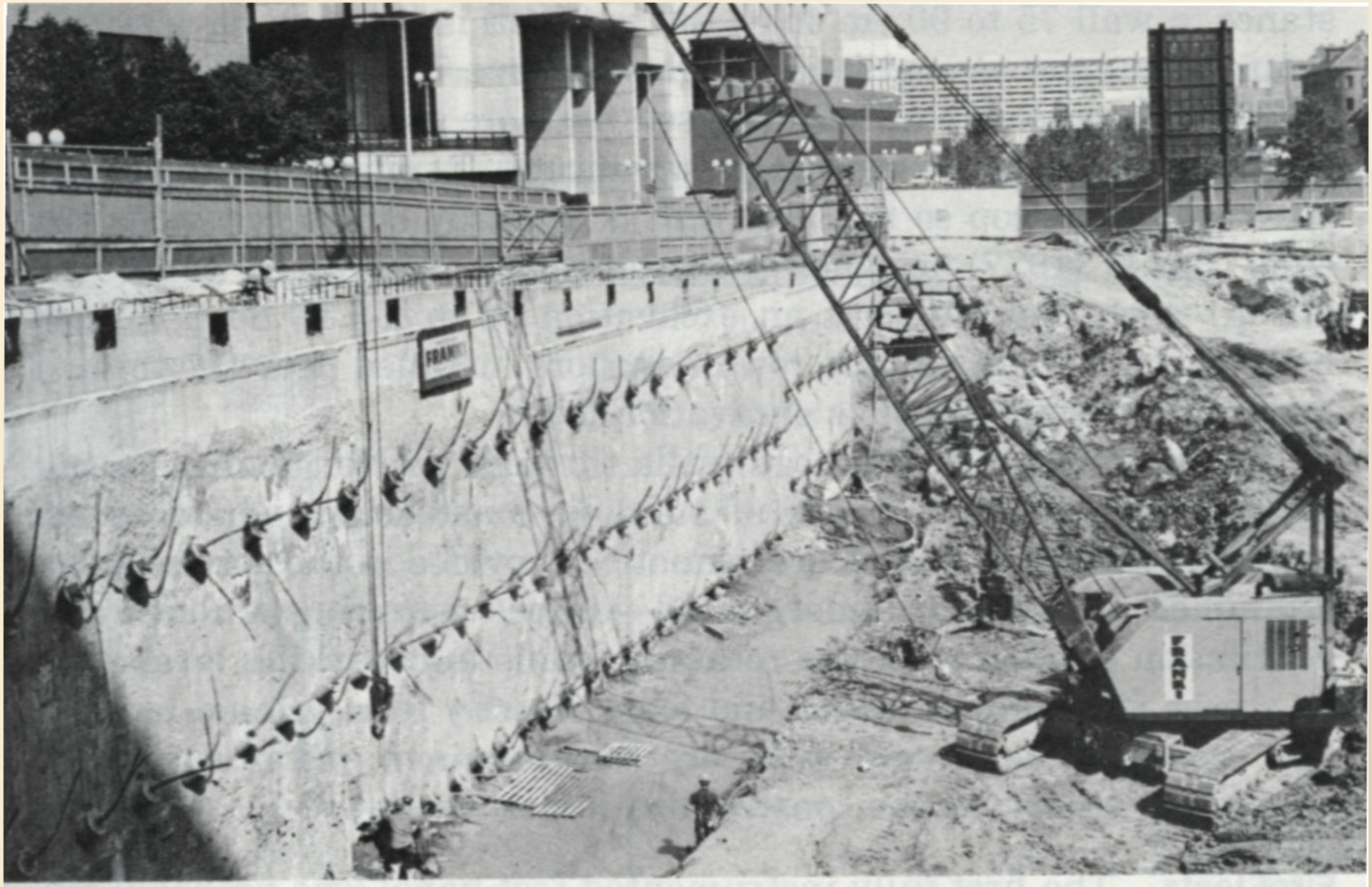


Figure 1-6 Diaphragm walls for the Sixty State Street Tower, Boston. (*Franki*.)

Xanthakos, 1991

5.9 Engineering Applications (Cont.)

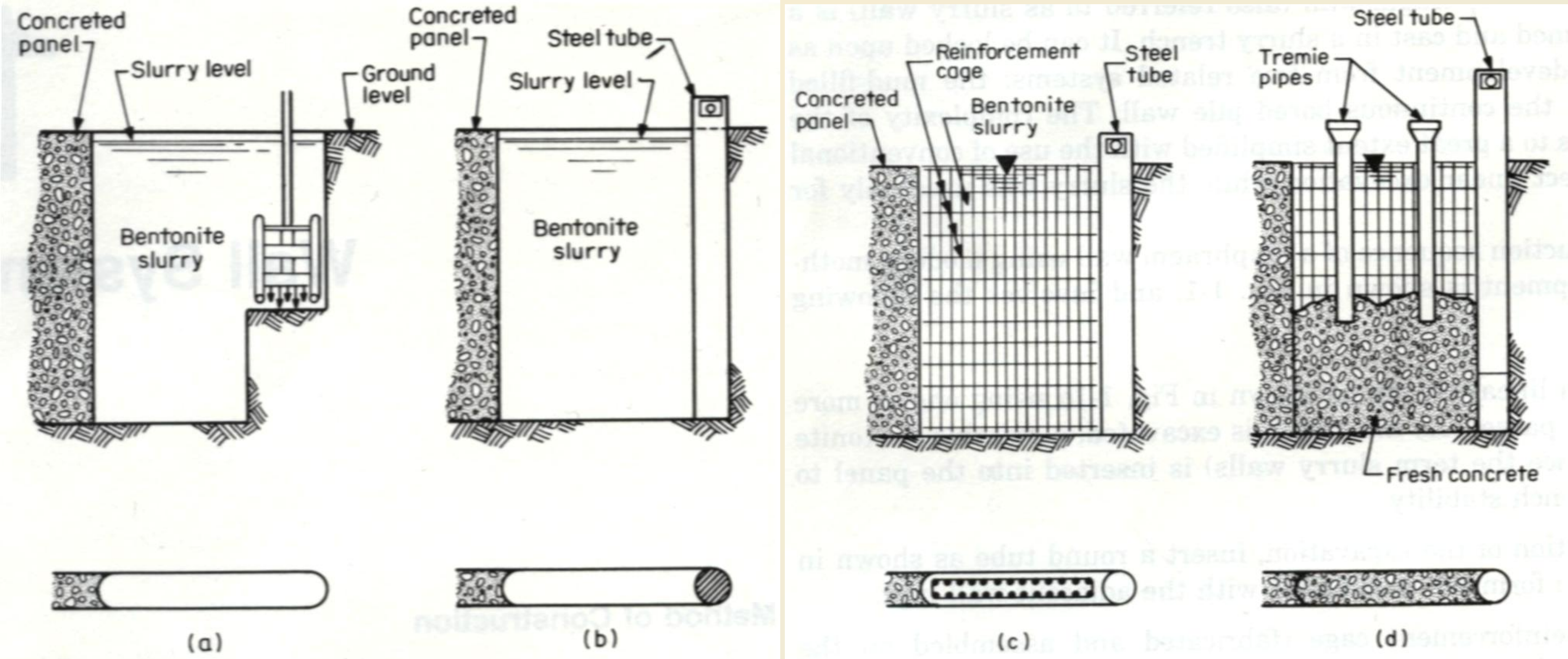


Figure 1-1 Typical construction sequence of a diaphragm wall, executed in four stages: (*a*) Excavation. (*b*) Insertion of steel tubing. (*c*) Placement of reinforcement cage. (*d*) Concrete placement.

Xanthakos, 1991

5.9 Engineering Applications

Dispersion agents (drilling mud; hydrometer analysis)

- Sodium hexa-metaphosphate ($NaPO_3$) and sodium silicate (Na_2SiO_3) are used as the dispersion agent in the hydrometer analysis. How does this dispersion agent work?
- *Three hypotheses:*

(1) Edge-charge reversal

The anions adsorption onto the edge of the clay particle may neutralize the positive edge-charge or further reverse the edge-charge from positive to negative. The edge-charge reversal can form a negative double layer on the edge surfaces to break down flocculated structure, and assist in forming a dispersed structure.

(2) Ion exchange

The sodium cations can replace the divalent cations existing in the clay particles such as Ca^{2+} and Mg^{2+}. The decrease of cation valence can increase the thickness of the double layer and interparticle repulsion, which can assist in forming a dispersed structure.

(3) pH

The higher pH may make the edge-charge tend to be negative, which can break down the flocculated structure and assist in forming a dispersed structure. The adding of dispersing agent such as sodium carbonate may slightly increase the pH.

6. Soil Structure and Fabric

6. Soil Structure and Fabric

- **The *structure* of a soil is taken to mean both the geometric arrangement of the particles or mineral grains as well as the interparticle forces which may act between them.**

- Soil *fabric* refers only to the ***geometric arrangement*** of particles (from Holtz and Kovacs, 1981).

  **Fabric and structure are used interchangeably sometimes.*

- The ***interparticle forces*** (or surface forces) are relatively important for fine-grained soils at low confinement (low state of stress).

- "Although the behavior of a **coarse-grained soil can often be related to particle size distribution**, **the behavior of a fined-grained soil usually depends much more on geological history and structure than on particle size**" (from Lambe and Whitman, 1979).

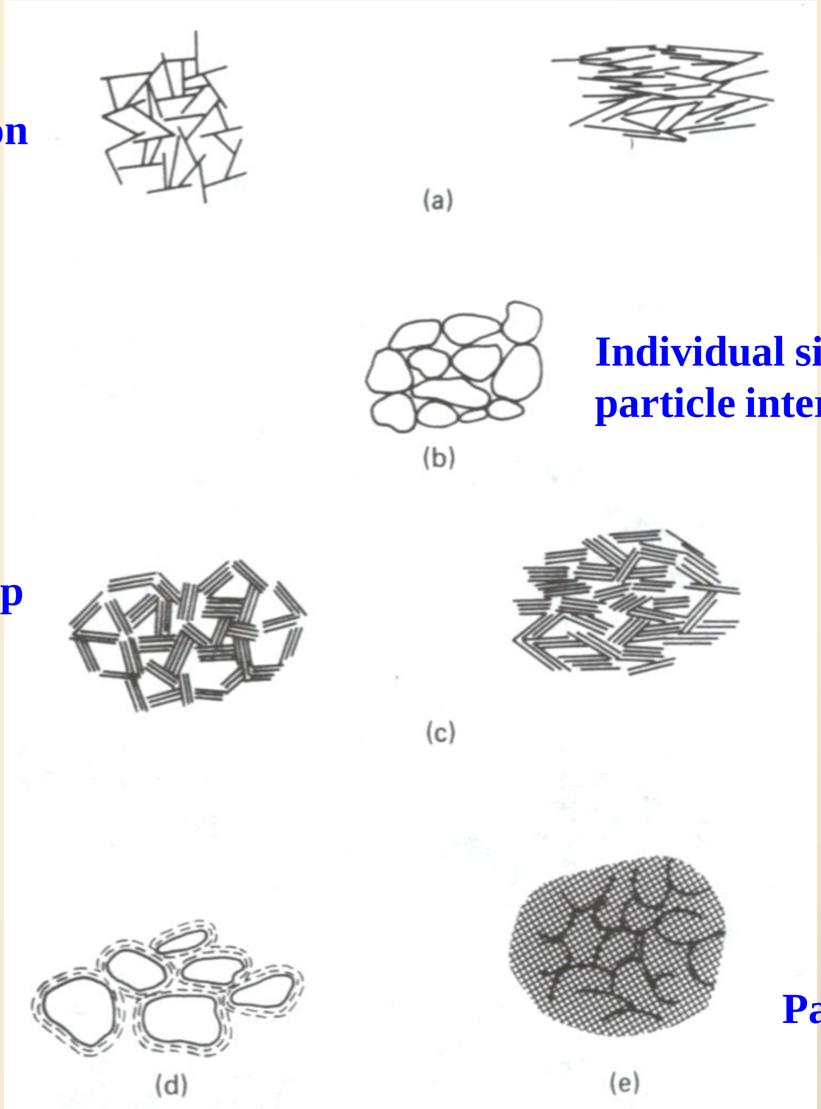
7. Soil Fabric-Natural Soil (fine-grained soils)

7.1 Microfabric Features in Natural Soils

1. **Elementary particle arrangements**, which consist of single forms of particle interaction at the level of individual clay, silt, or sand particles or interaction between small groups of **clay platelets or clothed silt and sand particles.**
2. **Particle assemblages**, which are units of particle organization having **definable physical boundaries and a specific mechanical function**. Particle assemblages consist of one or more forms of elementary particle arrangements or smaller particle assemblages.
3. **Pore spaces** within and between elementary particles arrangements and particle assemblages.

(from Holtz and Kovacs, 1981)

7.1 Elementary Particles Collins and McGown, 1974



Individual clay platelet interaction

Individual silt or sand particle interaction

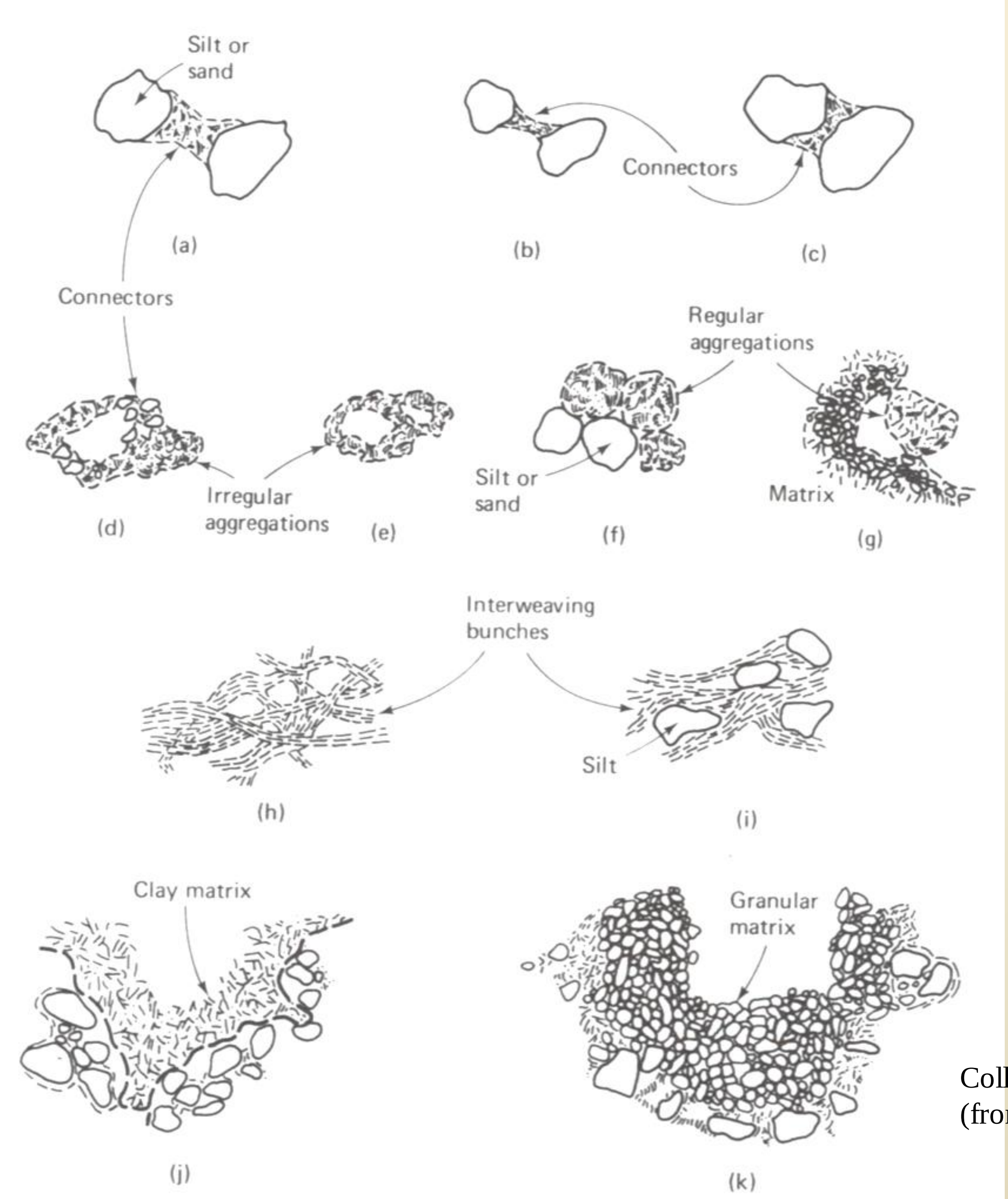
Clay platelet group interaction

Clothed silt or sand particle interaction

Particle discernible

Collins and McGown, 1974
(from Holtz and Kovacs, 1981)

7.2 Particle Assemblages **Collins and McGown, 1974**



Collins and McGown, 1974
(from Holtz and Kovacs, 1981)

7.3 Pore Space Types

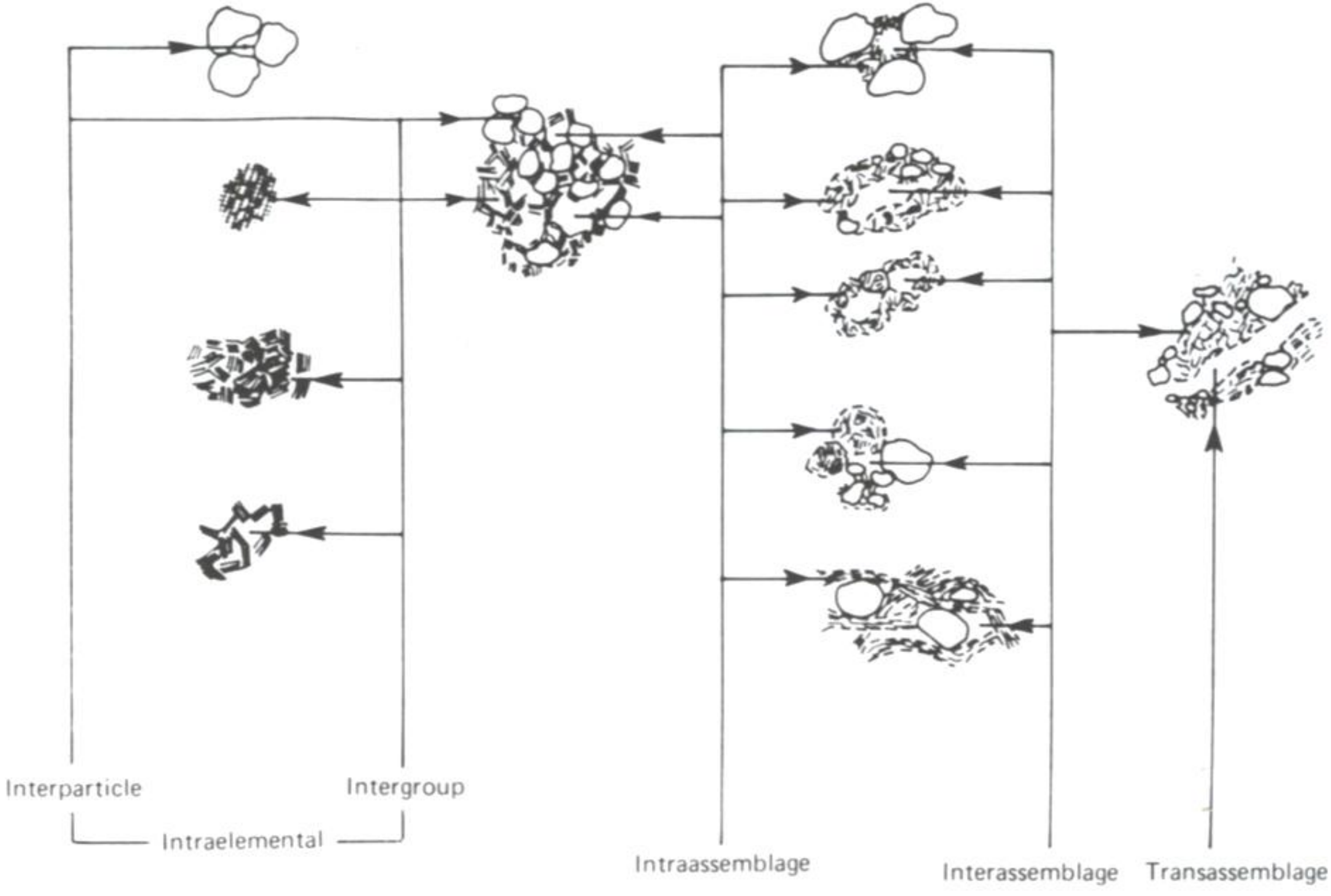
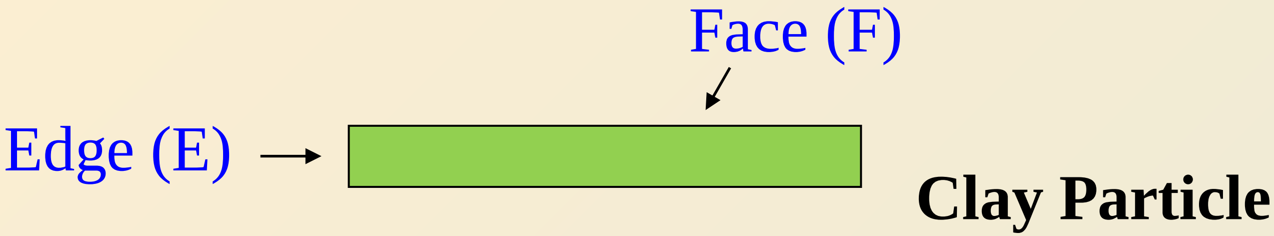


Figure 8.4 Schematic representation of pore space types (Collins and McGown, 1974).

Collins and McGown, 1974 (from Mitchell, 1993)

8. Soil Fabric-Clay Soils

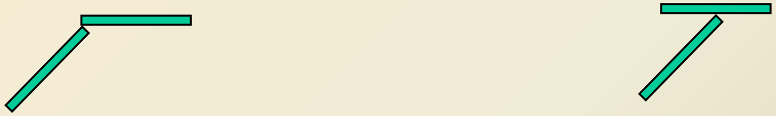
8.1 Terminology



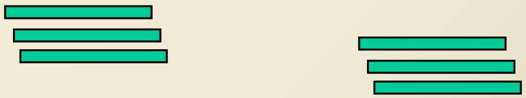
Dispersed: No face-to-face association of clay particles

Aggregated: Face-to-face association (FF) of several clay particles.

Flocculated: Edge-to-Edge (EE) or edge-to-face (EF) association

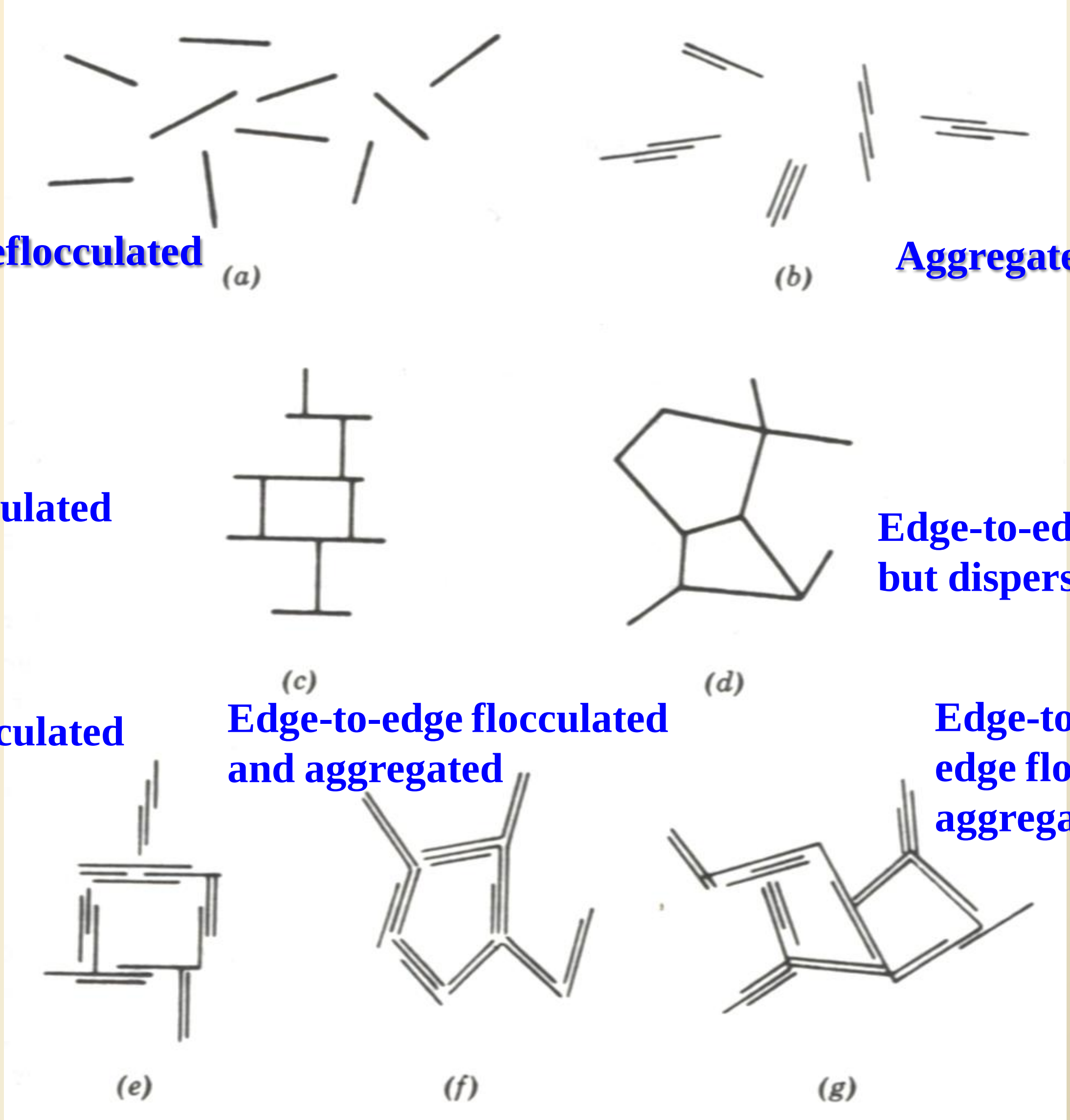


Deflocculated: No association between aggregates



(from Mitchell, 1993)

8.2 Particle Associations



Dispersed and deflocculated

Aggregated but deflocculated

Edge-to-face flocculated
but dispersed

Edge-to-edge flocculated
but dispersed

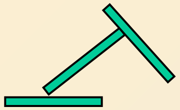
Edge-to-face flocculated
and aggregated

Edge-to-edge flocculated
and aggregated

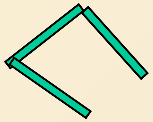
Edge-to-face and edge to
edge flocculated and
aggregated

8.3 Summary

Flocculated fabric

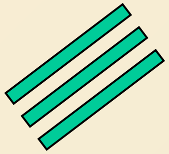


Edge-to-face (EF): positively charged edges and negatively charged surfaces (more common)

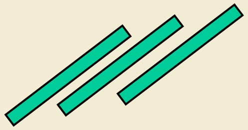


Edge-to-edge (EE)

Aggregated fabric



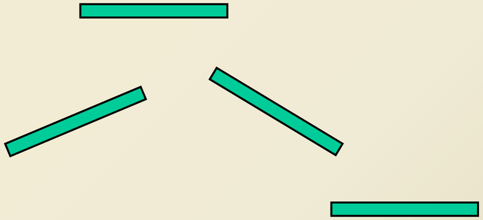
Face-to-Face (FF)



Shifted

Face-to-Face (FF)

Dispersed fabric



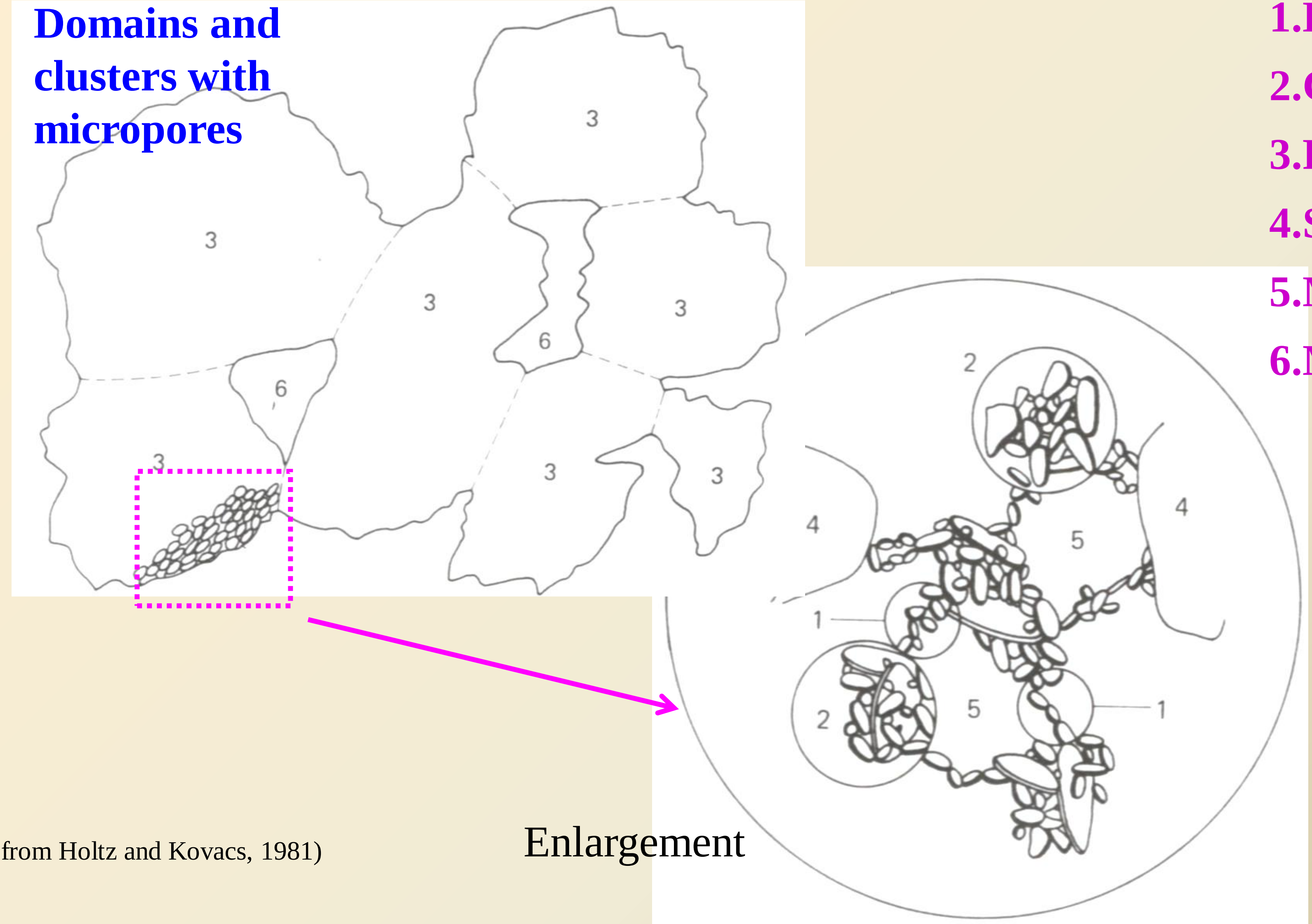
The net interparticle force between surfaces is repulsive

8.4 Fabric of Natural Clay Soils

"The individual clay particles seem to always be aggregated or flocculated together in submicroscopic fabric units called ***domains*. Domains then in turn group together to form *clusters*, which are large enough to be seen with a visible light microscope. Clusters group together to form *peds*** and even groups of peds. ***Peds can be seen without a microscope***, and they and other macrostructural features such as joints and fissures constitute the macrofabric system" (from Holtz and Kovacs, 1981).

Domain → Cluster →Ped

8.4 Fabric of Natural Clay Soils



Domains and clusters with micropores

Enlargement

(from Holtz and Kovacs, 1981)

1.Domain

2.Cluster

3.Ped

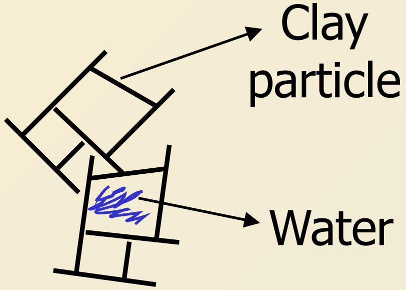
4.Silt grain

5.Micropore

6.Macropore

8.4 Fabric of Natural Clay Soils (cont.)

- **Macrostructure**, including the stratigraphy of fine-grained soil deposits, has an important influence on soil behavior in engineering practice. Joints, fissures, silt and sand seams, root holes, verves, and other defects often control the engineering behavior of the entire soils mass.
- The **microstructure** **reflects the depositional history and environment of the deposit,** its weathering history (both chemical and physical), and stress history.



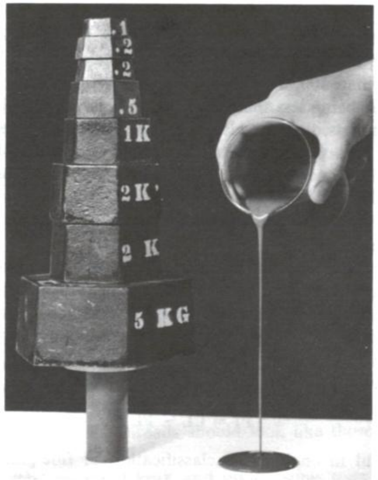


Fig. 2.9 (a) Undisturbed and (b) thoroughly remolded sample of Leda clay from Ottawa, Ontario. (Photograph courtesy of the Division of Building Research, National Research Council of Canada. Hand by D. C. MacMillan.)

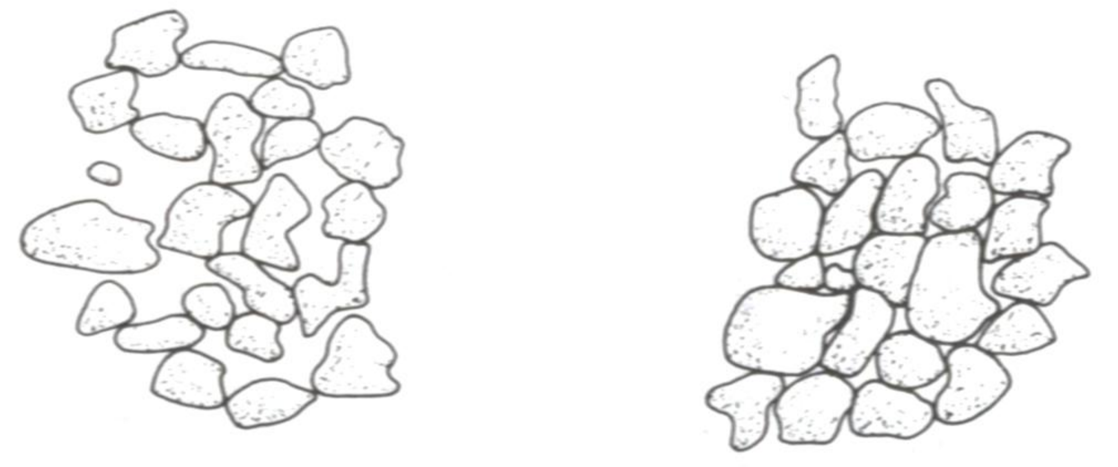
Holtz and Kovacs, 1981)

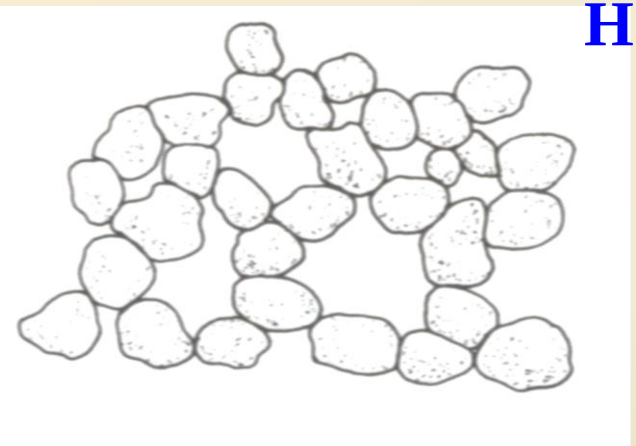
9. Soil Fabrics-Granular Soils

9.1 Packing

Loose packing

Dense packing





Honeycombed fabric

- **Meta-stable structure**
- **Loose fabric**
- **Liquefaction**
- **Sand boil**

Holtz and Kovacs, 1981

9.1 Packing (Cont.)-Sand Boil

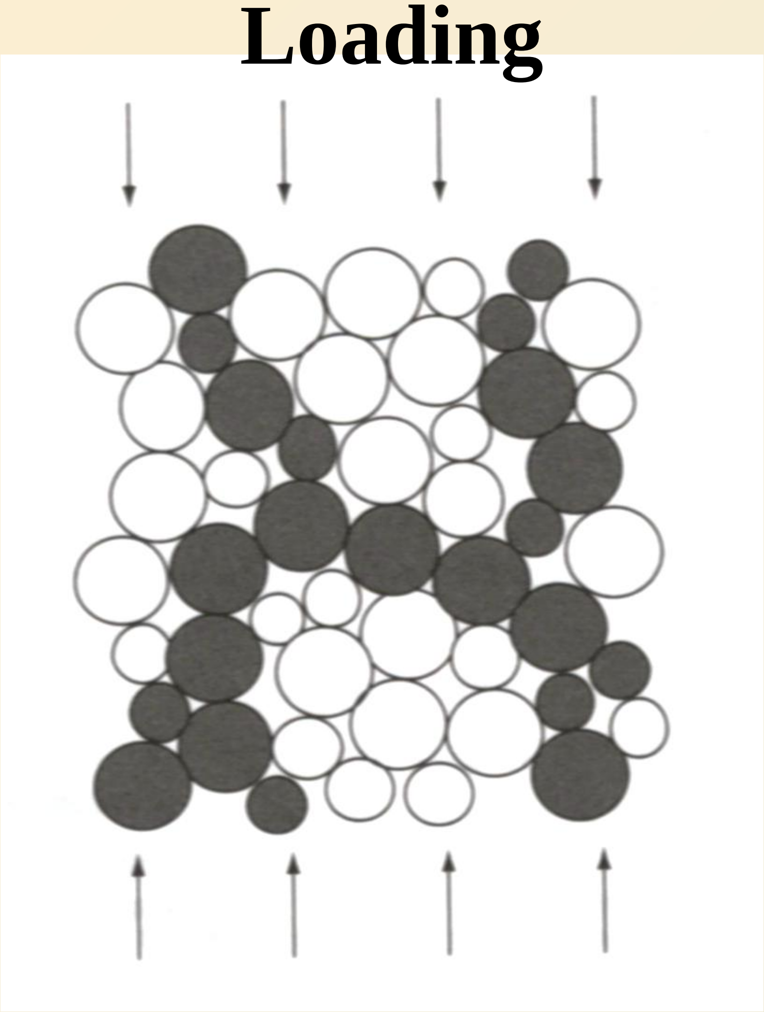
Kramer, 1996

Figure 1.10 Sand boil in rice field following the 1964 Niigata earthquake (K. Steinbrugge collection; courtesy of EERC, Univ. of California).

9.1 Packing (Cont.)

“Contrary to popular belief, it is not possible to drown in quicksand, unless you really work at it, because the density of quicksand is much greater than that of water. Since you can almost float in water, you should easily be able to float in quicksand “(from Holtz and Kovacs, 1981).

9.2 Load Transfer



The black particles carry most of load. The remaining particles prevent the buckling of the load-carrying chains (From Santamarina et al., 2001)**.**

9.3 The Relative Density (D_r)

The relative density D_r is used to characterize the density of **natural granular soil**.

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100\%$$

$$= \frac{\gamma_{d\,max}}{\gamma_d} \times \frac{\gamma_d - \gamma_{d\,min}}{\gamma_{d\,max} - \gamma_{d\,min}} \times 100\%$$

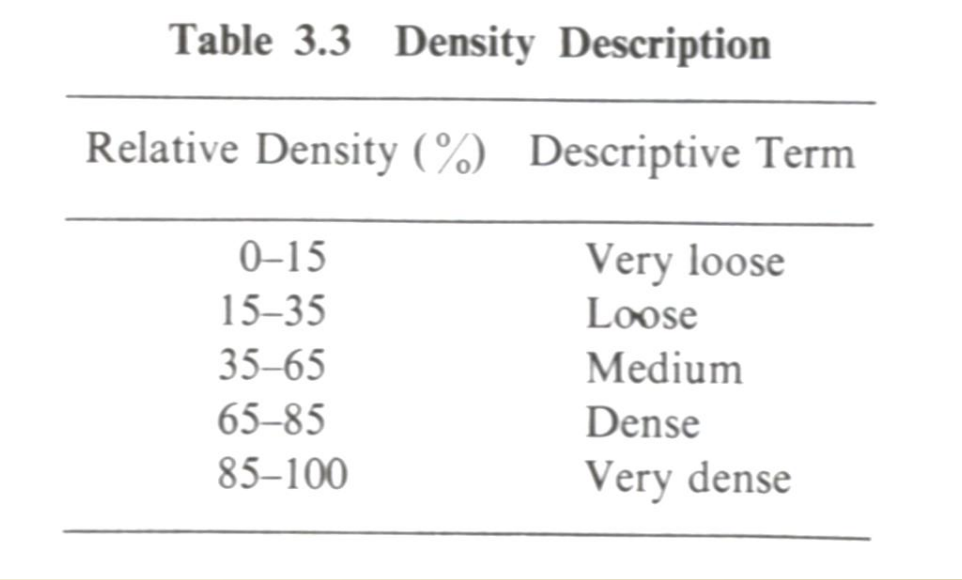


Table 3.3 Density Description

Relative Density (%)	Descriptive Term
0–15	Very loose
15–35	Loose
35–65	Medium
65–85	Dense
85–100	Very dense

(Lambe and Whitman, 1979)

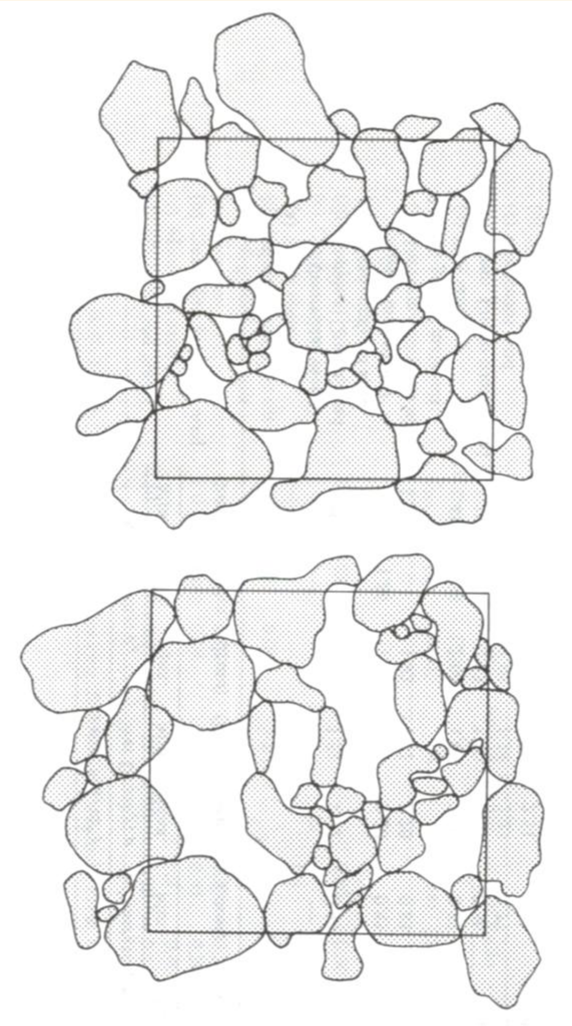
The relative density of a natural soil deposit very strongly affects its engineering behavior. Consequently, it is important to conduct laboratory tests on samples of the sand at the same relative density as in the field (from Holtz and Kovacs, 1981). (compaction)

Derivation

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100\%$$

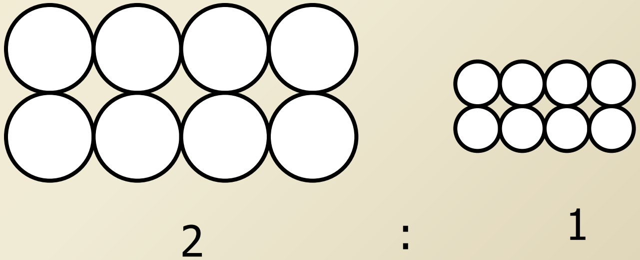
$$= \frac{\gamma_{d\,max}}{\gamma_d} \times \frac{\gamma_d - \gamma_{d\,min}}{\gamma_{d\,max} - \gamma_{d\,min}} \times 100\%$$

9.3 The Relative Density (Dr) (Cont.)



Holtz and Kovacs, 1981

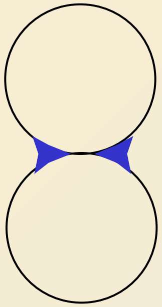
"The relative density (or void ratio) alone is not sufficient to characterize the engineering properties of granular soils" (Holtz and Kovacs, 1981). Two soils with the same relative density (or void ratio) may contain very different pore sizes. That is, the pore size distribution probably is a better parameter to correlate with the engineering properties (Santamarina et al., 2001).



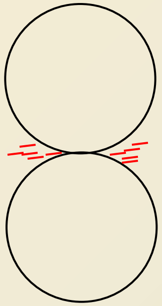
10.Loess

- Loess is a type of ***aeolian soils***, and the particles are predominantly silt-size. The soil structure is mainly stabilized by (1) the capillary force and (2) light cementation arising from the salt and fines (e.g. clay) precipitation around the contacts (Holtz and Kovacs, 1981; Santamarina, 2001).

Capillary force

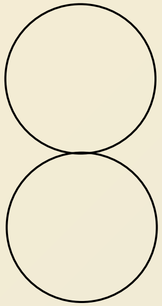


Cementation

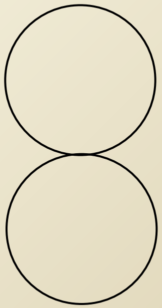


- After loess is submerged, collapse of the soil structure occurs due to loss of suction and cementation

~~Capillary force~~



~~cementation~~



Why?

The interaction between water and salts and clay

1. Read Chapter 4 (Holtz)
2. Problem 4-1, 4-3, 4-4, 4-5, 4-6, 4-8(plus all exercises)

11. References

Holtz, R.D. and Kovacs, W.D. (1981). *An Introduction to Geotechnical Engineering*, Prentice Hall. (Chapter 4)

Mitchell, J.K. (1993). *Fundamentals of Soil Behavior*, 2nd edition, John Wiley & Sons (Chapter 3).