
PETROLOGY
SHAASHAMDAN

INDEX

SOURCES

DR. G. JARRAR, LECTURES, & SLIDES
K. HEFFERAN, J. O'BRIEN, EARTH MATERIALS, 1ST ED
H. BLATT, R. TRACY, B. OWENS, PETROLOGY OF IGNEOUS, SEDIMENTARY, & METAMORPHIC ROCKS 3ED
F. K. LUTGENS, E. J. TARBUCK, FOUNDATION OF EARTH SCIENCE, 8TH ED
W.D. NESSE, INTRODUCTION TO MINERALOGY
ALEX STRECKEISEN SITE

INTRODUCTION

- **Earth's sphere:** Hydrosphere, Biosphere, Atmosphere, & Geosphere (lithosphere)
- **Why do we study Petrology:** petrology occupies central position between earth's science, building upon mineralogy with strong connection to structural geology, tectonics, sedimentalogy, geochemistry, & geophysics (becouse we study Geosphere which consist of minerals & rocks)
- **Petrology:** is the study of rocks, or explanation or understanding of a given rocks
- **Rocks**: naturally occurring, machanically coherent aggregates of minerals or mineraloids (mineral-like such as opal, glass, & coal), some with interstitial fluids, & most consist of several different minerals
- **Rock types: 3 major types of rocks**
  1. **Igneous**: formed by solidification of molten or partially molten materials (magma)
  2. **Sedimentary**: formed by consolidation of loose materials that has accumulated in the layers (one of the major feature of sedimentary rock)
  3. **Metamorphic:** derived from preexisting rocks by mineralogical, chemical, structural changes (in the solid state), in response to marked changes in T, P, Sharing stress, & chemical environments at the depth in the earth surface (below the zone of weathring & cementation)

Igneous rocks

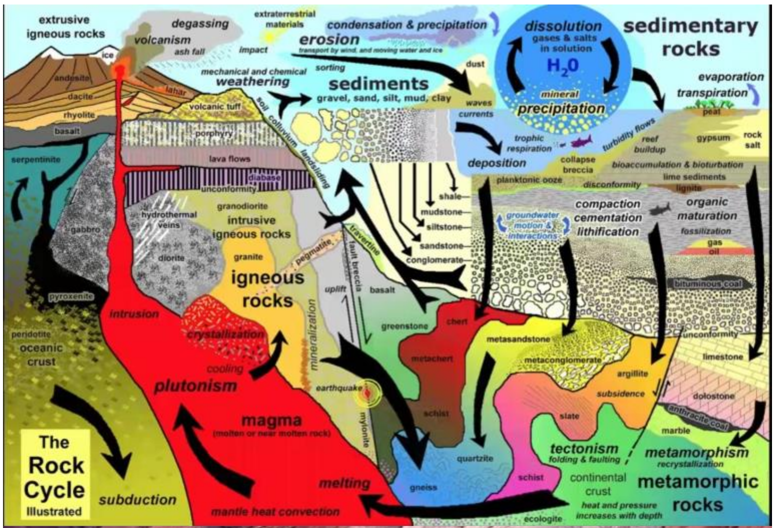
- **Most of magma consist of** rock fragments, minerals, & molten materials
- **Why the word *solidification* is used in definition of igneous instead of *crystallization*?** If the magma reach the surface, it cools fast, & there's no time for it's ions to be formed in a regular order to make crystals, But it hardens randomly to produce glass

Sedimentary rocks

- **Most of sed. rocks formed in:** aqueous medium
- **Types of sedimentary rocks:**
  1. **Clastic:** machanically formed fragments of older rocks that has transported from their source & deposited in water
  2. **Chemical:** formed by precipitation in solution
  3. **Organic:** contain remains of plants & animals

Metamorphic rocks

- **Matamorphic processes tack place :** between igneous & sedimentary processes
- **Transitional or proad area(gradual limit)**200°-700°
- **Intensity of metamorphism & recrystallization depend on** T, **mineralogy & structure of rocks & Folds depend on** P




LAYERING IN SEDIMENTARY ROCKS


FOLDS IN METAMORPHIC ROCKS

- **The chemical changes during the metamorphism depend on** the chemical composition of the rocks

اذا كان التركيب بسيط يحدث تغير بال texture فتقوم المكونات بتنظيم نفسها بنفس التركيب لكن بحجم بلوري اكبر من الامثلة very-fine grain limestone الذي يتحول الى marble وكلاهما يتكون من Ca-carbonate ايضا quartz & sandstone يتبلورا لتصبح الحدود بين البلورات straight line عوضا عن rounded واذا كان معقد (مكونات مختلفة) تتكون index mineral وهي معادن تدل على ظروف التحول

- **Nature isn't segregated into discrete with obvious boundaries, it's a continuum**
- **Borderline (Transitional area):** rock exist & end up in one or another of the categories due to historical precedence or the bais whim of the classifier
- **Examples include transitional rocks**
  1. **Pyroclastic rocks:** transitional rocks between igneous & sedimentary rocks, such as ***Tuffs*** that consists of layering & formed by magma
  2. **Migmatites:** transitional rock between igneous & matamorphic, outcrop-scale mixture of light & dark rocks, represent the onset of melting in crust at high-grade metamorphism

PYROCLASTIC ROCKS : TUFFS, IGNEOUS ROCK WITH LAYERING

VOLCANIC TUFFS ARE ROCKS THAT ORIGINATE IN VOLCANOES. CLASSIFIED AS IGNEOUS, & REFERRED TO AS VOLCANIC SEDIMENTS.

ANGULAR CLASTS, & THE VERY FINE-GRAINED OF THE ASH MATRIX (WHITE)

MIGMATITES

OCCUPIES A GRAY ZONE AT THE BOUNDARY BETWEEN THE CONDITIONS OF METAMORPHISM & MAGMATIC CONDITIONS, & CAN BE CLASSIFIED AS PARTLY METAMORPHIC & PARTLY IGNEOUS

- If the metamorphic rocks produced by volcanic ash which consists of basaltic material (olivine, pyroxene, & Ca-plagioclase) the melting of these rocks start at high T (800 – 850)°C because these minerals are high T minerals, so the area between 700-800° is the transitional zone between metamorphic & igneous rocks, at 700° start to melt to magma that crystallize to produce Ignouse Rock but consist of flods (matamorphic feature)
- In the rock consist of felsic (silica & feldspar) melting start at T < 700°
- The foliation is produced in the area of regional metamorphism near subduction zones (high-grade metamorphism)
- In the contact metamorphism the grain size is increasing with the direction of contact (magmatic body)
- The differences between gneiss & schist: gneiss formed in high-grade regional metamorphism (so that foliation can see in the naked Eye)

BOUDINAGE STRUCTURE IN MIGMATITE

القطع الفاتحة غنية في الQUARTZ & FELDSPAR حدث لها THINNING فتحولت الى SCHIST (الاسود ويوجد به FOLIATION) نتيجة تعرض الصخر لضغط في الSUBDUCTION-ZONE والطبقات السوداء تحتوي BIOTITE والذي يحدث له DEFORMATIONولا يتفتت

طبقات ال COMPETENT يحدث لها PLASTIC-DEFORMATION اما ال INCOMPETENT و هـ BRATTLE يحدث لها FRAGMENTATION

الصخور ال LIGHT-COLOR الموجودة في جنوب الاردن من منطقة القويرة الى العقبة تتكون من FELSIC-MINERALS مثل QUARTZ & FELDSPAR وهو GRANITE والصخور ال DARK-COLORED تتكون من DARK-HORNFELS

- **Structure:** is the large- or macro-scale, in the field
- **Texture:** Micro-scale (what we see in the hand-speciment & the relationship between grains)

Outcrops characteristics & structure of rock types

Igneous	Sedimentary	Metamorphic
1. Volcanoes, & lava flows 2. Cross - cutting relations & Charac-teristic size & shapes (laccolith, lopolith, sill, stock, batholes & lava flow) 3. Thermal effects on adjacent rocks (recrystallization, color change, reaction zones) 4. Chilled (finer-grained) borders against rocks 5. Lack of fossils & stratification (except for pyroclastic rock) 6. structureless rocks composed of inter-locking grains 7. in Preca-mbrian or orogenic terranes	1. Stratification (layering) & sorting 2. ripple mark, cross - bedding , or mud cracks Structures 3. widespread & inter bedded with known sediments 4. The shape of sedimentary rocks may be characteristic form delta, bar, river, & drainage systes 5. The rocks may be consolidated or unconsolidated	1. Distorted pebbles, fossils, or crystals 2. Parallelism of planar, & elongate grains 3. Located adjac-ent to igneous, occasionally as a zoned aureole 4. in Precambrian ,orogenic terrane 5. Rock cleavage related to regio-nal structures 6. Progressive change in mineralogy over a wide area 7. Some are massive hard rocks composed of interlocking grains

Volcanoes, lava flows

If the magma is basaltic so these T around 1200° because basaltic & Gapproic magma solidified at T near 1100°C

Tectonic setting (Tectonic position) determine the magma composition, for example at the mid-oceanic ridge the magma is basaltic, & in the continental crust the magma is granitic

Cross - cutting relations (dikes, veins, stocks, & batholiths)

الdike او الsell (موازي للfolliation) عبارة عن magma اندفعت عبر شق من صخور موجودة سابقا وثم تصلبت فيه، وليس بالضرورة دائما ان يصل الdike الى السطح بل ربما يمتد جانبيا ليشكل الsell

Batholith: Hugh igneous body, most of the batholiths have granitic composition وهو اضخم واعمق الاجسام النارية

Granitic magma have high viscosity so don't reach the surface, basaltic have low viscosity so reach the surface

Orogenic terranes : مناطق بناء الجبال عند حدود الصفائح المتقاربة

Thermal effects on adjacent rocks

هذا الجسم الناري قريب من السطح لانه fine-grained ولان درجة الحرارة تزداد مع العمق geothermal-gradant بمقدار 30° لكل كم ولو كان عمق هذه الصخور 3كم اذا درجة حرارتها 90°± ولان درجة حرارة الmagma حوالي 1000° ستنتقل الحرارة من الجسم الناري الى الصخور المحيطة وهذا ما شكل عملية الشواء حول الجسم الناري ولم يحدث -contact metamorphism لان سماكة هذا الجسم الناري قليل جدا (حوالي 3م) انه سيبرد سريعا ولن يكون هناك وقت كافي لانتقال الحرارة وحدوث contact metamorphism

Chilled (finer-grained) borders against rocks

حدثت عملية تبريد سريع لاطراف الdike بسبب برودة الصخور المجاورة فصنعت -very fine-grained crypto crystalline structure على الاطراف وفي الوسط تبلورت بلورات courser اي عملية التبريد على الاطراف حدثت اسرع من الوسط

Gappro or diorite because consist of plagioclase & pyroxene

الpyroxene كان موجود ثم تبلور الplagioclase لان الpyroxene غير منتظم ويغطي الفراغات بين بلورات الplagioclase المنتظمة

اذا احتوى olivine يكون Gappro

Stratification

من اهم صفات الصخور الرسوبية

sorting

The rocks may be unconsolidated or not

هذه الصخور من ال Ordovician ورغم انها كانت مدفونة الا انها unconsolidated لانه لم يتم ترسيب cementing materials بين حباتها

اخذت هذا الشكل بسبب عمليات النقل

Parallelism of planar, elongate grains over large areas

الصخور التي تحولت نتيجة اندفاع magma في داخلها هي contact-metamorphism ولا تحتوي foliation لان الضغوط كانت من كافة الاتجاهات متساوية مثل hornfels, granofels
ال Arkose صخر رسوبي اذا تحول by contact-metamorphism ولم يحدث له deformation يتحول الى granite وكلاهما يتكون من quartz + feldspar
ال marble يتحول عن ال limestone وكلاهما يحتوي calcium-carbonate والذي يحدث اثناء التحول هو ان البلورات ف تعيد ترتيب نفسها لتصبح اكبر حجما

The light-color is quartz or feldspar, & the dark is amphibole (oreanted & prismitic crystals)

ال regional-metamorphism يحدث عند ال subduction-zone لانه يوجد compression ناتج عن حركة الصفائح بشكل معاكس لبعضها البعض ومن هذه الحركة تنتج ال foliation

Texture & characteristic minerals in each of the rock types

Rock	Igneous rock	Sedimentary rock	Metamorphic rock
Texture	Porphyritic, glassy, vesicular, amygdaloidal, graphic, pyroclastic, interlocking aggregate	Fragmental, fossiliferous, oolitic, pisolitic, stratified, interlocking aggregate	Brecciated, granulated, crystalloblastic, or hornfelsic
Mineral	Olivine, pyroxene, Amphibole, Micas, Quartz, Feldspar, Leucite, ,Nepheline, , & Glass	quartz, clays, carbonates (calcite & dolomite), Anhydrite, Halite, Chert (microcrystalline quartz), Gypsum	Amphibole, Andalusite, Cordierite, Epidote, Feldspar, Garnet, Graphite, Glaucophane, Kyanite, Sillimanite, Staurolite, Tremolite-actinolite, Wollastonite, Micas, Quartz

QUESTIONS

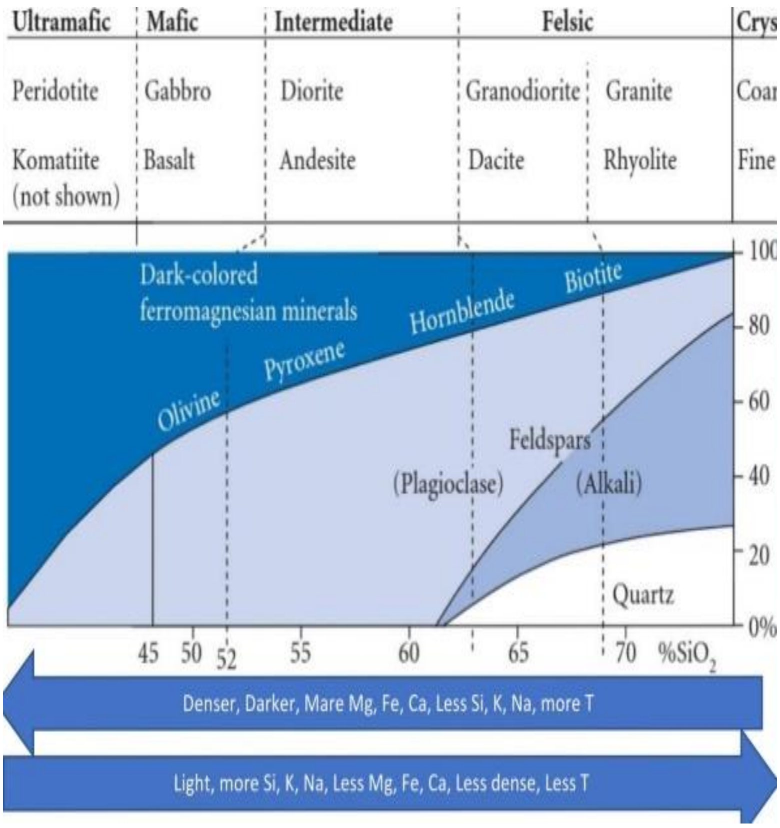
- **Question 1 : Defined the following**
  - A. Petrology
  - B. Rocks
  - C. Magma
  - D. Chilled
  - E. Sediments
  - F. Batholith
  - G. Pyroclastic rocks
  - H. Migmatites
  - I. Igneous rocks
  - J. Sedimentary rocks
  - K. Metamorphic rocks
  - L. Clastic sedimentary rocks
  - M. Chemical sedimentary rocks
  - N. Organic sedimentary rocks
  - O. Borderline (or Transitional area)
- **Question 2 : Complete the following**
  - A. Earth's sphere are Hydrosphere, Biosphere, Atmosphere, & __________
  - B. Most of ________ consist of rock fragments, minerals, & molten materials
  - C. Most of sedimentary rocks formed in ________ medium
  - D. Matamorphic processes tack place in between _________ & ________ processes
  - E. Transitional or proad area (gradual limit) of metamorphic rock between ____________
  - F. Transitional rock between igneous & matamorphic rocks is ____________, & Transitional rock between igneous & sedimentary rocks is ___________
  - G. One of the most characteristic of sedimentary rocks is _________
- **Q3: Explain the following**
  - A. We use the word solidification in definition of igneous rocks instead of crystallization. Why?
  - B. We study Petrology!, Why?
  - C. Limestone is a protolith for Marble, Why?
  - D. Granitic magma don't reach the earth's surface, but basaltic do, Why?
  - E. We don't see foliation in the contact metamorphic rocks, but we can see this in regional matamorphic rocks, Why?
- **Q4: Choose the correct answer**
  - A. Intensity of metamorphism depend on
    1. Pressure 2. Temperature
    3. Rock Mineralogy 4. Rock Structure
  - B. Mineralogy & structure of metamorphic rocks depend on
    1. Pressure 2. Temperature
    3. Rock Mineralogy 4. Rock Structure
  - C. Folds in metamorphic rocks formed due to
    1. Pressure 2. Temperature
    3. Rock Mineralogy 4. Rock Structure
  - D. Recrystallization in metamorphic rocks formed due to
    1. Pressure 2. Temperature
    3. Rock Mineralogy 4. Rock Structure
  - E. The chemical changes during the metamorphism depend on
    1. Pressure 2. Temperature
    3. Rock Mineralogy 4. Rock Structure
  - F. Thermal effects on adjacent rocks
    1. The heat transfer from rock into dike
    2. The heat transfer from dike into rock
    3. The heat don't transfer in the system
    4. The heat transfer randomly in system
- **Q5: T/F**
  - A. The foliation is produced in the area of regional metamorphism near subduction zones at high-grade metamorphism
  - B. In the contact metamorphism the grain size is decreases with the direction of contact (magmatic body)
  - C. gneiss formed in high-grade regional metamorphism (so that foliation can see in the naked Eye)
  - D. Texture is the large- or macro-scale (what we see in the field), & Structure is Micro-scale (what we see in the hand-speciment & the relationship between grains)
  - E. If the lava is basaltic so these T around 1200° because basaltic & Gapproic magma solidified at T near 1100°C
  - F. Tectonic setting (Tectonic position) determine the magma composition
  - G. at the mid-oceanic ridge the magma is granitic, & basaltic in the continental crust
- **Q6: List at least 5 points for each of the following**
  - A. characteristics of igneous rocks
  - B. characteristics of sedimentary rocks
  - C. characteristics of metamorphic rocks
  - D. Texture of igneous rocks
  - E. Texture of sedimentary rocks
  - F. Texture of metamorphic rocks (just 4)
  - G. Common minerals in igneous rocks
  - H. Common minerals in sedimentary rocks
  - I. Common minerals in metamorphic rocks

PART 1
IGNEOUS ROCKS

IGNEOUS ROCK CLASSIFICATION (REVIEW) FROM EARTH MATERIALS

Classification	Disruption	Composition
Ultramafic	Dark & greenish	Olivine + pyroxene ± amphibole
Mafic	Dark	Pyroxene ± amphibole ± olivine ± biotite
Intermediate	Grayish to salt, pepper	Plagioclase, amphibole ± biotite ± quartz
Felsic	Light, red	K-feldspar, quartz ± biotite ± muscovite

	Plutonic/Granitic	Volcanic / Basaltic
Occurrence	Intrusive	Extrusive
Produced by	Magma	Lava, volcanic debris
Solidifies	within Earth	at surface
Cools	slowly	rapidly
Producing	large crystals (phaneritic)	small crystal (Apha-nitic), noncrystalline
Ultramafic	Peridotite	Comatiite
Mafic	Gabbro	Basalt
Intermediate	Diorite	Andesite
Felsic	Granodiorite, Granite	Dacite, Rhyolite



Texture	very dark (ultramafic)	Dark-colored (mafic)	gray (intermediate) to salt & pepper
SiO_2	< 45%VolSiO_2 (ultrabasic)	45% - 52%VolSiO_2 (basic)	50 – 65%vol SiO_2
Plutonic	Peridotite, or Pyroxenite	Gabbro, in lower crust of ocean basin	Diorit
Volcanic	Comatite (rare)	Basalt, common volcanic, encompa-ssing upper kilometers of ocean crust	Andesite, common around Pacific Ring of Fire
Minerals	Rich in Pyroxene, olivine, ± amphibole ± plagioclase	Rich in plagioclase, pyroxene, olivine	Rich in hornblende, pyroxene, & plagioclase

Texture	Light-colored (felsic) rocks	Light-colored (felsic) rocks
SiO_2	≈ 65%vol	> 65%vol (silicic or acidic)
Plutonic	Granodiorite, between granite & diorite	Granite, occur in continental crust
Volcanic	Dacite, occurs around the Pacific rim	Rhyolit, erupts in thick, continental crust
Minerals	Plagioclase, alkali feldspar, quartz, & small amounts of hornblende & biotite	quartz, alkali feldspar, & small amounts of plagioclase & biotit

Texture	Rock	Color	Notes
Vesicular	Pumice	Light-colored	Lightweight rock rich in gas holes (vesicles)
	Scoria	Dark-Colored	Lightweight rock rich in gas holes (vesicles)
Glassy	Obsidian	Black to Reddish	Glassy luster & Conchoidal fracture
Pyroclastic	Volcanic tuff	————	Fine grain ash to sand size volcanic fragments
	Volcanic Breccia	————	Coarse grain gravel & larger size volcanic fragments

MANTEL PETROLOGY

2.1 Introduction

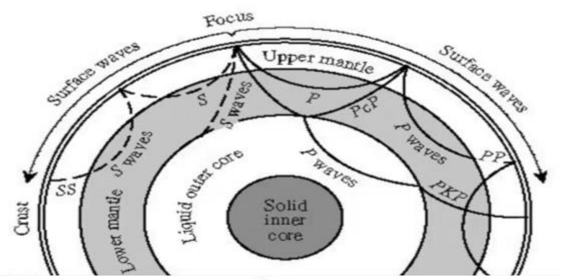
- **Igneous rocks are produced by molten or partially molten magma from the mantle or the crust**
- **The earth at the beginning, mostly it was homogeneous sphere (in the molten form) due to meteorite bombardment**
- **Knowledge of the chemical & physical characteristic of the deep interior of Earth is** indirect, be cause of physical inaccessibility
- **much of information about mantle is based on** geophysical measurements (gravity, magnetism, seismic velocities) meteorite compositional data, & New techniques such as computer enhancements
- **Direct observation of mantle rocks is limited to** rare samples of the mantle that have been brought to the surface as ultramafic xenoliths in mantle-derived magmas, & these magma can provide information about their mantle source areas

Short summary

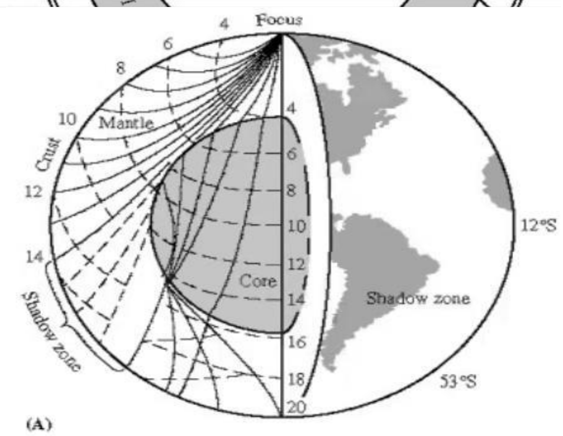
- **Source of information about mantle Petrology:** meteorites, mantle xenolith & xenocrysts, experimental Petrology
- The observation & study of the rocks of the crust & mantle is the source of information that constrains most of our ideas & models About history of Earth

2.2 Cross Vertical structure of the interior

- **Most information about Earth's interior comes from** interpretation of arrival times & travel paths of seismic waves within Earth



Wave reflected & refracted from different layers



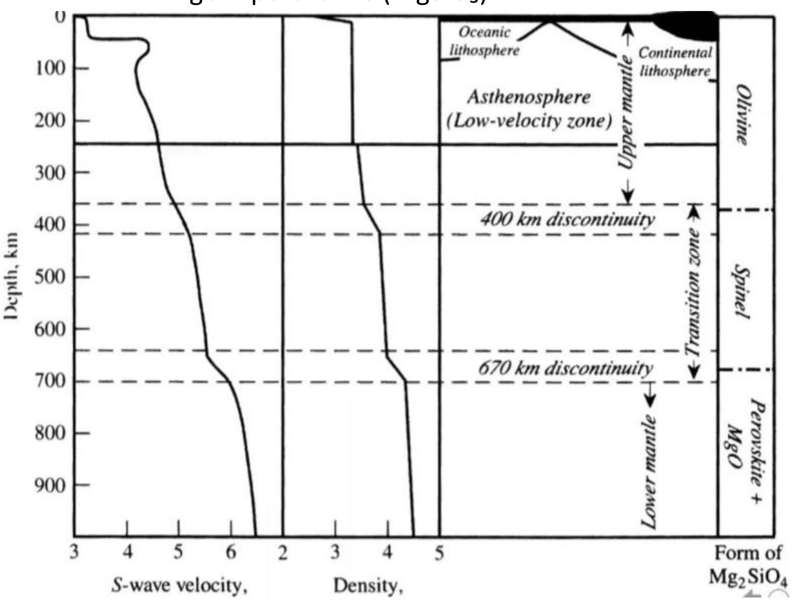
Layering structure of earth based on seismic wave data

- ❖ **S-wave:** transverse (or shear), transfer in solid
- ❖ **P-wave:** propagate through both solids & fluids

Layer	Thickness (Km)	Extended (Km)
Crust	< 10 in oceans >30-70 in continent	Surface- Moho 0 – 70
Mantle	≈ 2800	Moho – 2890 Upper moho -660 Lower 660 - 2890
lithosphere	70 oceanic, Thin to 0 at mid ocean ridges 100 in continents	Crust + upper mantle 0 - 100
Asthenosphere	50 – 100	lithosphere- 250
Core	3480	Outer2890-5000 Inner5000-6370

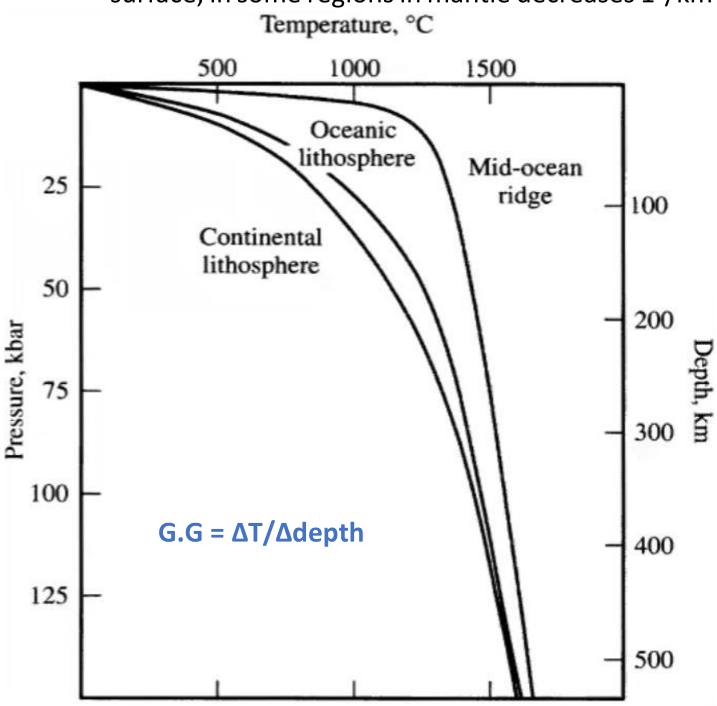
- **Crust** a thin layer at Earth's surface
  - ❖ The average density of the crust ≈ 2.8 g/cm³
  - ❖ **Oceanic** young (150-200Ma) composed of basaltic with minor ultramafic rocks
  - ❖ **Continental crust** oldest 4Ga, plutonic, metamorphic, with a thin sedimentary veneer
  - ❖ The base of the crust is defined by avery distinct & abrupt increase in seismic velocity called the Moho boundary
- **Discontinuity**: is the boundaries between Earth's layers, such as mohosphere (the boundary between asthenosphere & lithosphere)
- **Mantle, Outer Core, & Inner Core**
  - ❖ ***lithospheric mantle*** uppermost mantle & Crust
  - ❖ ***asthenosphere*** low velocity, below lithosphere
  - ❖ **few volume percent of interstitial melt in asthenosphere leads to:**
    1. reduced rock density, & seismic velocity
    2. less mechanically Rigid (more plastic) than the lithosphere & deeper mantle
  - ❖ **all igneous rocks derived from** melting within the outer 250 km (the crust & upper mantle)
  - ❖ **seismic velocity increases in** lower mantle corresponding to ρ increases with increasing P
  - ❖ **The termination of S waves at the core-mantle boundary indicates** outer portion of the core is a liquid which has no shear strength & will not allow transmission of shear waves
  - ❖ **inner core suggested by** refraction of P waves
  - ❖ **Newly, lower mantle has been the focus of co-nsiderable interest in Petrology for 2 reasons:**
    1. Seismic evidence shows that at least some subducted slabs probably sink to the vicinity of the core-mantle boundary
    2. Mantle plumes are originate in this area

- **Mineralogic transitionl zone** The base of the upper mantle at 410 km (P = 100-120 kbar) is marked by Mineralogic transitionl zone
  - ❖ causes a notable & fairly abrupt increase in the density of mantle rocks
  - ❖ is the polymorphic shift of Mg_2SiO_4 from the α-olivine to the denser β-Mg_2SiO_4 (wadsleyite), Which is a distorted spinel-like structure
  - ❖ **at a depth 400 km** Mg_2SiO_4 is converted to the true silicate-spinel structure of Mg_2SiO_4
  - ❖ **At a depth 670km** spinel is converted to the MgO + perovskite ($MgSiO_3$)



2.3 Tempercture Distribution

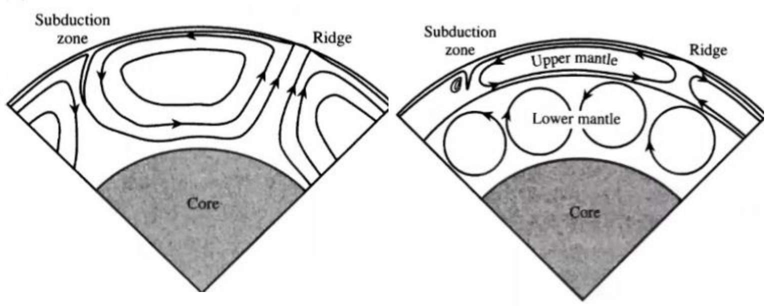
- **geothermal gradie GG:** The change of T with depth
- T decreases linearly upward with decreasing depth 500 - 1000 km, & exponentially from there to the surface, in some regions in mantle decreases 1°/km



- the geothermal gradient for oceanic lithosphere is higher than that for continental lithosphere
- Knowledge of T distribution is critical in developing a theory of formation & ascent of basaltic & related magmas within the upper mantle
- Heat sources :
  1. **Stored in earth due to accretion** (adding new component to earth, meteorites) from 4.5Ga
  2. **Radioactivity: LILE** (large ion lithofile element)
  3. **Frictional heat generated**
- **The increasing in GG in the upper crust > mantle, why?** Magmatic processes result in the move of the large cation from the mantle into a crust, so crust are rich in the LILE that increasing T

2.4 Mantle convection

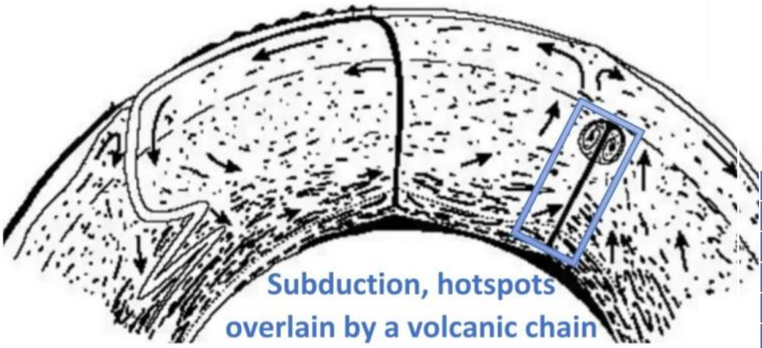
- **Mantle convection** is the cycling of hotter mantle toward the surface as cooler mantle sinks, is the primary mechanism by which heat is transported from the interior of Earth to the exterior (to the base of lithosphere, where heat transfer becomes Conductive rather than convective)
- **Models of conduction cells**: there are 2 model



Convection currents in mantle derived force for the horizontal movement of the lithosphere plates mantle at high T	Convection is achived by creep of mantle at high T

يفترض النموذج الاول انه يوجد تيارات حمل في الستار تنقل الحرارة من اللب الخارجي الى ال asthenosphere ويوجد تيارات حمل اخرى في ال asthenosphere تحرك القارات وبناء القشرة وتدميره، الثاني يفترض وجود تيارات حمل وحدة تمتد من اللب الخارجي للقشرة

- **Subduction zone** is the destructive margins for the oceanic crust but constructive for continental crust, subducted plate descending beyond 670km
- The partial melting of oceanic crust occurs near oceanic ridges, hot spots, & subduction zone
- **Mantle plumes:** is the igneous body, move from the hot outer core by currents (from lower to a higher level) & originating near core-mantle boundary, hot-spot track above a plume tail, & melting at the top of a plume producing mafic magma above hot spot



2.5 Mantel Petrology

- **Core:** inner core is solid & composed of Ni, & Fe, & outer core is molten (conduction currents in the outer core produce earth magnetic field)

ممكن ان يوجد تيارات حمل بالحالة الصلبة لكن الحركة تكون بطيئة ويحتوي الستار ايضا على تيارات حمل في الAsthenosphere

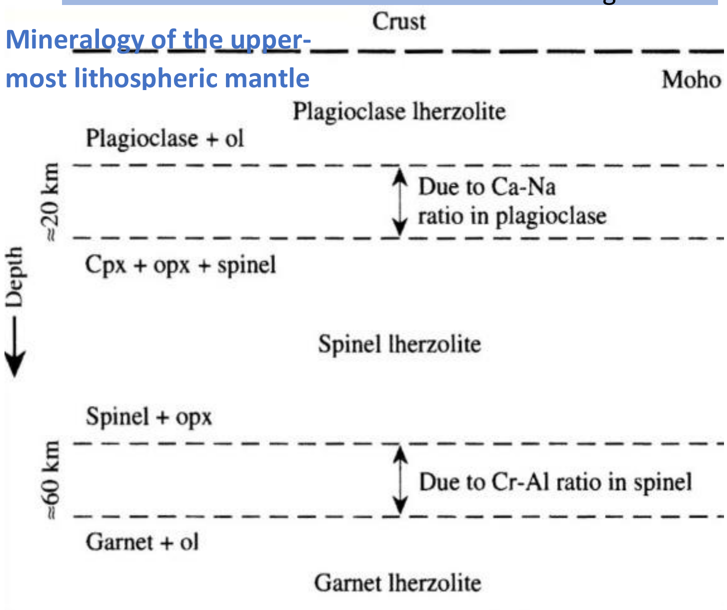
- **Why is the outer core is present in liquid state & the inner is solid?** In the outer core there are other element such as S & Si, & these elements lowering the melting point of the solution
- **The T at the center of earth 6450km depth = 5500°**
- Most of magma come from **asthenosphere** (100 – 250 km depth) & some come from melting of the **lithosphere** (100Km depth), but in some area (rare) come from discontinuity that at 640km depth

في ال asthenosphere تنشأ basaltic magma فقط وليس ال granitic لان ال granitic تحتوي quartz وهو unstable في upper mantle وعندما تنتقل ال basiltic الى السطح او lithosphere فأنها تتبلور واثناء حركتها تنتج كمية قليلة من ال granitic لكن اغلبها يتبلور ك mafic (basalt or gappro) وممكن ان يحدث لها fraction وتنتج ال diorite or Andisitite

- **Granitic magma (batholiths) forms by** partial melting of oceanic crust & sediments near subduction zone

تسبب ال conduction currents عملية شد extension والتي تؤدي لتحرك الصفائح وبناء ال oceanic crust وتخفيض الضغط بسبب عملية الشد هو السبب الرئيسي لحدوث ال partial-melting اسفل ال mid-oceanic ridge

Mineralogy of the upper-most lithospheric mantle

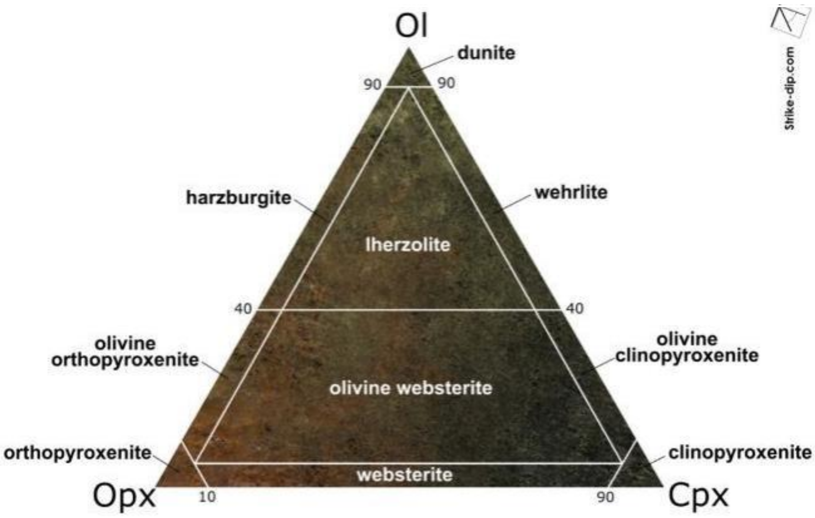


- **Mantle compositions:** the mantle contain ultramafic rocks, that contain olivine, pyroxene (orthopyroxene & clinopyroxene), & garnet

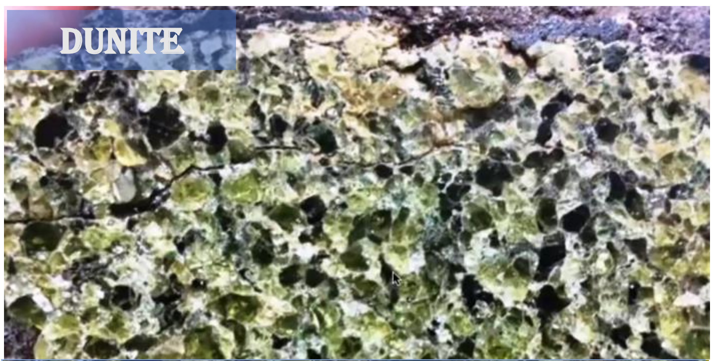
Mantel chemistry

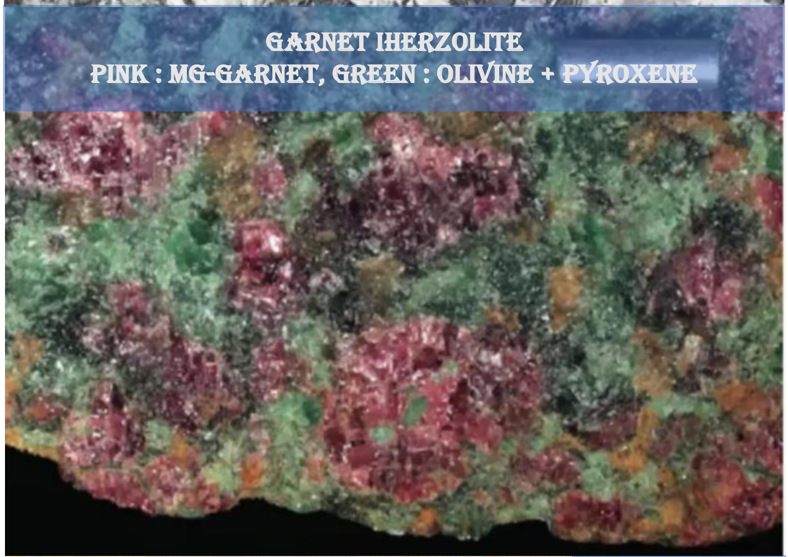
	X_1	X_2	Y_1	Y_2	Σ
SiO_2	43.8-46.6	45.89	42.3-45.3	44.20	45.2
TiO_2	0.07-0.18	00.09	0.05-0.18	00.13	0.71
Al_2O_3	0.82-3.09	01.57	0.43-3.23	02.05	3.54
Cr_2O_3	0.22-0.44	00.32	0.23-0.45	00.44	0.53
FeO	6.44-8.66	06.91	6.52-8.90	08.29	8.48
MnO	0.11-0.14	00.11	0.09-0.14	00.13	0.14
NiO	0.23-0.38	00.92	0.18-0.42	00.28	0.20
MgO	39.4-44.5	43.46	39.5-48.3	42.21	37.48
CaO	0.82-3.06	01.16	0.44-2.70	01.92	3.08
Na_2O	0.10-0.24	00.16	0.08-0.35	00.27	0.57
K_2O	0.03-0.14	00.12	0.01-0.17	00.06	0.13
P_2O_5	0.00-0.08	00.04	0.01-0.06	00.06	—
100Mg / (Mg+Fe)	89.0-93.0	—	89.1-92.6	—	—
100Cr / (Cr+Al)	7.40-18.6	—	7.00-31.7	—	—

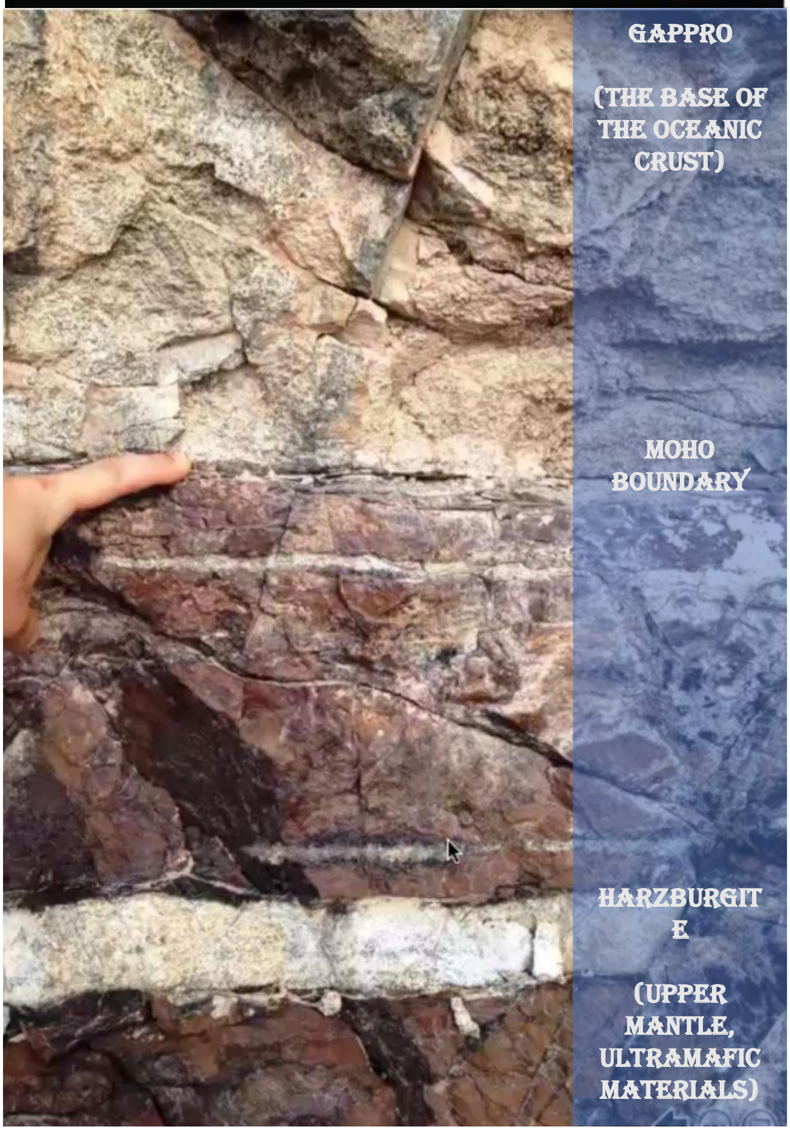
X_1: Range for garnet iherzolite, X_2: Average for garnet iherzolite
Y_1: Range for spinel iherzolite, Y_2: Average for spinel iherzolite
Σ : Ringwood's pyrolite model



ال lherzolite قطعة من الستار تم حملها الى السطح مع ال magma وتتكون من olivine, + clinopyroxene, + orthopyroxene







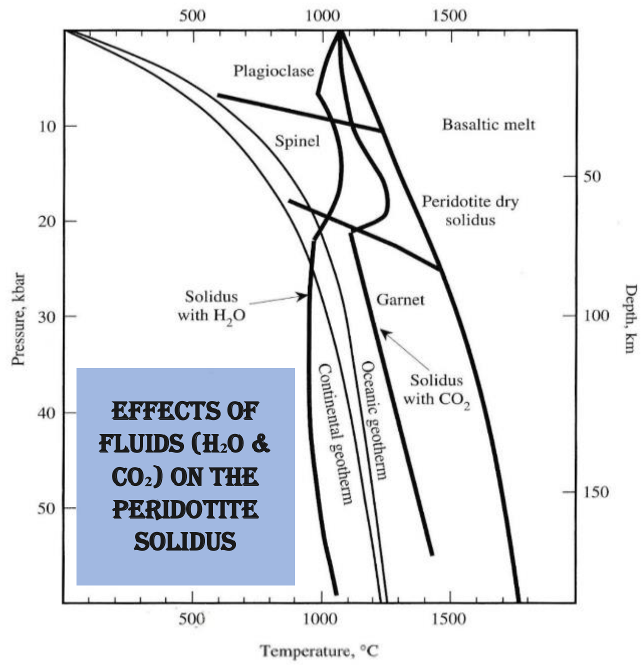
- **Ophiolite:** Part of the oceanic lithosphere Rich surface by abduction process

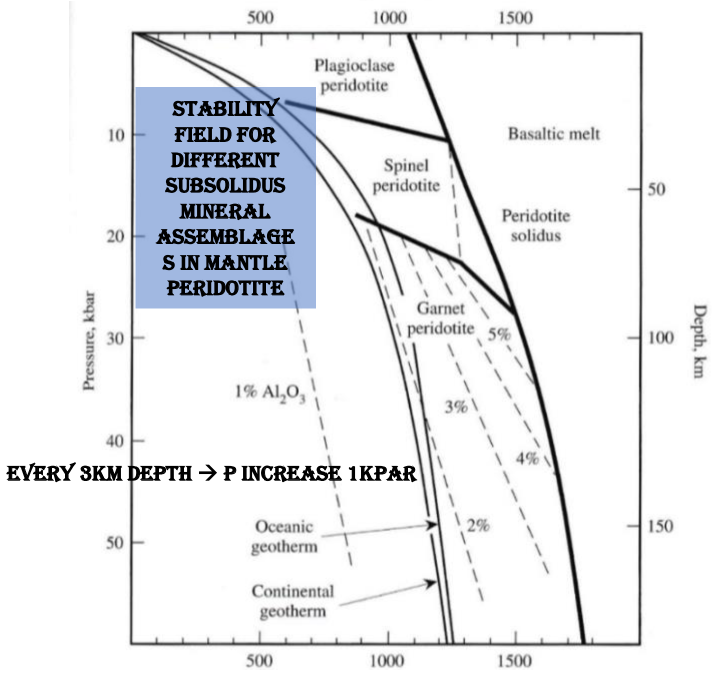
الفرق بين ال Gappro و norite : ال norite يحتوي orthopyroxene, ال Gappro يحتوي clinopyroxene

- **why rocks melt in the upper mantle:** 2 reasons
  1. Adding the fluid such as H_2O or CO_2
  2. Decreasing load P (by transfer the rock by convection currents between levels)

     تزداد درجة الانصهار milting point مع زيادة الضغط (او العمق)
- basaltic magma is more compressible than solid minerals. with increasing depth in the upper mantle, magma undergo a more rapid increase in density than solid peridotite
- basaltic magma has the same density as the solid rock that confines it at depths 100 - 150 km (30-45kbar). Therefore deep basaltic magmas have no buoyancy, or gravitational driving force for upward movement, & can remain trapped in the mantle no matter what the degree of melting or of coalescence

عندما ينصهر الصخر تقل كثافته فيتحرك الى الاعلى (عندما تنضغط مادة صلبة بمادة سائلة تبدأ المادة السائلة بالتحرك للأعلى)، واذا انخفضت درجة حرارة الصهير بشكل كافي قبل وصولها الى السطح تتبلور لتكون صخور plutonic or intrusive igneous rocks واذا حافظت على درجة حرارتها ولزوجتها ستشكل البراكين وتتصلب مشكلة volcanic rocks or glass



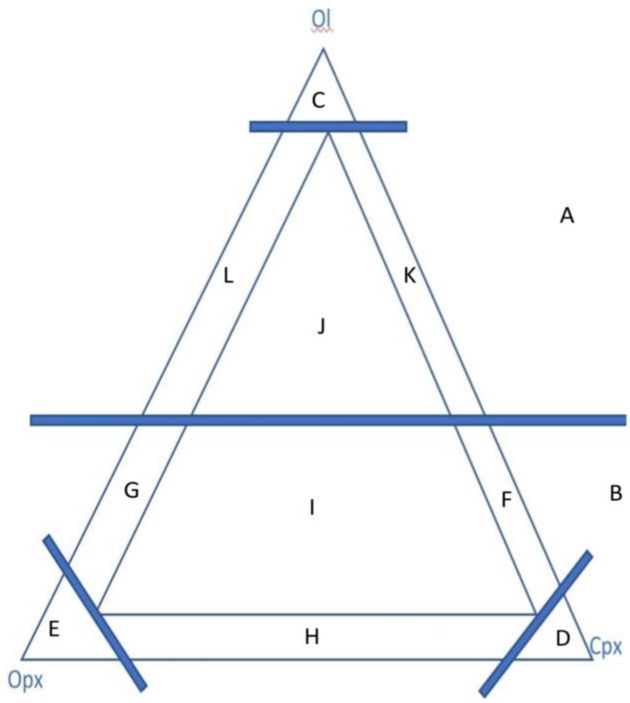


QUESTIONS

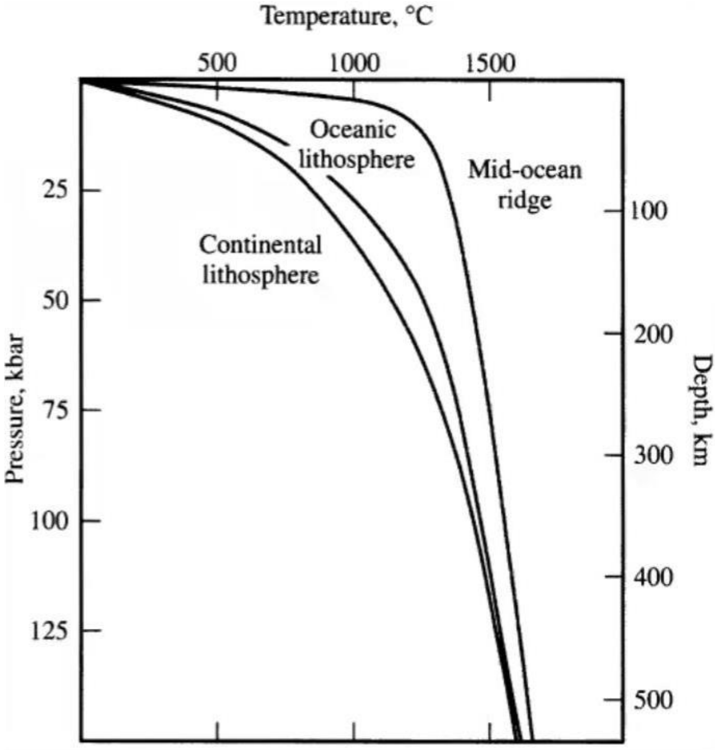
- **Q1 : Defined the following**
  A. Accretion
  B. Discontinuity
  C. Asthenosphere
  D. Mantle plumes
  E. Mantle convection
  F. geothermal gradie GG
  G. Ophiolite
- **Q2 : Complete the following**
  A. Igneous rocks are produced by magma that come from ________ or __________, & in some area (rare) come from ___ depth
  B. The earth at the beginning, mostly it was homogeneous sphere (in the molten form) due to ________________
  C. Direct observation of mantle rocks is limited to __________ or __________
  D. Discontinuity between mantle & crust is called _____________
  E. Thickness of Asthenosphere ____km, & extends to a depth of _____km
  F. The average density of the crust ___g/cm^3
  G. The base of the crust is defined by avery distinct & abrupt increase in seismic velocity called ________
  H. All igneous rocks derived from melting within the outer _____ km
  I. The termination of S waves at the core-mantle boundary indicates that the outer portion of the core is ______ which has no shear strength & will not allow transmission of shear waves
  J. The Inner core is suggested by refraction of _______ wave
  K. There are important mineralogic transition at 410 km or 100-120 kbar, This transition is the polymorphic shift of Mg_2SiO_4 from ______ to the denser ______, & at a depth 500 km Mg_2SiO_4 is converted to the ____ structure, & at 700km depth converted to____ + ____
  L. T decreases ________ upward with decreasing depth 500 – 1000 km, & ________ from there to the surface
  M. ___________ is the primary mechanism by which heat is transported from the interior of Earth to the exterior
  N. Subducted plate descending beyond __km
  O. Hot-spot track above a _____ tail
  P. Olivine sand found in ___________
  Q. The main source that cause of partial melting below mid-oceanic ridge is _____ due to ___________
  R. ______ magma forms by partial melting of oceanic crust & sediments near subduction zone extension process that building continental crust & moving the plates
  S. ________ causes a notable & fairly abrupt increase in the density of mantle rocks
- **Q3: Explain the following**
  A. Knowledge of the chemical & physical characteristic of the deep interior of Earth is indirect, Why?
  B. In the asthenosphere rock density & seismic velocity are reduced, & the rock is less mechanically Rigid (more plastic) than the lithosphere above & deeper mantle below, Why?
  C. Newly, lower mantle has been the focus of considerable interest in Petrology, Why?
  D. Geothermal-gradant Increasing in the upper crust greater than in mantle, why?
  E. the outer core is present in liquid state & the inner is solid, Why?
  F. Most of magma in the asthenosphere are basaltic magma, Why?
  G. Deep basaltic magmas have no buoyancy, or gravitational driving force for upward movement, & can remain trapped in the mantle no matter what the degree of melting or of coalescence, Why?
- **Q4: Choose the correct answer**
  A. Thickness of continental crust
  1. 30 – 70km 2. > 70km
  3. 10 – 20km 4. <10km
  B. Physical layer, consist of upper mantle & crust (thickness 0 - 100km) is
  1. Asthenosphere 2. Lithosphere
  3. Geosphere 4. Hydrosphere
  C. Seismic wave that transfer in solid only is
  1. S-Wave 2. Transverse wave
  3. Shear Wave 4. All of them
  D. Oceanic crust is
  1. Thicker layer of earth surface
  2. young (150-200Ma), basaltic&ultramafic
  3. Oldest 4Ga, plutonic & metamorphic
  4. Non of the above
  E. Lithospheric plates move due to
  1. Mantle convection 2. Accretion
  3. Thermal energy 4. Kinetic energy

F. Is the destructive margins for the oceanic crust & constructive for continental crust
   1. Mid-oceanic ridge 2. Subduction zone
   3. Volcanoes 4. Lava flow

- **Q5: T/F**
  A. Most information about Earth's interior comes from interpretation of arrival times & travel paths of seismic waves
  B. Thickness of continental crust 30 - 70km
  C. Outer core, consist of Fe, Ni in solid state
  D. P-wave can be transfer via solid only
  E. The geothermal gradient for oceanic lithosphere is lawer than that for continental lithosphere
  F. At base of lithosphere, the heat transfer become conductive rather than convective
  G. Melting at the top of a plume producing granitic magma above hot spot
  H. Conduction currents may be found in solid state, but they're slow
  I. The mantle contain ultramafic rocks, that contain olivine, pyroxene (orthopyroxene & clinopyroxene), & garnet
  J. The differences between gappro & norite, Gappro composed of Opx, & norite Cpx
- **Q6: List at least 3 points for each of the following**
  A. Information source of mantle Petrology
  B. Heat sources
  C. partial melting of oceanic crust occur near
  D. The three most common oxides in the mantle are
  E. Rocks melt in the upper mantle due to
- **Q7: Complete the following triangle (UM rocks)**



- **Q8: use the following graph to calculate geothermal-gradant between 1000° – 1500°C depth (on the oceanic, & continental lithosphere)**



- **Q9: The dike in the following picture composed of________ & the surrounding rock is __________**

- **Q10: in the following picture what is the name of boundary between 2 type of rocks, & why?**

THE ORIGIN OF THE MAGMAS

3.1 Introduction

- **The magmatic origin of basalt & rhyolite recognized through** observation of active volcanoes & correlation of their known products with similar-looking ancient rocks by a group of geologists known as Plutonists
- **Theory of the origin of basalt propounded by** the Neptunists held that it was precipitated from a primeval ocean, much as evaporates & Limestone

الشيء المشترك بين ال basalt & rhyolite هم انهما volcanic rocks رغم اختلافهما في التركيب basalt is & rhyolite is felsic و mafic, فكلاهما aphanitic or fine-grained or volcanic وهي الماغما التي تصل الى السطح (راجع الصفحة رقم 8)

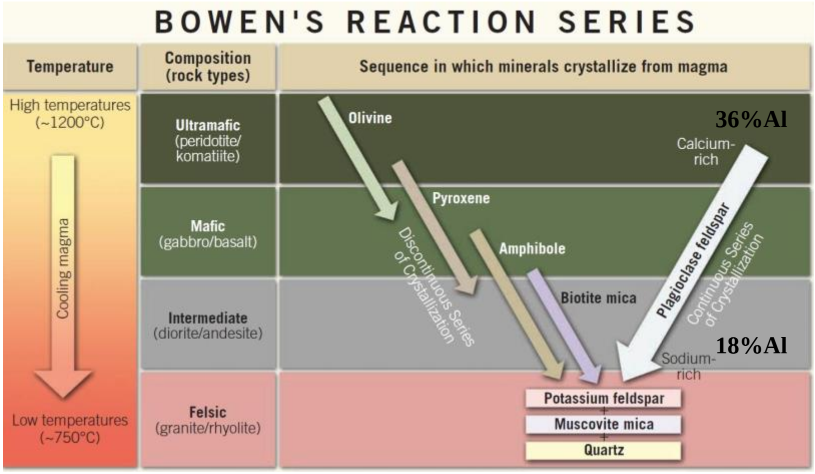
- **James Hutton (founder of Plutonism)**
  - ❖ **Uniformitarianism principal (by Hutton)**: the present is the key of the past
  - ❖ **He heated basalt samples & found that they:**
    1. melted over a range of T (800 - 1200°C)
    2. Very Rapid cooling produced a glass
    3. Slow cooling produces coarse-grained structure & Rapid produced fine-grained
  - ❖ **Granitic rocks crystalline (or solidified) over a range of T, why?** Due to several different minerals found in composition of basalt
- Lab Experiment & application of crystallization of milting theory to infer physical conditions of magma formation & crystallization
- understanding of igneous rock formed mainly from
  1. observations in the field (especially variation in mineralogy or texture)
  2. laboratory study of thin section (minerals)
  3. analyses of chemical composition of the rocks

القشرة المرشحة لانتاج ال magma هي القشرة القارية وليست المحيطية لان درجة حرارة قشرة المحيط اقل من القارة (مثلا لو كان geothermal-gradant 40 وسمك قشرة المحيط 10كم اقصى درجة حرارة ممكنة ستكون 40 * 10 = 400 وهي حرارة قليلة نسبيا لانصهار المعادن) وذلك بعيدا عن mid oceanic ridge والذي تكون به قشرة المحيط خفيفة جدا وتخرج منه ال magma واسفل القشرة القارية قد تصل 850 - 900 (>40كم)

3.2 Bowen's reaction series

- **Discontinuous series:** due to different structure, If the magma is Fe- or Mg-rich the olivine first crystalline & then Mg-pyroxene (orthopyroxene), Ca-pyroxene (clinopyroxene), then amphibole…etc
- **Continues series:** Ca & Al substitute by Si & Na (solid solution series), no change in structure

$$Ca^{2+} + Al^{3+} \leftrightarrow Na^{+} + Si^{4+}$$



3.3 Equilibrium & Thermodynamics

- **Equilibrium** a geologic system (rock or magma) is in state where there is no driving force for change
  - ❖ **If the physical conditions are changed (T or P)** the system shift type of minerals, or amount & composition of melt to achieve new equ. state
  - ❖ ***Thermodynamics systems:***
    1. **a closed system:** can exchange thermal & mechanical energy, but not mass
    2. **an open system** can exchange both energy & mass with the surroundings
    3. **An isolated system:** cannot exchange both energy & mass, theoretical system
       - **Geological system are open or closed**
       - **Systems are consisting of phases, which are described by components**
- **Phases** equilibrium relationships of minerals & melts described graphically by phase diagram
  - ❖ **A phase**: Homogeneous part of a system, that can be mechanically separate from other phases, & can have either a fixed composition (eg. Quartz SiO_2) or a variable (eg. melts or solid solution phases such as plagioclase)
  - ❖ **The phase diagram** fundamental tool used by any scientist deals with molten materials to illustrate crystallization & melting
  - ❖ A number of phase diagrams are used to introduce several principles which are used to interpret magma formation & crystallization
  - ❖ **A spontaneous attainment** of equilibrium in petrology is a process of energy minimization
  - ❖ Eg. In granite each mineral is phase (Quartz, Biotite, Muscovite, K-Pheldspare, Na-Feldspar)
- **Components:** minimum number of constituents that needed to describe all phases in a system, & can have the same compositions as mineral phases
  - ❖ In any system: # of components ≤ # of phases

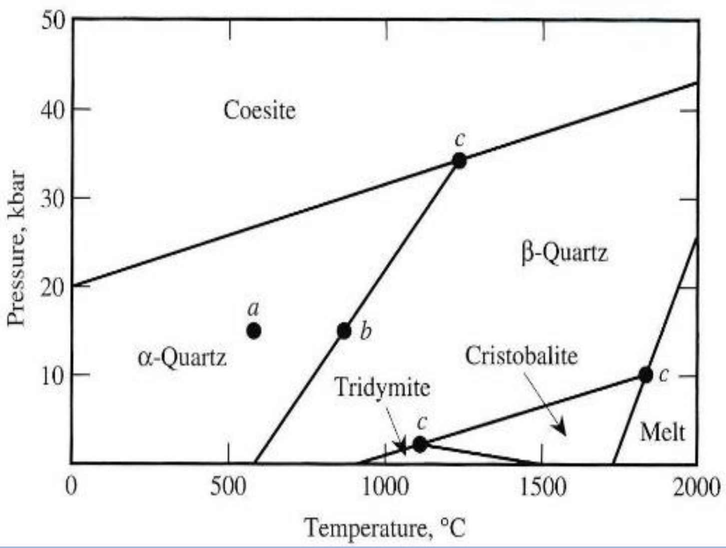
3.4 The Phase Rule

- All igneous & metamorphic minerals are in metastable state (in a process of change but over long periods of time) since they are at higher energy than stable equilibrium phase

F = C – P + X

F : decreases in freedom (variance)
C : number of components
P (or Φ) : number of phases
X : T & P varince, one of them (1), poth (2)
Phase Rule: Relates number of components to the number of phases to T-P variation

- **Number of decreasing in freedom (variance)** is the maximum number of variable of a given system which can be changed independently without changing the state of the system



Stishovite occur by meteorite impact, or about 2000km depth in the earth's surface

اثناء التسخين يحدث phase transformations ثم تبدأ عملية recrystallization عند حدود ال stability fields وال components هي المكونات و هي field stability

At point a in the diagram:
Number of phase = 1, component = 1
F = 1 – 1 + 2 = 2 (can be change T or/& P)
At point b in the diagram: (univariate line)
Number of phase = 1, component = 2
F=1-2+2=1 (can be change one variableT,orP)
At points c: (invariant line)
Number of phase = 1, component = 3
F=1-3+2=0, connect be change any variable

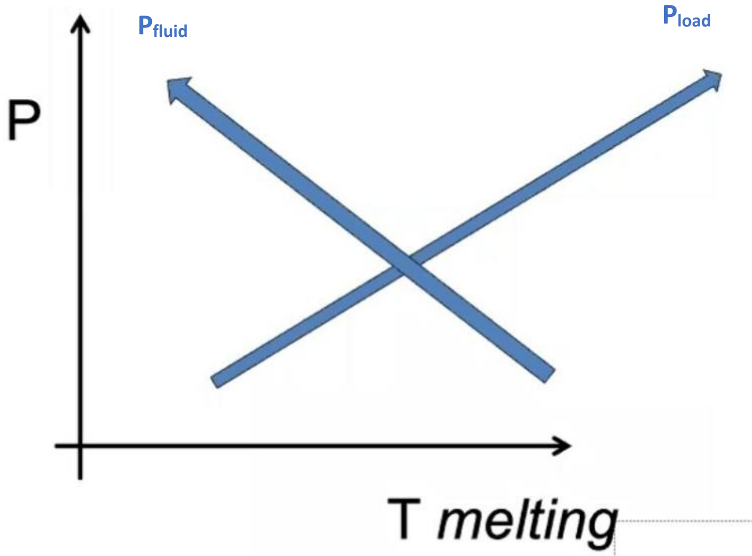
- Max. number of phases exist in any system at equilibrium = number of components + 2

F = C – P + 2 = 0 → P = C + 2

- **Pressure (P):** known as an isobaric condition
- **Temperature (T):** known as isothermal condition

3.5 Pressure affect

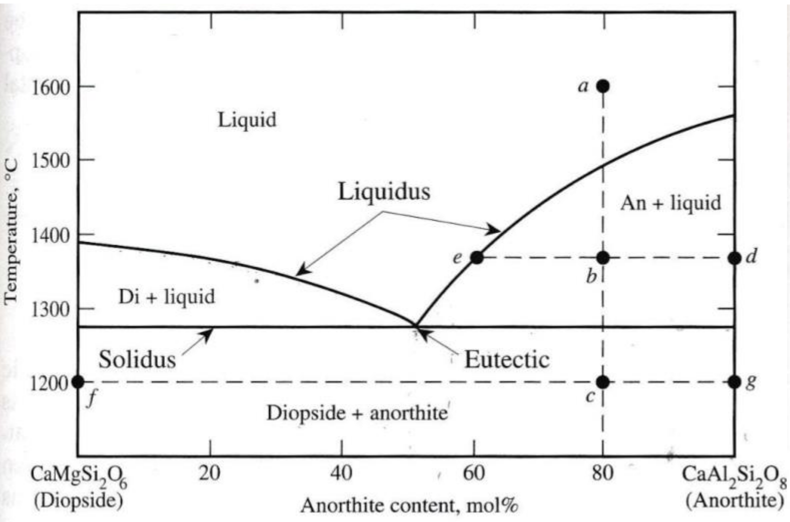
- 2 type of pressure effect milting point:
  1. **Load Pressure P_{load}** (or lithostatic): increases crystallization point & milting point, by rocks
  2. **Fluid Pressure P_{fluid} :** decreases crystallization point & milting point, by fluids such as H_2O, CO_2



زيادة الضغط تؤدي لزيادة درجة الانصهار في انظمة المعادن النقية التي لا يحدث بها **solid solution series** ولا ينطبق مثلا على ال **pyroxene, plagioclase, olivine** لانه يوجد **2-end- members** يحدث بينها **solid solution series**

3.6 Two-component system

- **2-component system (binary)**: bounded at ends by 2 pure solids, & represented by 2D-diagram that plots T versus composition (isotherm diagram) or P versus composition (isobaric diagram)
- **Congruent melting** means that a pure solid phase melts completely at its melting T to produce a liquid of the same composition as the solid
- **Fractional melting** melt is continuously removed from the solid, so the system is divided in 2 fraction One consists of melt & the other consists of solids, no bulk composition constraint or mass balance
- **Isopleth line**: vertical line, represent composition
- **Isotherm line**: horizontal, represent Temperature
- the phase rule for an isobaric binary system is F = c – p + 1, there are 2 components (binary) & 3 phases (anorthite, diopside, & melt), so F=2-3+1 = 0, & this point is the 1280°C eutectic



binary system diopside-anorthite

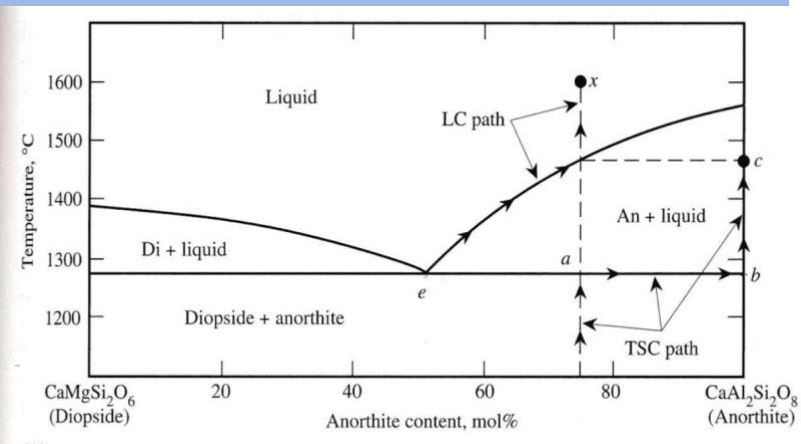
- This system is mafic or intermediate because pyroxene, Ca-plagioclase is the intermediate or mafic minerals, & granitic system are rich in K-feldspar, Na-feldspar, & quartz
- There are three phases on this diagram: diopside (pure $CaMgSi_2O_6$), anorthite (pure$CaAl_2Si_2O_8$), & silicate melt
- The milting of the pure phase (mineral) which consist of one component take place at a fixed T
- **Solidus**: The single horizontal line that forms the upper boundary of the region in which only solids exist
- **The solidus temperature =** T at which the lowest T liquid can exist in the system
- **Eutectic point**: The single point where the 2 liquidus lines meet the solidus line, represents both the T & composition of the lowest T melt (anorthite:diopside = 53:47)

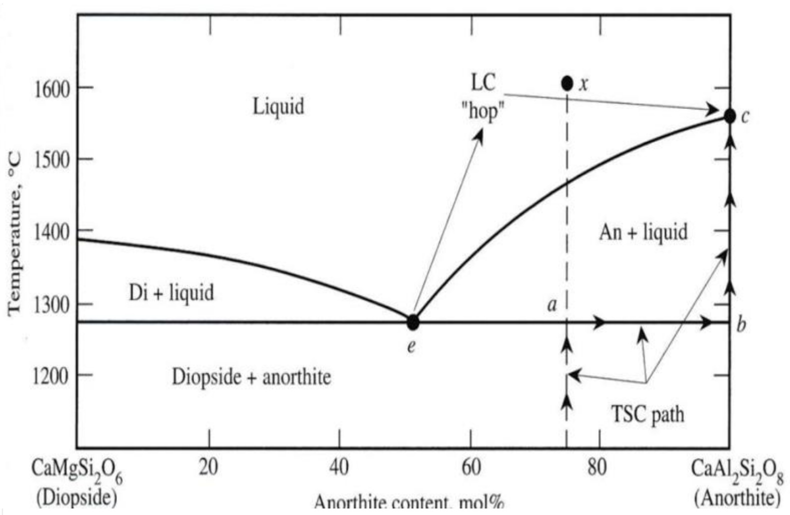
على اطراف ال field تتكون بلورات anorthite كبيرة لانه على عمق كافي في الارض وعند الوصول الى السطح (عند ال eutectic point) سيفقد النظام الطاقة بشكل سريع ما يؤدي لحدوث عملية تبريد سريعة فتنشأ بلورات phenocryst anorthite كبيرة ووحولها groundmass من anorthite & diopside

Example: if we changing T from point a to point c (solidified), From 1600 – 1500 No changes, At 1500: first crystal (anorthite), From 1500 – 1290: the composition of liquid change & the anorthite solid increase by volume, At eutectic point: first diopside crystal, & Under the solidus, Complete solidified occurs with the original composition

Any point on the diagram represent composition, phase, T, & P

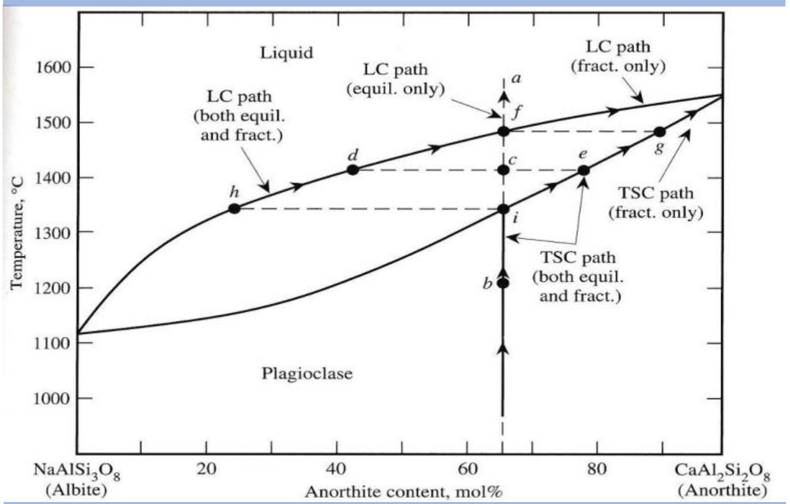
- Point a: 80%An, 20%Di, melt phase, 1600°, 1par
- Point b: 1380°, 1bar, Solid: 100%An, & Melt: 60%An
- Point c: 80%An, 20%Di, solid phase, 1200°, 1par





Change the amount of melt during melting in fractional melting system

- **TSC** : Total Solid Composition, **LC** : Liquid Composition
- **Instante solid or melt composition:** is the composition at any point during crystallization or melting
- في ال fraction نفصل ال eutectic melt فينشأ new system تكون به درجة الانصهار او التبلور هي درجة انصهار او تبلور المعدن نفسه ثم عند درجة الانصهار الاصلية مثلا صخر مكون من dioside anorthite &وكمية ال diopside اكبر سينصهر اول مرة عند eutectic point ≈ 1280 وثاني مرة عند درجة انصهار ال diopside ≈ 1390



Binary Systems with Complete Solid Solution

- Such as olivine, pyroxene, & plagioclase systems
- Under the solidus there are one mineral (homogeneous)

تتشكل ال zoning بواسطة هذه العملية، فهي اطارات كل اطار يحتوي كمية An مختلفة (80٪ بالمركز والاطراف alpite) واذا كانت ال magma تتحرك سريعا لن يوجد وقت ل Si & Na لينتقلا داخل البلورة ويحدث couple substitution

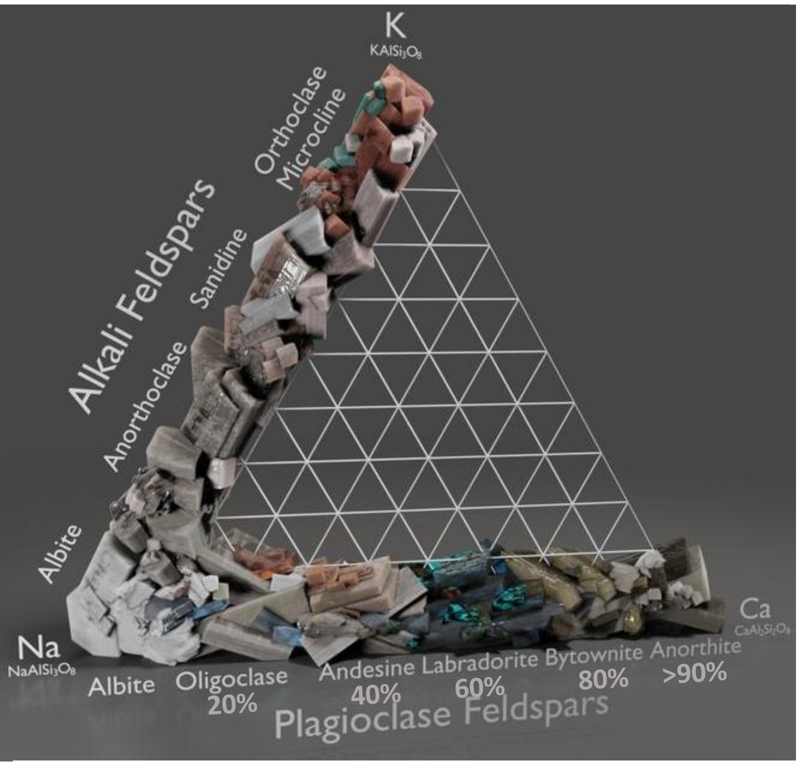
$$Ca^{2+} + Al^{3+} \leftrightarrow Na^{+} + Si^{4+}$$

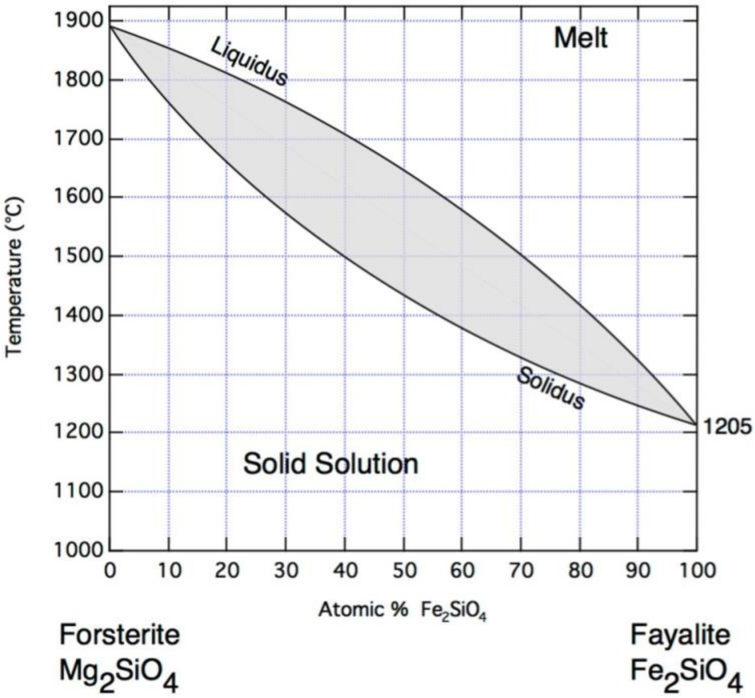
اذا كانت الاطر متدرجة (اي هناك تناقص تدريجي منتظم بين الاطار الخارجي الى مركز البلورة) نسمي هذا التركيب normal zoning

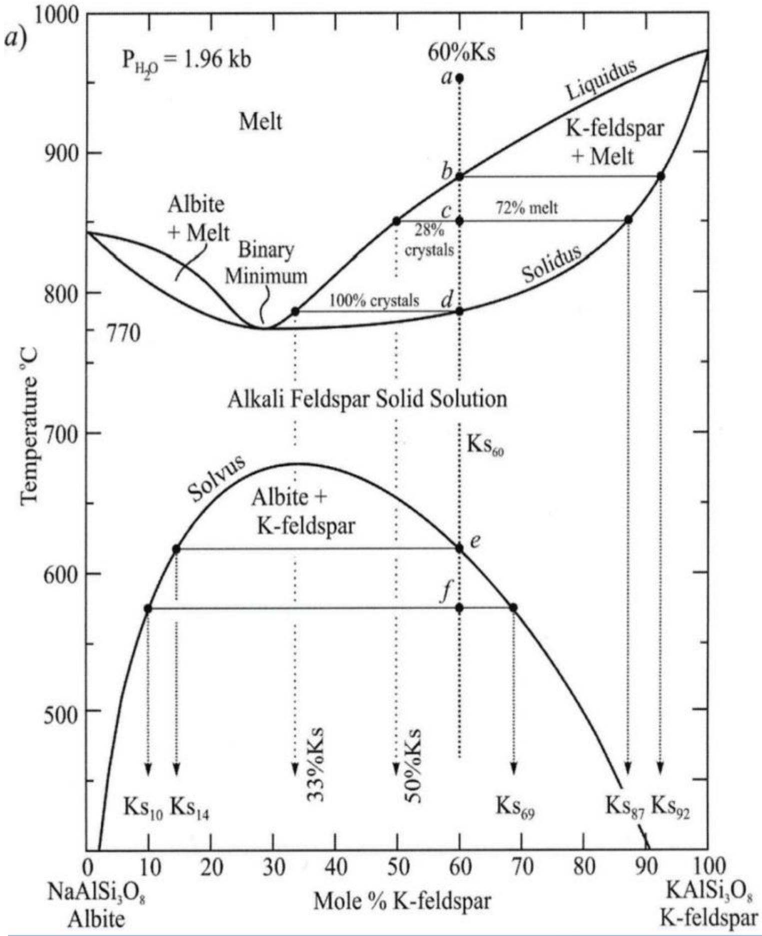
اذا قل الضغط (عند وصول ال magma الى السطح) تنخفض خطوط ال liquidus & solidus فينشأ تركيب يسمى oscillatory zoning (متذبذب في An)، وممكن ان تتبخر ال fluid عبر الشقوق فيرتفع الضغط مجددا

Zoned crystals commonly found in volcanic rocks, & can be found (less common) in gappro & diorite

Zoning found in the plagioclases & can be found in other minerals such as pyroxene (clinopyroxene)





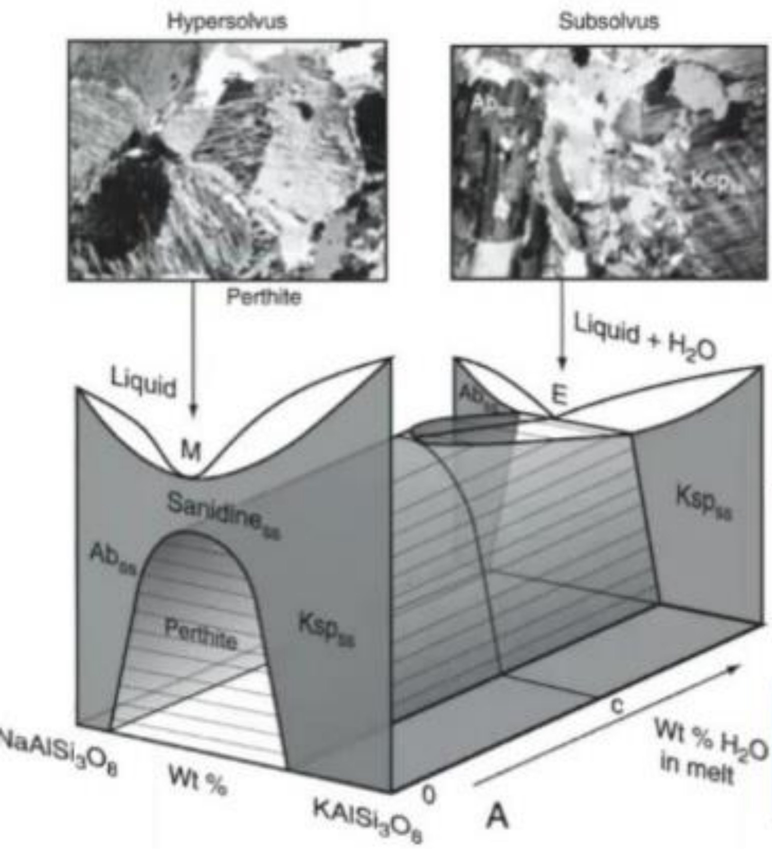


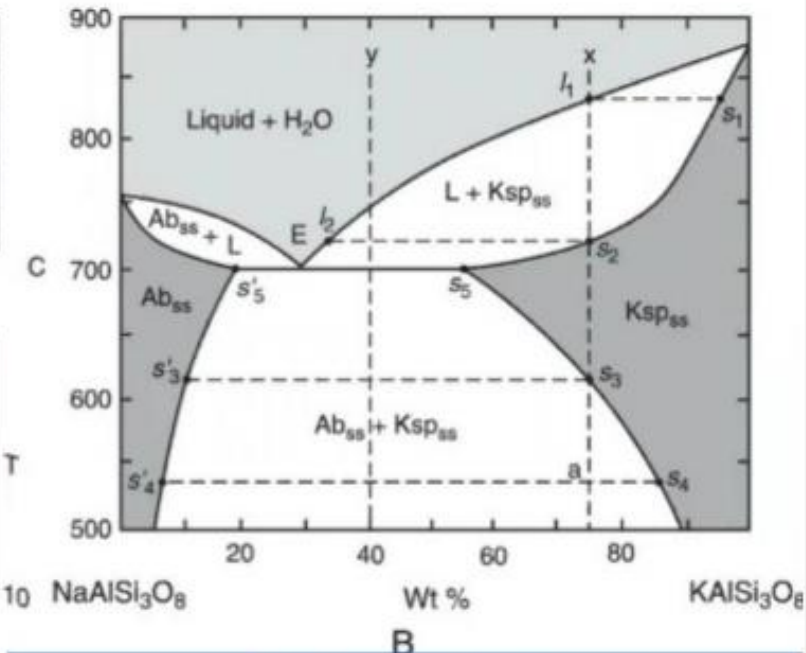
Olivine diagram

- Perfect & Rapid substitution ($Fe^{2+} \leftrightarrow Mg^{2+}$) because size, electronegativity, & charge are almost similar
- Olivine found in ultramafic rocks, Gappro, & Basalt
- Why we don't see many volcanoes with UM materials??
  لان الحصول عليها يتطلب صهر جزء من ال mantle بنسبة 100٪
- Comatite : is the volcanic equivalent for peridotite (found in Archean rocks, (لان مخزون الارض من الحرارة كان اكثر)
- Kimberlite : Carrying diamonds to the earth's surface
- Magmatic differentation: from one parent magma you can get different magma in different composition
- Why we can see zoning in plagioclase but not in olivine? Due to type of substitution

Granite: because consist of K-feldspar (orthoclase) & Na-feldspar (albite)

- نقطة تلاقي solidus مع liquidus هي minimum crystallization point والفرق بينها وبين ال eutectic انه عندها يوجد melt + homogenies solid وعند eutectic : melt + 2different solid
- ال solvus هو الخط الفاصل بين homogenies crystals وبين ال 2 feldspar (K-feldspar & Na-feldspar)
- في انظمة ال limit substitution تحل الايونات محل بعضها في حال رفع درجة الحرارة بسبب فرق الحجوم بينها وفي ظل درجات الحرارة المتدنية يحدث exsolution lamellae
- Perthitic texture: An intergrowth of 2 feldspars (K-rich)
- Antiperthitic texture: intergrowth of 2 feldspar (Na-rich)
- Hypersolvus: above solvus line لم يتم الفصل بين المعادن





Alkali feldspars system

- زيادة ضغط الماء يؤدي لانخفاض ال liquidus + solidus وتقاطعها مع ال solvus فتتشكل ال minimum crystallization point أي eutectic

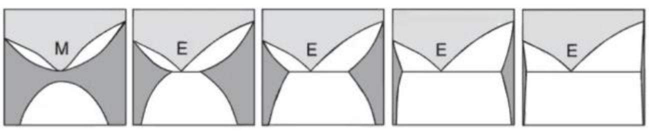
- **Hydrothermal solution:** fluids that transported & milting some rock, & carry ions, & when the T of fluids decreases precipitate the ions to form rocks
  - ❖ 2 type of hydrothermal solutions:
  1. Water that goes deep into earth, heated by GG
  2. Water that separates from the magma during magma differentation
  - ❖ Ultramafic rocks consist of 1.5%Vol H_2O
  - ❖ Mafic rocks consist of 3%Vol H_2O
  - ❖ Felsic (granitic) rocks consist of 6%Vol H_2O

صخر ال **bigmatite** هو **very coarse grained granite** اخر ما يتبلور من ال **granitic** لذا تكون به نسبة ال **fluids** عالية ما يؤدي لتسريع حركة الايونات فتتكون بلورات كبيرة

ما اهمية التمييز بين ال **hypersolvus & subsolvuse** : اذا وجدنا **granite** يوجد به **tow feldspar** نستنتج ان كمية ال **fluid** كانت به كبيرة نسبيا اي انه كان مصدرا لل **hydrothermal solution** والتي تتميز بحملها لمعادن لا مكان لها في المعادن الرئيسية مثل **gemstones, silver, gold..**

ال **hypersolvuse granite** يحتوي كمية ماء قليلة، وعملية التبلور تحدث فوق ال **solvus** فيتكون **homogenies feldspar**

ال **subsolvuse granite** يحتوي كمية ماء كبيرة، وعملية التبلور تحدث تحت ال **solvus** فيتكون **2feldspar**



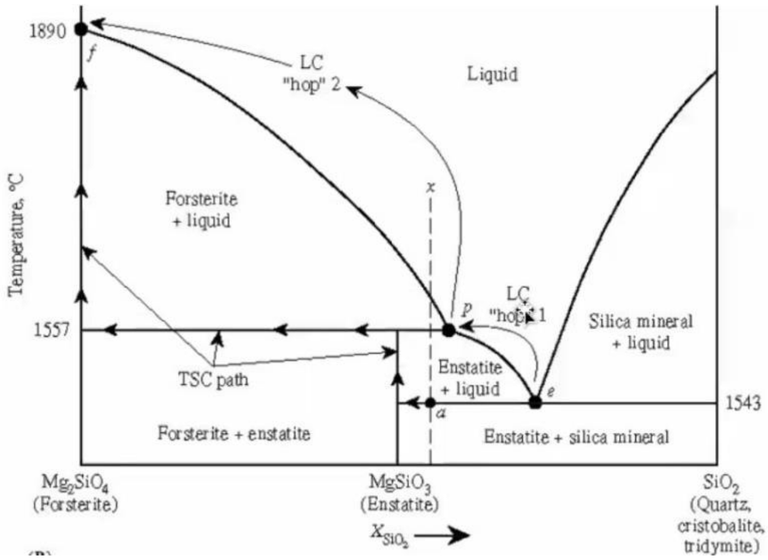
➔ **More water contents**

عند زيادة الماء وتقاطع خطوط ال liquidus & solidus مع solvus تتحول النقطة في الوسط الى eutectic point

اذا كانت ال magma غنية جدا في ال fluids مثل E يتكون pure albite & pure anorthite feldspar

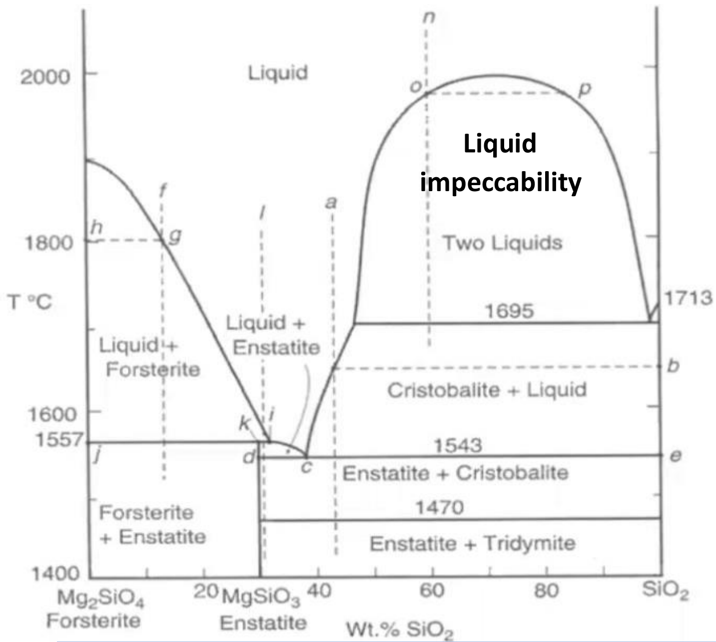
3.7 Icongruently phase diagram

- **Incongruent melting** if a solid phase doesn't melt to a liquid of its own bulk composition, but breaks down to form liquid & another solid phase
- Incongruent binary systems, such as:
  1. **Enstatite Opx $Mg_2Si_2O_4$ (intermediate compound)** which melt Icongruently to produce solid forsterite olivine Mg_2SiO_2, & forsterite + silica SiO_2 as (Peritectic liquid)
  2. **Quartz-feldspathoid**(leucite,nepheline)system



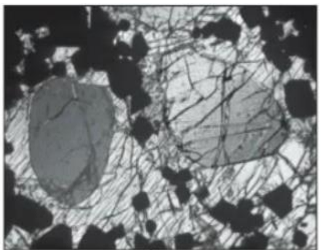
- there are 2 invariant points involving liquid:
  Eutectic(1543°C): between enstatite, & Tridymite
  Peritectic point (p) at 1557°C where we have Icongruently melt, all enstatite melting in this point & converted to silica + olivine

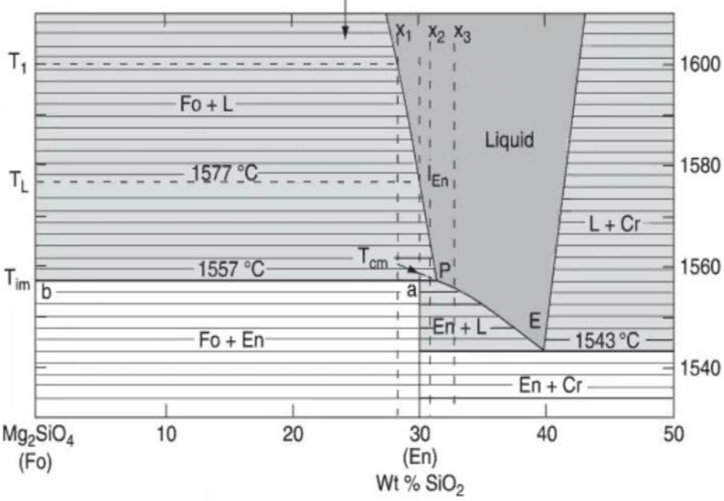
- **Peritectic point (called reaction points)** is quite different from the eutectic, because liquid can leave it as cooling proceeds, moving down the liquidus to the eutectic point, which is always the lowest T liquid composition in the system
- TSC path in fractional melting is continuous & is similar to that in equilibrium melting.
- the LC path is discontinuous, with liquid appearing only at invariant points & being restricted in composition to these Points.



Forsterite can be formed from all composition from the Peritectic point, & from eutectic point cannot be form (silica & enstatite only)

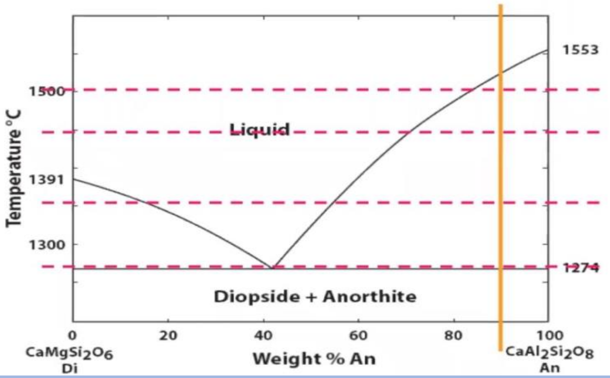
Forsterite Mg_2SiO_4 → is olivine, Enstatite $Mg_2Si_2O_6$ → is pyroxene





3.8 Magma Differentiation

- We can get from parent magma different rock types (or >one magma with different composition)
- Processes of magma differentiation (diversification of magmas start):
  1. Fractional crystallization
  2. Liquid impeccability
  3. Rock assimilation
  4. Magma mixing
  5. Degree of partial melting
- **Gravitational settling:** is the process by which particulates rise to the bottom of a magma due to gravity, important operation in many application, such as mining (Ores are formed by separating minerals)



الفرق بين هذا ال diagram والسابق هو موقع ال eutectic point والسبب بأن هذا تم التوصل له بالحسابات calculated اما الاخر experimental وهو الادق

partial melting	An wt%	Di wt%	Initial solid	17%	23%	35%	69%	100%
SiO_2	43.2	55.5	44.43	49.7	48.7	46.6	45.0	44.4
Al_2O_3	36.7	0.00	32.99	17.2	20.2	26.9	31.2	33.0
CaO	20.2	25.9	20.73	23.2	22.7	21.8	21.0	20.7
MgO	0.00	18.6	1.860	9.87	8.38	5.12	2.79	1.86

لحساب اي oxide باي معدن:(العمودين الثاني والثالث)

$(Mm_{oxide}/Mm_{mineral}) * 100\%$

Ex. We want to calculate amount of silica in An, Di

Step1 : calculate the Mm of silica & minerals

$SiO_2 = 28 + 2 * 16 = 60$ g/mol

$CaMgSi_2O_6 = 40 + 24 + 2*28 + 6*16 = 216$

$CaAl_2Si_2O_8 = 40 + 2*27 + 2*28 + 8*16 = 278$

Step2: Multiply oxide with #of mole in mineral

$CaMgSi_2O_6 \rightarrow Ca^{2+}O^{2-} + Mg^{2+}O^{2-} + 2(Si^{4+}O_2^{4-})$

$CaAl_2Si_2O_8 \rightarrow Ca^{2+}O^{2-} + Al_2^{6+}O_3^{6-} + 2(Si^{4+}O_2^{4-})$

$SiO_{2An} = 2 * 60 = 120$, $SiO_{2Di} = 2 * 60 = 120$

Step3 : Divide the # in step 2 on the $Mm_{mineral}$

$SiO_2An = (120/278)*100\% = 43.2$

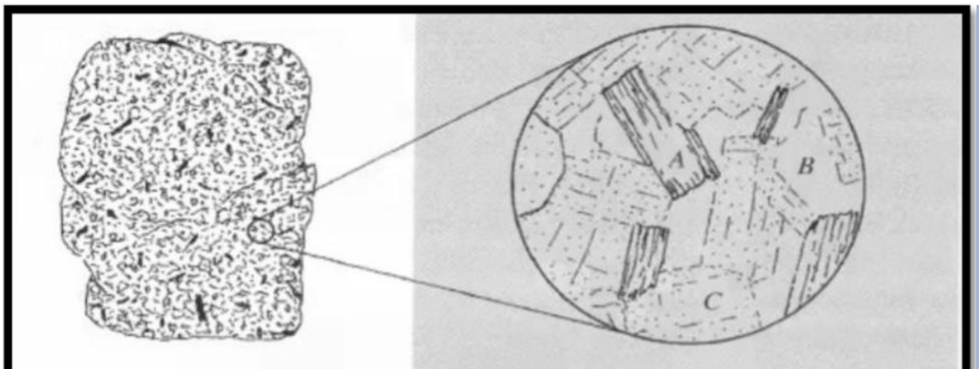
$SiO_2Di = (120/216)*100\% = 55.6$

لحساب ال degree of partial melting مثلاً ال initial solid

ولنفرض ان التركيب هو التركيب المبين في diagram

[SiO_2An(step3)*Vol%An] + [SiO_2Di(step3)*Vol%Di]

Ex. 43.2*0.9 + 55.6*0.1 = 44.44



	Wt.%	A	B	C
		Wt.%	Wt.%	Wt.%
SiO_2	65.71	37.17	99.82	64.50
TiO_2	0.51	3.14	0.05	0.00
Al_2O_3	16.16	14.60	0.06	20.25
Fe_2O_3	0.92	3.75	0.03	0.47
FeO	4.30	26.85	0.01	0.00
MgO	0.68	4.23	0.00	0.00
CaO	0.36	0.17	0.00	0.48
Na_2O	3.25	0.15	0.00	4.72
K_2O	7.87	8.25	0.01	9.60
H_2O	0.41	1.35	0.02	0.28
Total	100.17	99.66	100.00	100.30

	Vol.%
A	13.7
B	15.9
C	70.4
Total	100.0

	Wt.%
A	16.0
B	15.8
C	68.2
Total	100.0

يوضح الشكل العلاقة بين التركيب الكيميائي للمعادن المختلفة (نسبها) والتركيب الكيميائي للصخر ككل وكيف تتحكم نسب المعادن وكيميائيتها في كيميائية الصخر

نوع الصخر يمكن الاستدلال عليه من النسيج والتركيب فهو **coarse-grained, plutonic** ونسبة ال **biotite** به عالية اذا هو **granodiorite**

- **Feldspar = C ،Quartz = B ،Biotite = A**
- النسب تحت الصخر هي التركيب الكيميائي للصخر ككل (لنفرض انها x)، النسب تحت ال cross- section التركيب للمعادن الموجودة فيه (y)
- العمود الثالث هي النسب الحجمية والوزنية للمعادن الثلاث (لنفرض انها z) والتي يمكن ان تتساوى اذا كانت الكثافات متساوية
- لو اردنا حساب كمية ال silica في الصخر مثلا تكون نسبة ال silica في هذه المعادن كلها = نسبتها في الصخر

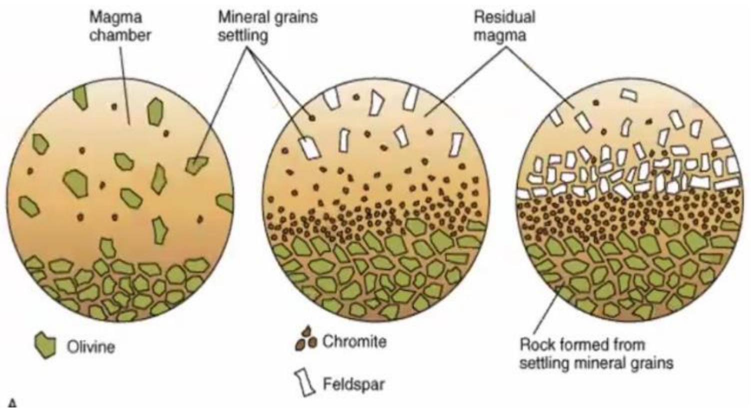
$(Wt\%SiO_{2Az}*Wt\%SiO_{2Ay})+(Wt\%SiO_{2Bz}*Wt\%SiO_{2By})+(Wt\%SiO_{2Cz}*Wt\%SiO_{2Cy}) = Wt\%SiO_{2x}$

Example: $SiO_2x = [(16.0*37.17/100\%) + (15.8*99.82/100\%) + (68.2*64.50/100\%)] = 65.71$

3.9 Fractional crystallization processes

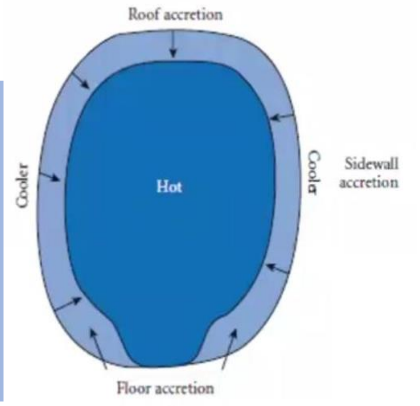
- **Fractional crystallization processes:** Separation of crystals from melt, lead to magma differentiation
- **Several models are suggested:**
  1. *Marginal accretion* due to preferential cooling of the boundaries of the magma chamber: roof, side wall, & floor
  2. *Gravitational settling*
  3. *Convection flow*
  4. *Filter pressing*
- **Filter pressing:** a process that expresses the exit of the magma from the solid pieces
  - ➢ This process is responsible for the formation of igneous layers (with Magma settling)

هذه العملية اهم من ال gravitational settling خاصة اذا كانت كثافات المعادن قريبة من بعضها البعض فال gravitational settling تعتمد على الفرق في الكثافة لتشكيل طبقات من الصخور النارية مختلفة في الكثافات



- **Marginal accretion**

The early formed mineral phases separated from the magma & the remaining magma enriched in the low T minerals

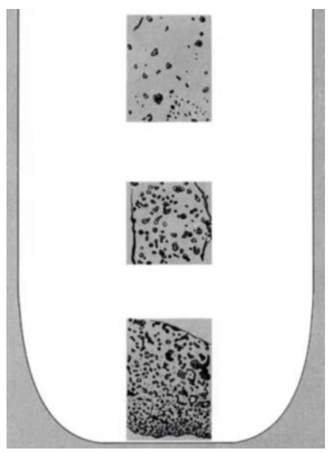


البلورات الخفيفة ترتفع لاعلى ويتشكل منها معادن مثل plagioclase

- **Gravitational settling (Magma settling)**

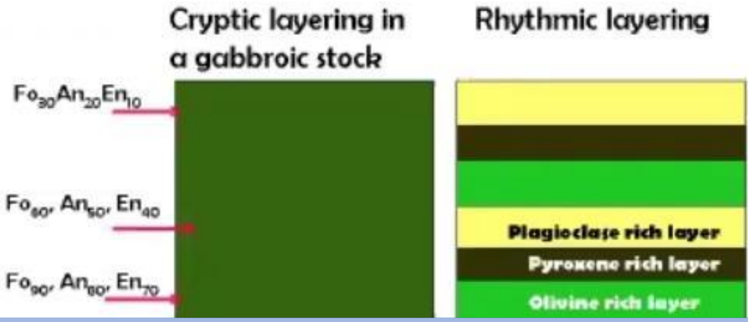
Bowen classical experiment showing the sinking of olivine crystals within melt. The melt was quenched after 15 min(olivine settled down up to 2cm in 15 min)

low P fractional crystallization followed by gravitational settling is still the widely accepted model for their formation



هذه العملية هي المسؤولة عن تكون الlayers اعتمادا على فصل المعادن بحسب كثافاتها، لكن اذا خرجت ال magma الى السطح لا يحدث layering ابدا الا اذا كانت pyroclastic مثل Tuffs (Transitional (area between igneous & sedimentary rock

- **Types of igneous layers**
  1. **Rhythmic layering:** sequences is repeated & you can see this repeated sequence in the field
  2. **Cryptic layering:** The sequence cannot be seen in the naked eye, but it can be inferred through chemical analysis, found in Gapproic rocks



ال Rhythmic ليس بالضرورة ان يحدث نفس التتابع ويمكن ان ينعكس

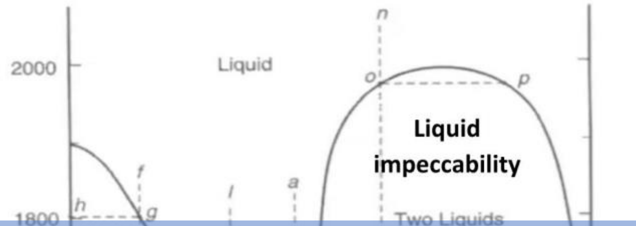
ال cryptic layering اذا اخذنا عينات من القاعدة الى القمة سنجد ان هناك اختلاف منتظم في كمية المعادن المكونة له, وتجدر الاشارة الى ان ال endmember الموضوعة هي دائما High-T للمعادن (Fo → olivine, (An → plagioclase, & En → orthopyroxene

- **Layering can be found in Gapproic, or Basaltic (Mafic) but there's no in granitic or Rhyolite Why?**
  1. ***Density*** There is no differences in densities between minerals in felsic rocks (Na-plagioclase, K-feldspar, & quartz all have almost the same density)
  2. ***Viscosity*** granitic rocks has very high viscosity (10 times of mafic viscosity) which prevents the mineral to move in the batholiths

chromitite-anorthosite Rhythmic layer, Bushveld complex

Magnitite layers

- **Liquid-Liquid impeccability** 2 melts controlling mineralogical of the crystallization of the magma



هذه العملية مسؤلة عن ال carbonate magma والتي عندما تتبلور تعطي صخر يحتوي Ca-carbonate وهو بركان واحد نشط في العالم من ال 500 بركان بتنزانيا، وايضا نوع اخر غنية في sulfide وهو اكثر ندرة من الاول

Fractional crystallization calculation

Oxides	Glass	Olivine	Pyroxene	Plagioclase	O:75%gl,15 %Ol, 10%Px	A: 80%Ol, 20%Px	B:10%Ol,40 %Px,50%Pl	FM1	FM2
SiO_2	48.8	38.8	46.6	52.5	**47.1**	**40.4**	**48.8**	**48.8**	**50.7**
TiO_2	2.68	0.05	3.80	0.15	**2.40**	**0.80**	**1.60**	**2.80**	**3.40**
Al_2O_3	14.4	0.03	6.27	29.1	**11.4**	**1.27**	**17.0**	**14.0**	**16.3**
FeO	11.1	20.0	8.25	0.89	**12.1**	**17.7**	**5.75**	**10.8**	**8.75**
MnO	0.17	0.27	1.03	0.03	**0.27**	**0.42**	**0.45**	**0.23**	**0.27**
MgO	6.65	40.6	13.5	0.10	**12.4**	**35.2**	**9.50**	**6.74**	**0.36**
CaO	11.7	0.30	19.6	12.3	**10.7**	**4.17**	**14.0**	**12.4**	**15.2**
Na_2O	2.74	0.04	0.59	4.33	**2.12**	**0.15**	**2.41**	**2.61**	**3.01**
K_2O	0.79	0.02	0.05	0.37	**0.60**	**0.03**	**0.21**	**0.74**	**0.85**

O : original magma composition, A Cumulate, B Cumulate, FM1: composition of fractional melting after separation 20% of magma in form of cumulate A, FM2: composition of the remaining magma after separation 30%Ol

The cumulate form by gravitational settling, Water are 100% complementary

To calculate any oxide continents in O, A, or B

Σ(Oxide%in mineral * Wt% of mineral)/Wt% of mineral

Example: we have to calculate silica continents in O

There are 0.75glass, 0.15Ol, & 0.1Px

Wt% of mineral = Total percent = 0.75 + 0.15 + 0.10 = 1.0

Σ(Oxide*Wt)=(48.8*0.75)+(38.8*0.15)+(46.6*0.1) = 47.11

Silica continent = 47.11/1.0 = 47.11 ≈ 47.1

To calculate silica continent (in FM1) after separation 20% of magma in form of cumulate A

Oxide in FM1 = (Oxide in O – Oxide in A)/Remaining Oxide

Example: SiO_2 in O= 47.1*1 = 47.1, SiO_2 in A =40.4*0.2 =8.1

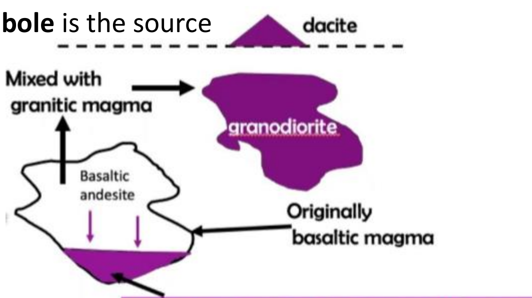
Remaining SiO_2 = 100% - 20% = 80% = 0.8

SiO_2 in FM1 = (SiO_2 in O – SiO_2 in A)/Remaining SiO_2

SiO_2 in FM1 = (47.1 – 8.1) / 0.8 = 48.57

لون ال Obsidian الاسود ناتج عن التوزيع ال uniform لذرات ال Fe (والتي تشكل max 3%Vol) وهذا التوزيع (الانتشار) في كل الزجاج) يجعل ال Obsidian لا يمرر الضوء (اسود)

Garnet, & amphibole is the source of Al in mantle, & **Phlogopite** "Biotite-Like" is the source of Al & K



Gravitational settling of olivine and Pyroxene Gives an intrusive coarse-grained Peridotite (Olivine + pyroxene)

QUESTIONS

- **Q1 : Defined the following**
  - A. Phase
  - B. Variance
  - C. Phase Rule
  - D. Equilibrium
  - E. Isopleth line
  - F. Isotherm line
  - G. Eutectic point
  - H. Peritectic point
  - I. Marginal accretion
  - J. The phase diagram
  - K. Gravitational settling
  - L. Hydrothermal solution
  - M. Magma differentiation
  - N. Fractional crystallization
  - O. Liquid-Liquid imeccability
  - P. Uniformitarianism principal
  - Q. Instante solid or melt composition
- **Q2 : Complete the following**
  - A. The magmatic origin of basalt & rhyolite recognized by a group of geologists known as __________
  - B. ________ volcanic equivalent for peridotite
  - C. Founder of Plutonism: ______________
  - D. Basalt melted over range of T ___ to ___
  - E. Rapid cooling produces ______structure & Slow produced ______
  - F. If the magma are rich in Fe & Mg, the first mineral crystallize is ______
  - G. Solid solution series in bowns reaction series is _____ + _____↔_____ + ______
  - H. If the ______ are changed the equilibrium system shift type of minerals, or amount & composition of melt to achieve __________
  - I. Systems are consisting of phases, which are described by _________
  - J. _____ is a Homogeneous part of a system, that can be mechanically separate from another, & can have either a fixed composition (eg. SiO_2) or a variable (eg. Melts or solid solution phase: plagioclase)
  - K. A/An ___________ of equilibrium is a process of energy minimization
  - L. ____________ is the minimum number of constituents that needed to describe all phases in a system, & can have the same compositions as mineral phases
  - M. All igneous & metamorphic minerals are in _________ state (in a process of change over long periods of time) since they are at higher energy than equilibrium phase
  - N. ________ known as an isobaric condition & ________ known as an isotherm condition
  - O. Ultramafic rocks consist of ___%Vol H_2O, Mafic rocks ___%, &Felsic (granitic) ____%
  - P. T versus composition diagram is called _________ diagram & P versus composition diagram is called ________ diagram
  - Q. Most important process responsible for the formation of igneous layers is ________ (That doesn't depend on density!)
  - R. ________ & _________ is the source of Al in mantle, & the __________ is the source for poth Al & K
  - S. _________ is the biotite-like mineral
- **Q3: Explain the following**
  - A. Granitic rocks crystalline (or solidified) over a range of T, why?
  - B. Granitic magma formed by partial melting of lower continental crust (rether than oceanic crust), Why?
  - C. Boiling point in the pure mineral system that don't contain solid solution series increasing with increase P, This doesn't apply to systems that contain solid solution series, Why?
- **Q4: Choose the correct answer**
  - A. who say in the theory of the origin of basalt & rhyolite: was precipitated from a primeval ocean, as evaporate & Limestone
    1. Plutonists 2. James Hutton
    3. Igneousists 4. Neptunists
  - B. Very Rapid cooling of magma produced
    1. Coarse-grained rock 2. Volcanic rock
    3. Plotonic rock 4. Volcanic glass
  - C. The mineral of Discontineouse Bowns reaction series differ in
    1. Composition 2. Structures
    3. Composition & structure 4. Non of them
  - D. Thermodynamic system which can exchange energy, but not mass, is
    1. A closed system 2. An open system
    3. An isolated system 4. All systems
  - E. Geological Thermodynamic systems is/are
    1. A closed system 2. An open system
    3. An isolated system 4. All except isolated
  - F. Lithostatic pressure is
    1. Load pressure 2. Atmospheric pressure
    3. Fluids pressure 4. All of them
  - G. Zoned crystal commonly found in ___ rock
    1. Volcanic 2. Plutonic 3. Gapproic

H. Zoning most commonly found in
1. Plagioclase & Pyroxene 2. Olivine
3. Plagioclase & olivine 4. Amphibole

I. A pure solid phase melts completely at its melting T to produce a liquid of the same composition as the solid
1. Congruent melting
2. Equilibrium melting
3. Fractional melting
4. Incongruent melting

J. occur by meteorite impact, or about 2000km depth in the earth's surface
1. β-quartz silica 2. Crystabolite silica
3. Stishovite silica 4. Trydimite silica

K. if a solid phase doesn't melt to a liquid of its own bulk composition, but breaks down to form liquid & another solid phase
1. Congruent melting
2. Equilibrium melting pressure
3. Fractional melting
4. Incongruent melting

L. Chromitite-Anorthite layers which found in Bushveld complex is formed due to
1. Gravitational settling
2. Liquid-Liquid impeccability
3. Convection currents
4. Marginal accretion

M. The rare magma composition such as carbonate & sulfur magma formed due to
1. Gravitational settling
2. Liquid-Liquid impeccability
3. Convection currents
4. Marginal accretion

- **Q5: T/F**

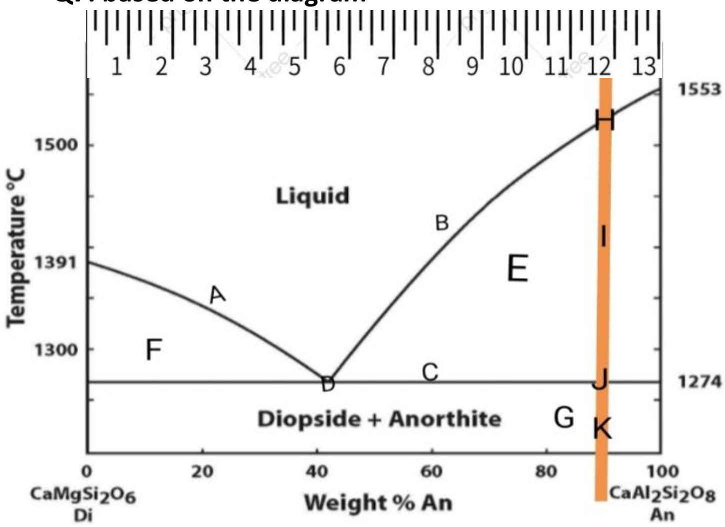
A. Basalt & rhyolite are aphanitic or fine-grained or volcanic rocks, & both are felsic
B. The rock melted over range of T
C. A number of phase diagrams are used to introduce several principles which are used to interpret magma formation & crystallization
D. In granite all minerals are one phase (Quartz, Biotite, Muscovite, K-Na-feldspar)
E. In any system: number of components ≥ number of phases
F. Max. Number of phases exist in any system at equilibrium = number of component + 2
G. 2-component system (binary): bounded by 2 pure solids, & plots T versus composition or P versus composition diagra
H. In equilibrium melting:melt is continuously removed from the solid, so the system is divided in 2 fraction One consists of melt & the other consists of solids, no bulk composition constraint or mass balance
I. Rhythmic layers formed by gravitational settling & you cannot see layering in the field (observe through chemical analysis)

- **Q6: List at least 3 points for each of the following**

A. The magmatic origin of basalt & rhyolite recognized by Plutonists through
B. understanding of igneous rock formed mainly from
C. 2 type of pressure effect milting point
D. Processes of magma differentiation
E. 2 type of hydrothermal solutions
F. List 2 incongruent binary system
G. 2 invariant points involving liquid in incongruent binary systems
H. fractional crystallization processes

I. Layering can be found in Gapproic, or Basaltic (Mafic) rocks but there's no in granitic or Rhyolite (felsic) rocks Why?

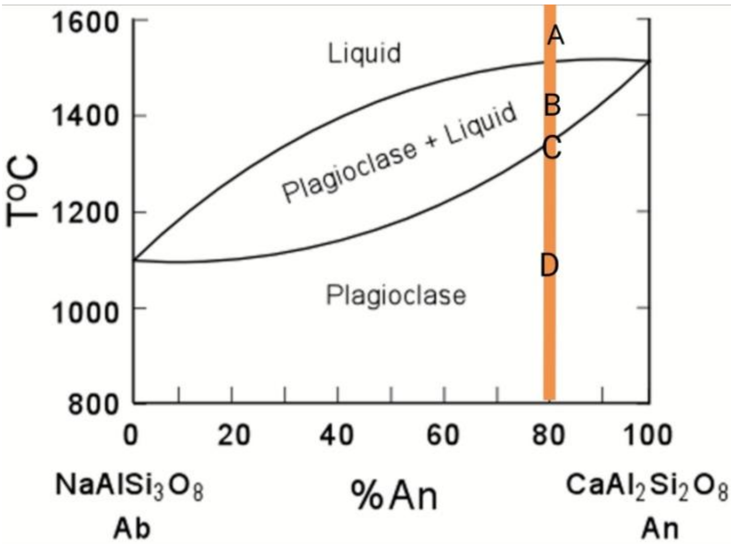
- **Q7: based on the diagram**



1. What is the type of this system, & does it contain solid solution series?
2. How many liquidus line exist & what are their symbols?
3. What is the solidus line symbol?
4. What is the phases in G, E, & F field?
5. If we cooling sample composed of anorthite & diopside (As shown in the orange line) , At what T do you see the first enortoite crystal & at what T is the first diopside crystal?
6. At what point does the process of crystallization of the solution begin & at what point does it end?

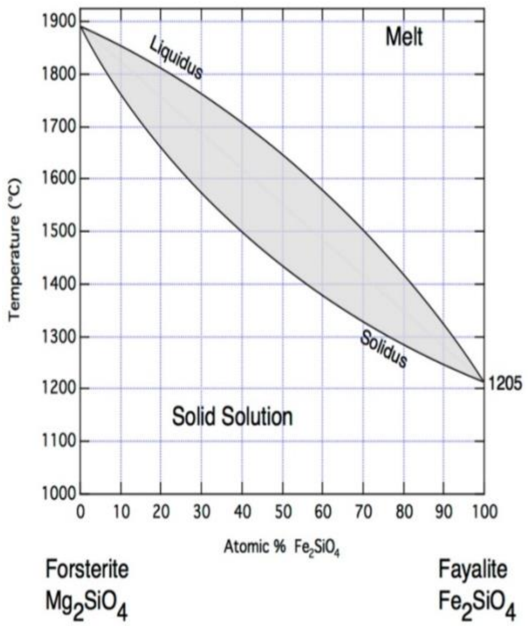
7. system is (mafic, intermediate, felsic), & Why?
8. How many phases on this diagram?
9. T at which the lowest T liquid can exist in the system called _______
10. Describe point I (P, T, composition)

- **Q8: based on the diagram**



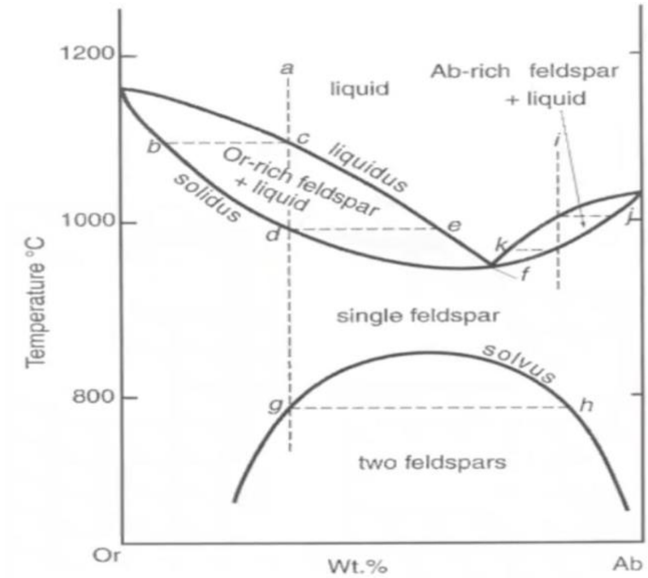
1. What is the type of this system, & does it contain solid solution series?
2. What is the phases at point A, B, & D?
3. At point C the number of decreasing in freedom equal ____
4. If we cooling sample composed of anorthite & alpite (As shown in the orange line) , At what T do you see the first crystal? (with composition)
5. List other systems that such as this system
6. How many minerals exist under the solidus?
7. Write tha substitution formula of f this system

- **Q9: based on the diagram**



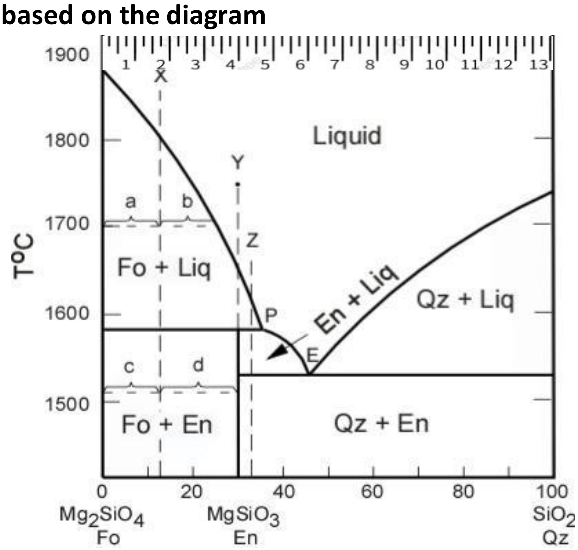
1. Write the substitution (with type)
2. Olivine found in ultramafic rocks, Gappro, & Basalt rocks, Why?
3. Why we don't see many volcanoes with UM materials??
4. Why we can see zoning in plagioclase but not in olivine?

Q10: Answer the following question based on diagram



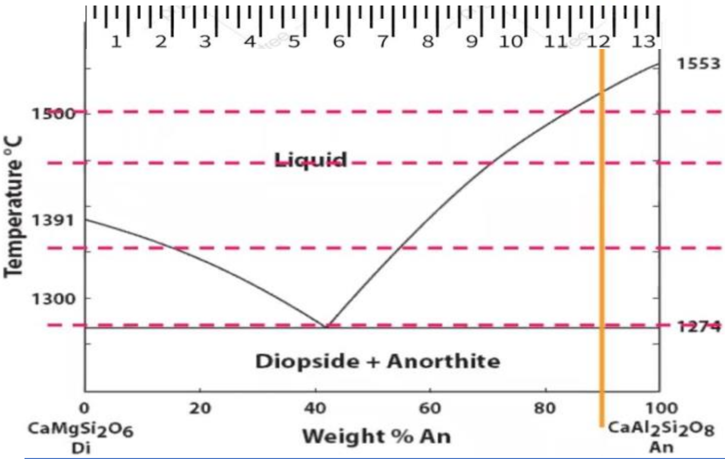
1. What happens if water is added to this system? & what happens if a lot of water is added?
2. This system is (Granite, basaltic) & Why?
3. What's the name of point at the solids & liquidus lines intersection? & What's the difference between this point & eutectic?
4. What is the solvus line?
5. if K-feldspar (alpite) is more than Na-feldspar, the textural is called _______
6. If K-feldspar (alpite) is less than Na-feldspar, the textural is called _______
7. What is the importance of distinguishing between Hypersolvus & subsolvuse?

Q11: based on the diagram



1. Point E called_______, & point P called ______
2. Describe the center point at 1700 degrees
3. Write the reaction at the Peritectic point
4. Forsterite completely melting at T = ______°C

- **Q12: Depending of the following diagram, Complete the following Table**



Oxides	Wt%An	Wt%Di	Degree of partial melting (for melt)			
			1st solid	17%	35%	100%

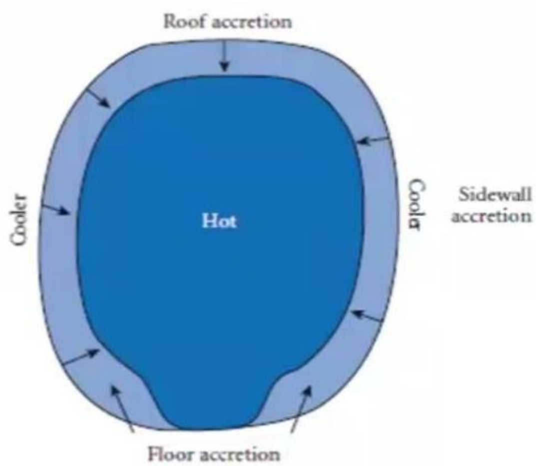
Mm:Ca=40.1,Mg=24.3,O=16.0,Al=27.0,Si=28.1

Q13: Complete the following Table

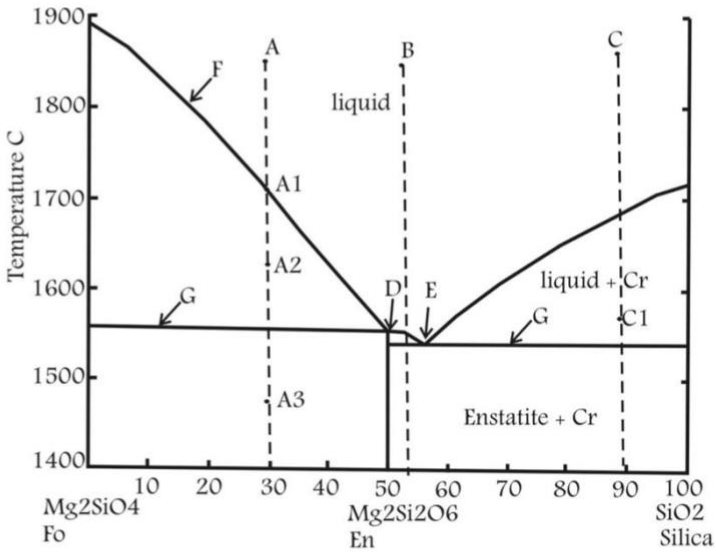
Oxides	A	B	C	D	O: 55%A, 15%B, 30%C	E: 80%C, 20%D	F:10%A, 40%C,50%D	FM1	FM2
1 st	48.8	38.8	46.6	52.5					
2 nd	14.4	4.60	6.27	29.1					
3 ed	17.2	40.6	27.5	6.10					
4 th	19.6	16.0	19.6	12.3					

O : original melt, 55%A, 15%B, & 15%C
E : Cumulate include 80%C, 20%D
F: Cumulate include 10%A, 40%C, 50%D
FM1 : fractional melting include remaining magma after separation 30% of magma in form of cumulate E
FM2 : fractional melting include remaining magma after separation 30%C in form of cumulate F

Q14: The following image expresses (mention the name of the phenomenon & explain it)



Q15: Study the phase diagram



1. The name of the lines indicated by F & G
2. Name of the points D & E
3. Describe the reactions that take place at D & E in both directions
4. Name & amount of phases at the isotherms passing through A2 & A3 for melt A
5. A solid that consists of 95%Fo has been heated at what T start to melt?
6. At this T express the composition of the melt in terms of Wt%SiO_2-MgO provided that Fo consists of 57.32MgO & 42.6 8SiO_2
7. What is the composition the original solid in terms of these oxides?
8. What should happen for this melt to start change in composition?
9. At this point you decide to remove the melt, at what T would the remaining solid melt?

Q16: The next image represents layers, what kind of layers? What's the name of this complexity? What's the name of this rock? What processes led to this layer & where did it originate?

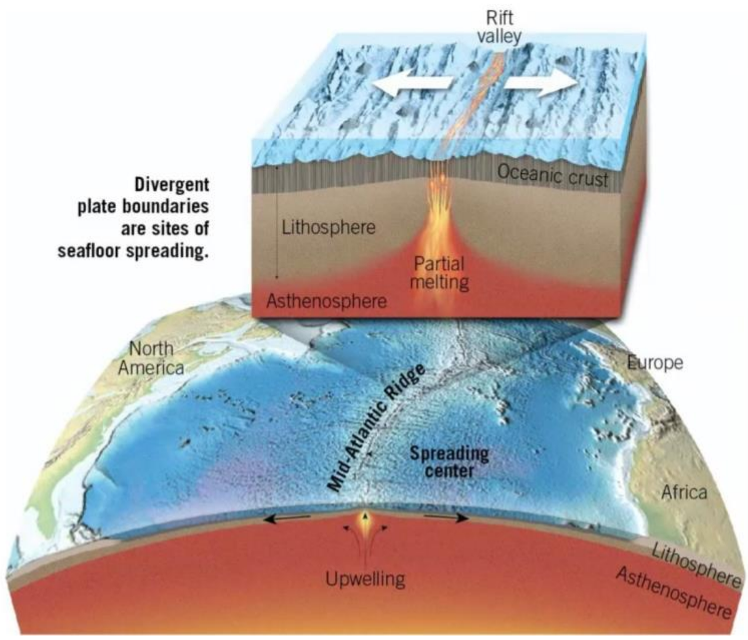
PLATE TECTONIC (REVIEW)

FROM FOUNDATION OF EARTH SCIENCE

	Definition	Occur on	Produce	Example	Machinesem
Divergent Plate Boundaries (constructive)	2 plates move apart	along the oceanic ridges	**Seafloor spreading** **Oceanic ridges** **Rift-valley**	**Hawaiian Island**	The leading edge of one is bent downward
Convergent Plate Boundaries (destructive)	Two plates move toward each other, one slides beneath the other	Oceanic-oceanic Oceanic-Continental Continental-Continental	**Trench (subduction zones)** : Surface expression of the descending plate **volcanic arc** **Mountains**	**Japan** (Island volcanic arc) **Andes & Cascades** (continental volcanic arc) **Himalayas, Alps** (Mountains)	Older (Cooler, denser) plates are returned to the mantle in Convergent Plate Boundaries
Transform Fault Boundaries (conservative)	Plates slide horizontally past one another & no new lithosphere is created or destroyed	between segments of the mid-ocean ridge on land (San Andreas Fault)	**Fracture zones** **Fault Zone**	**San Andreas Fault** **Deadsea Foult**	join 2 offset segments of a oceanic ridge along breaks in the oceanic crust

	Definition	Produce	Example
Oceanic-oceanic	2 oceanic plates, descends beneath the other	Volcanoes on the ocean floor Island volcanic arc	Japan (Island volcanic arc)
Oceanic-Continental	Denser oceanic slab sinks into asthenosphere	partial melting of mantle rock generates **magma** **Continental volcanic arc** mountain chain	Andes & Cascades (continental volcanic arc)
Continental-Continental	Less dense, buoyant continental lithosphere doesn't subduct	Resulting collision between 2 continental blocks deforms the sediment accumulations producing **mountain** belts	Himalayas, Alps

- **Oceanic ridges:** elevated areas of seafloor characterized by high heat flow & volcanism
  - Length 65,000km, 20% of earth surface
  - Width 1000 – 4000kms
  - Crest of ridges 2-3 km above seafloor
- **Rift-valley**: deep down-faulted structure along the axis of some ridge segments
- **Hot spots & mantle plumes**
- **Hot spot:** area of volcanism, high heat flow, & crustal uplift, caused by rising mantle plumes
- As hot plume ascends via mantle, confining P decreases causing partial melting of the upper surface of a plume (produced magma)
  - This activity is seen as hot spot on surface
- As Pacific plate moves over hot spot a chain of volcanic structures is built



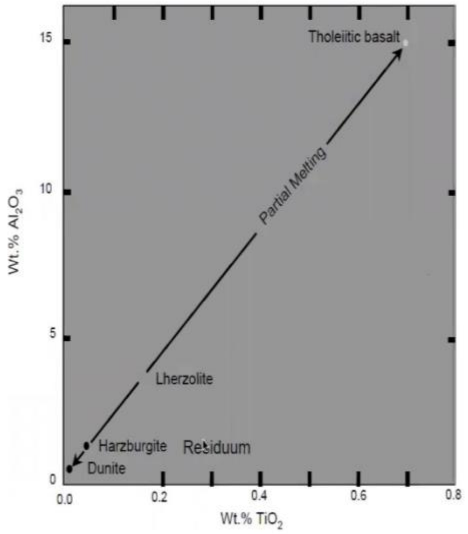
IGNEOUS ROCK IN OCEANIC LITHOSPHERE

4.1 Source Of Basalt

- **The principal magma type of the oceanic crust** is Gappro & basalt (mafic rocks)
- **Basalt** including 2 types ***mid-ocean ridge basalts (MORBs)*** & ***ocean island basalts (OIBs)***
- The differences between MORB & OIB in chemical composition but cannot be see in the hand species
- oceanic crust is made up almost entirely of MORB
- **The source rock for MORB** is spinel or garnet lherzolite, which undergoes significant degrees of melting & melt removed residual UM rock such as dunite or Harzburgite in the upper mantle

Lherzolite is probably fertile Unaltered mantle

Dunite & harzburgite are refractory residuum after basalt extracted

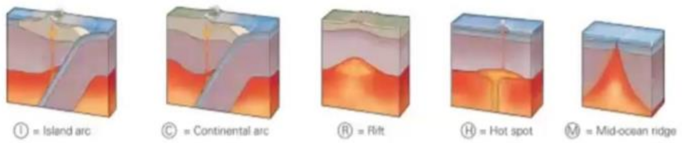


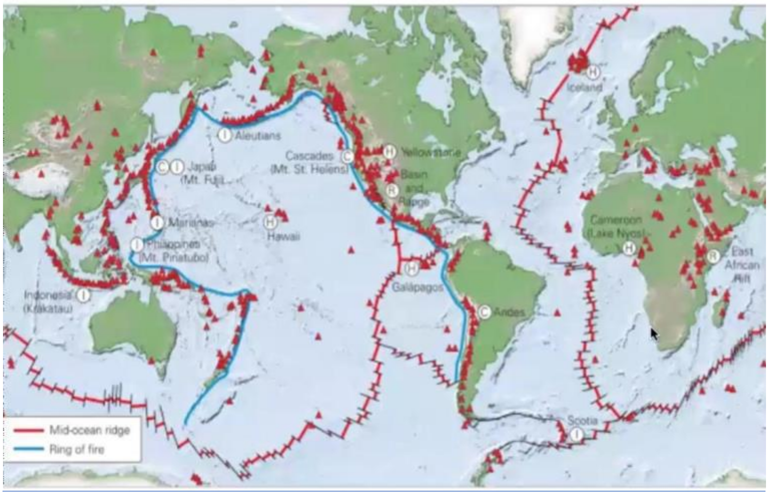
Mafic magma originates from the partial melting of the UM rocks of the upper mantle

- **The existence of residua UM rocks has been demonstrated by the presence of dunite & Harzburgite as xenoliths in intraplate basalts**
- Experimental studies have demonstrated low-P (shallow) mantle origin for most of these magmas
- **The source of the magmas** uppermost mantle, (lithosphere beneath ocean crust, asthenosphere)
- Compositional characteristics of magmas are indicative of tectonic setting (divergent plate boundaries) which can found in oceanic or continental plates
- OIB are the 2nd major type of magmatic occurrence in oceanic lithosphere, After MORB
  - ➢ is far less than the MORBs but provide important information about high-P melting processes in the mantle
  - ➢ Hawaiian Islands in the center of the Pacific plate are the example of an occurrence of OIB

4.2 MOR & igneous structures

- They were revealed using remote sensing & depth sounding instruments developed during the WWII
- The length of mid-oceanic ridge = 65,000 Km
- **Seafloor spreading theory:** new basaltic material was constantly added to the oceanic crust by active magmatism at the ridge & then transported away from the ridge, ultimately to be returned to the mantle through subduction at the oceanic trenches





The construction of the oceanic crust occurs along the MOR
The ring of fire is the blue line
اذا لم يكن موجود subduction zone اي تكون المنطقة pacific
margins مثل المحيط الاطلسي يكون ال MOR في منتصف المحيط

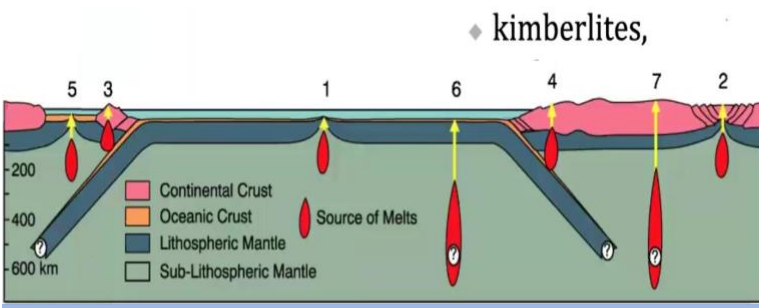
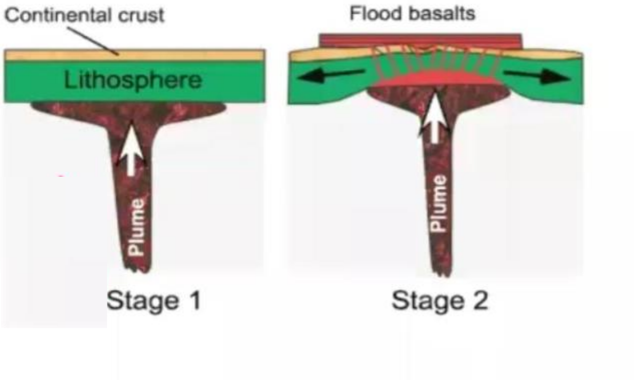
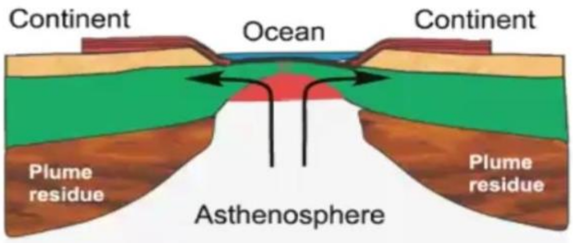


Plate tectonic features (igneous genesis)

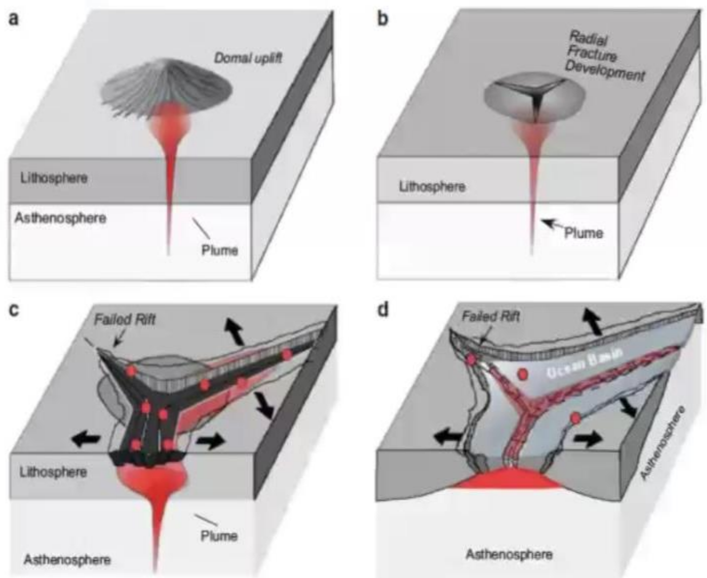
1. **Mid-Oceanic Ridge**
2. **Intracontinental rift:** such as Hawaii & Alps
3. **Island arcs:** such as Hawaii & Iceland (hotspots)
4. **Active continental margins:** such as roky, & Andes
5. **Back-arc basins :** such as Japan & mariana trenches
6. **Oceanic Island Basalt :** such as Hawaii (hotspots)
7. **Miscellaneous Intracontinental activity**

- **Intracontinental rift**: such as East African rift valleys, & red sea, is the first stage of the formation of the oceanic crust

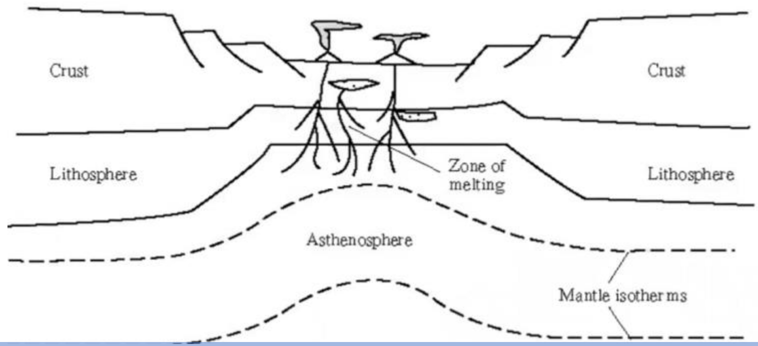




1. Partial melting of mantle plume (Upwelling) generate P beneath the continental crust
2. The crust extent & thinning (Upwarping) due to P
3. The foles will formed (channels for magma, so there's a lava flow in this regions)
4. Finally, the continental crust is separated from each other & the seafloor is form

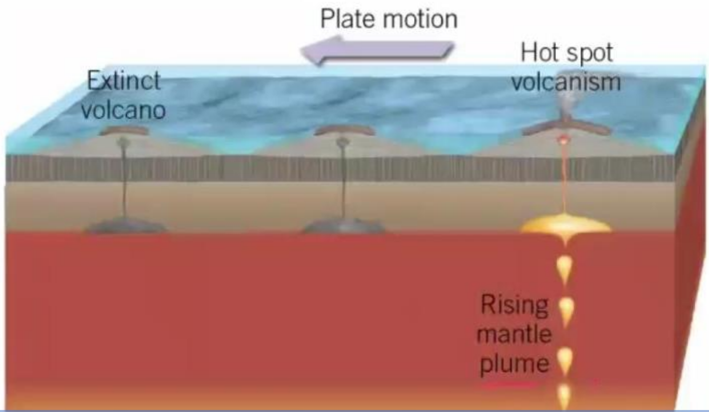


1. **Mantel blume generate P below the oceanic crust, & this P is equal in all directions.**
2. **The Domal structure formed due to rising magma from mantle blume**
3. **the crust is exposed to equal tension forces that lead to the formation of a triple junction (2 active arms & one not active) ≈ 120° غالبا تكون الزاوية بين الاذرع**



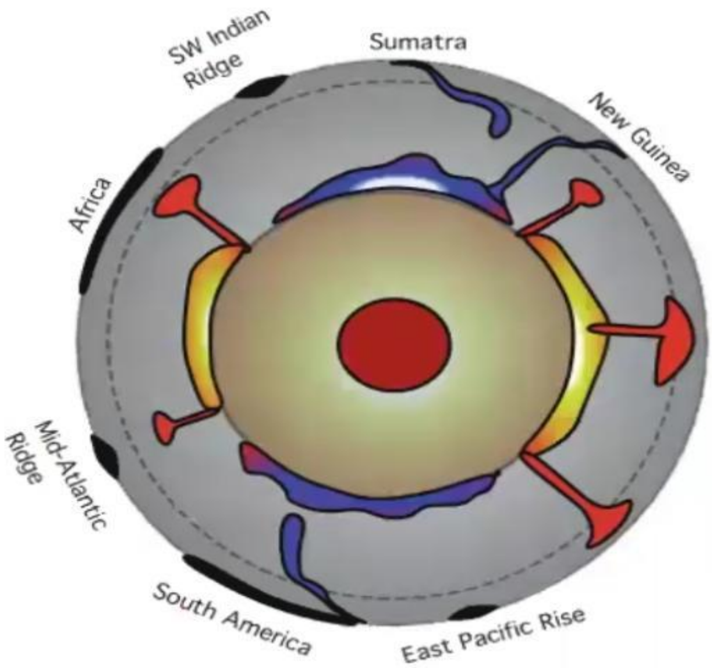
تحت ال EARS نتيجة لتكرار ال normal fault تقل سماكة ال crust
وستستمر عملية الشد حتى ينفصل الجزء الشرقي الجنوبي من افريقيا

- **Back-arc basin:** subduction zone, is the 1st stage of the formation of continents, destructive of the oceanic crust & constructive of continental crust
- **Oceanic Island Basalt:** Island arcs



These islands are formed by the release of magma (from mantel blume) to the surface, which forms arc-shaped islands, the oldest island → far from the hot spot

- **Islands move away due to the movement of plates!**
- **Hot spots** are volcanic regions underlying mantle that is Very hot compared with the surrounding mantle



Cross-section to the earth
Red: is the mantle plumes (rising hot mantle materials)

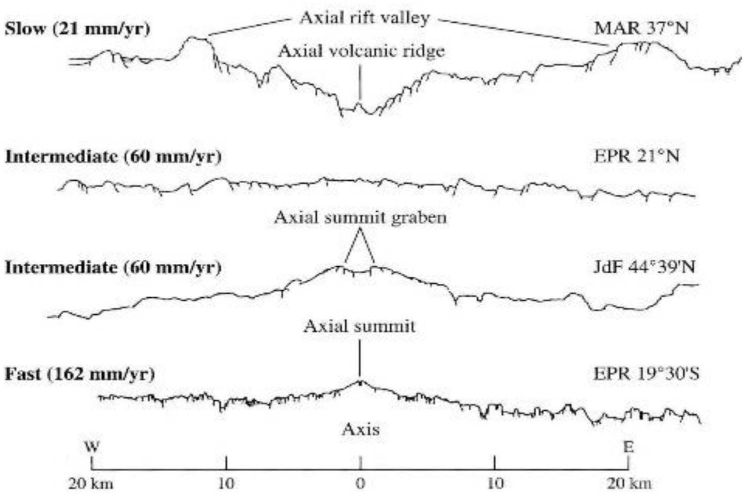
4.3 The Nature of MOR

- compositions of magmas erupted at the MOR are broadly similar, regardless of spreading rate
- There're different parts of the MOR system are characterized by different spreading rates
- **Spreading rates:** is the rate at which the plates move away from ridge

Rate of spreading	Range of rate (mm/yr)	Width of neovolcanic zone (m)	Speculative recurrence interval (yr)	Eruption volume (*10^6 m^3)
Fast	80 - 160	100 - 200	5	1 - 5
Intermediate	40 - 80	200 - 2000	50	5 - 50
Slow	10 - 40	2,000- 12,000	5,000	50-1,000

Slow rate: red sea & Atlantic (central or axial rift valleys)
Fast rate: such as Pacific ridge system

- **Slow-spreading ridges characterized by** prominent rift valley that range from 8-20km wide,1-2kmdeep
- **Fast-spreading ridges show** a topographic high at the ridge axis, with a very narrow axial trough that is only 5-40km deep & 40-250 m wide



4.4 Mg Number

- There's differences in element composition between slow-intermediate-fast-spreading Basalt
- Magmas in slow-spreading ridges have higher Mg#

Mg#=100Mg/(Mg + Fe), always decreases

Mg#= 100*$MgO_{mol\ prop.}$/$(MgO+FeO)_{mol\ prop.}$

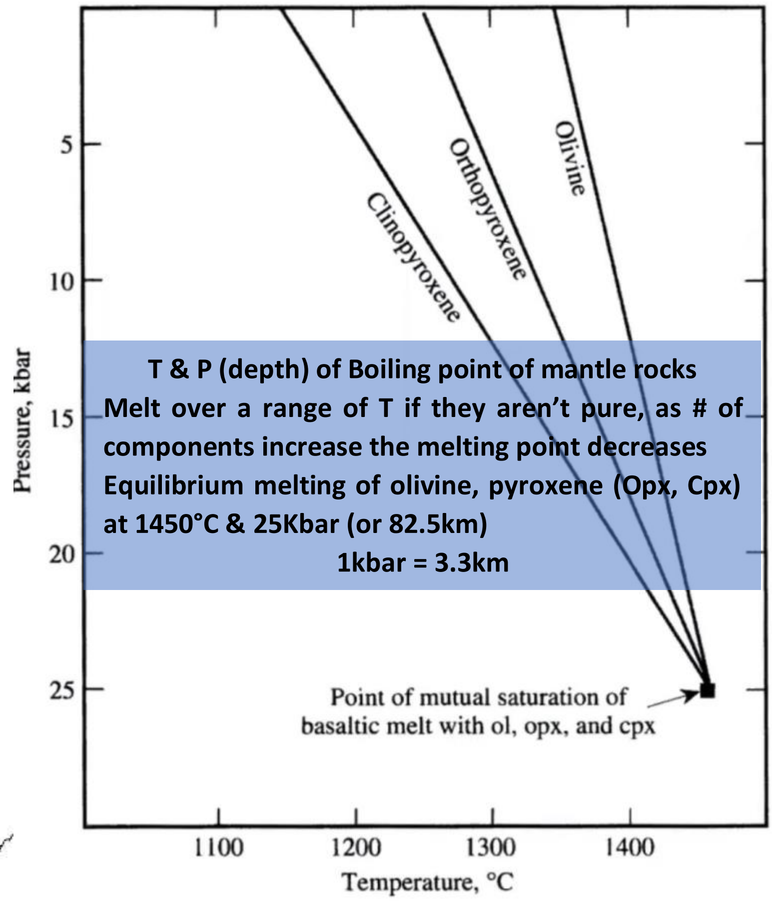
Mg#= 100$MgO_{prop.}$/$(MgO+FeO+Fe_2O_3)_{prop.}$

Mole proportion = $wt\%_{oxide}$/Mm_{oxide}

- **Mg number (Mg#):** is the chemical parameter, used to distinguish between basalt types
- **Mg# inversely proportional to the differentiation**

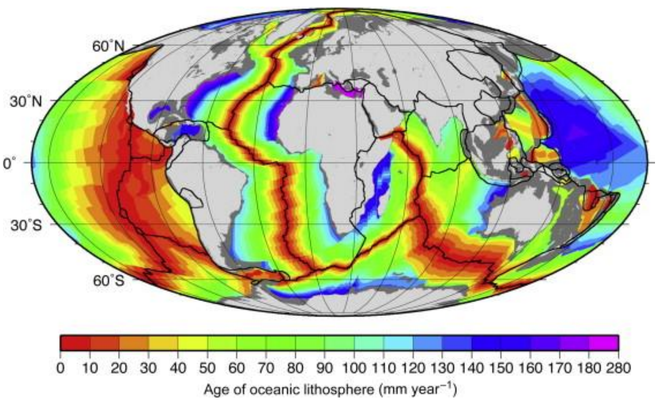
Mg#	> 65 (Primary)	< 65 fractionated
Spreading R	Slow	Fast
Evolved	Lass	More
Differentiated	Less	Highly
Mg Minerals	Rich (Px, Ol)	Separating Mg

- Near Mid-Oceanic Ridge, the partial melting < 40%



T & P (depth) of Boiling point of mantle rocks
Melt over a range of T if they aren't pure, as # of components increase the melting point decreases
Equilibrium melting of olivine, pyroxene (Opx, Cpx) at 1450°C & 25Kbar (or 82.5km)
1kbar = 3.3km

4.5 Oceanic lithosphere

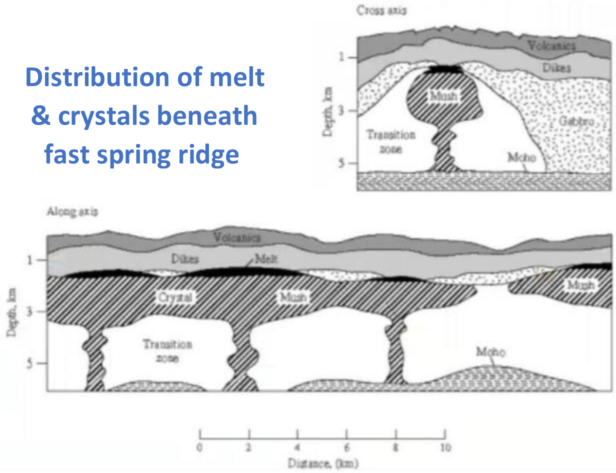


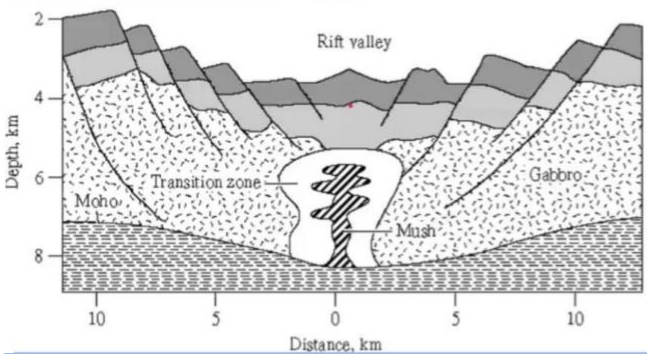
تزداد اعمار الصخور كلما ابتعدنا عن ال ridge وتحديد اعمارها هو احد الدعائم الرئيسية لل seafloor spreading والتي تم بعدها اعادة صياغة نظرية plate tectonic theory

Mid-oceanic ridge
منطقة مرتفعة من oceanic crust بوسطها rift valleys

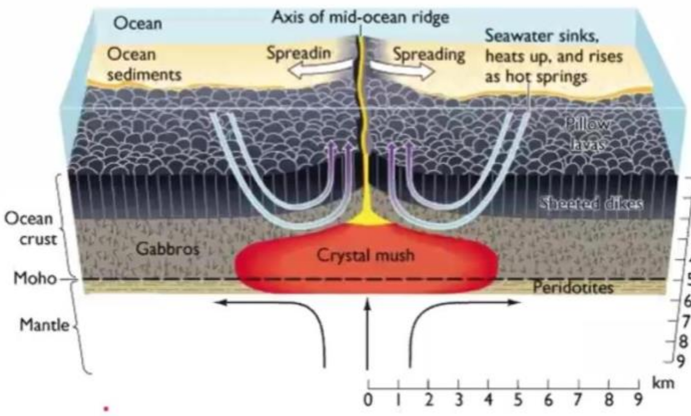
جزيرة ايسلندا هي المنطقة الوحيدة الذي يشاهد بها ridge فوق
القارة وقريبا من هذه البراكين تتكون ال continental crust

Distribution of melt & crystals beneath fast spring ridge





Distribution of melt & crystals beneath fast spring center, no melt lens below the ridge
المقطع على عمق 2 كم من سطح الارض (سطح الماء)
ال Gappro المكون الاكبر من oceanic lithosphere

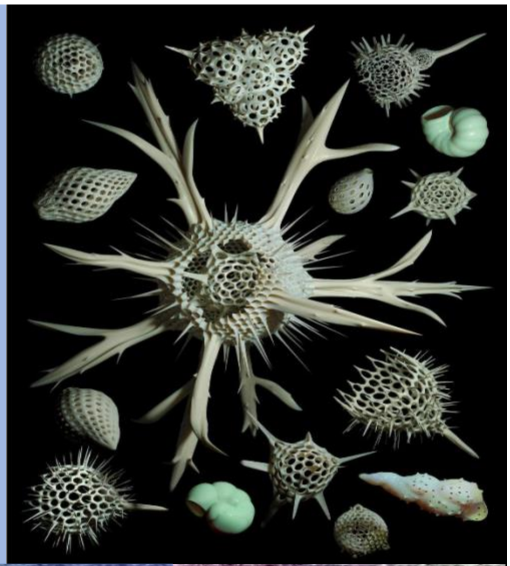


Thin sedimentary layer 0.5-1.0km	Chert or limestone
Pillow lavas & sheeted dikes 1.5-2.0km	Tholeiitic (alkali) basalt
Gappro (Two thirds of the ocean crust) 4.5-5.0km	Gappro, some diorite, & hydrothermal basalt

- **Thin sedimentary layer** fine clastic materials, & biogenic material (which made of silica)
  - **The thin layer of sediment consist of chert rether than limestone, Why?** Limestone (consist of $CaCO_3$) is stable as high Ph (> 7.8), but deep in the ocean, the Ph is < 7.8 (Alkali)

Shells of microorganisms make up the thin cover of chert & pelagic limestone

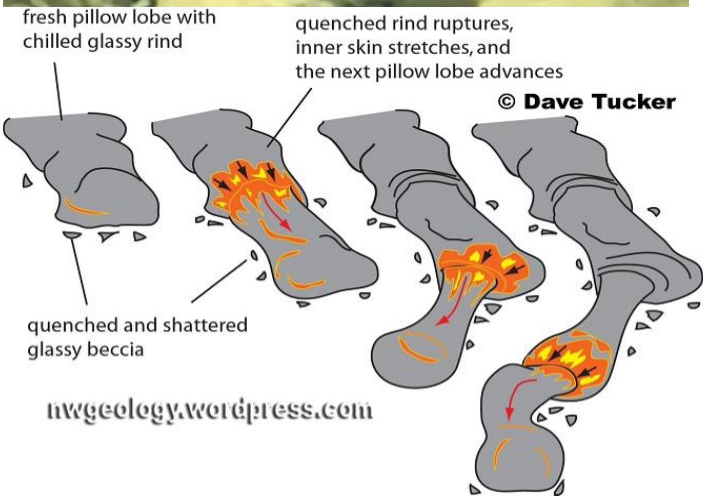
Such as radiolaria (made of silica) & foraminifera, Which live in the open sea

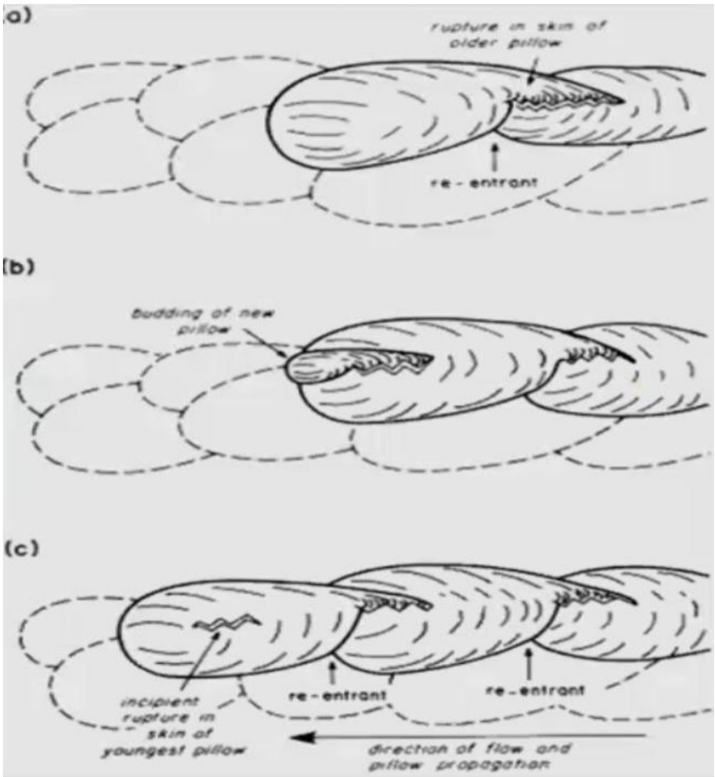


- Pillow lavas & sheeted dikes
  - **Pillow lava**: as lava solidified under the water
  - **sheeted dikes (Dolerite, or Diabas)**: tabular body (sill or dike) below pillow lavas
  - the upper part of magma chamber beneath the oceanic crust is molten & the lower is molten & crystals, The Gappro crystallizes from it & part move to the top of the oceanic crust via sheeted dikes forming Pillow lava
  - The borders near source of magma is finer than the far end of the dike (distinguished by the existence of Chilled on one side)
  - Chilled margin found in all ophitic sequences

Cross-section of pillow lavas

Radial crakes





Formation of pillow lavas

صفيحة من المادة المنصهرة الخارجة من ال dikes تتحرك باتجاه ما ولا تبقى متحركة نتيجة ملامستها للماء التي تعمل على تسريع تصلب سطحها الخارجي وتكوين (Chilled margin) وتبقى الmagma تندفع بها وتفصل الى pillows-like sheets اي ان الmagma المندفعة بها ستخرج منها وتشكل pillow جديدة وهكذا

- **Gappro layer**

Basalt: Dark, fine grained, with vesicular

Norite with ultramafic xenolith (olivine)

Typical Gappro (isotropic)

Plagioclase (light) + mafic minerals

Layered gappro texture

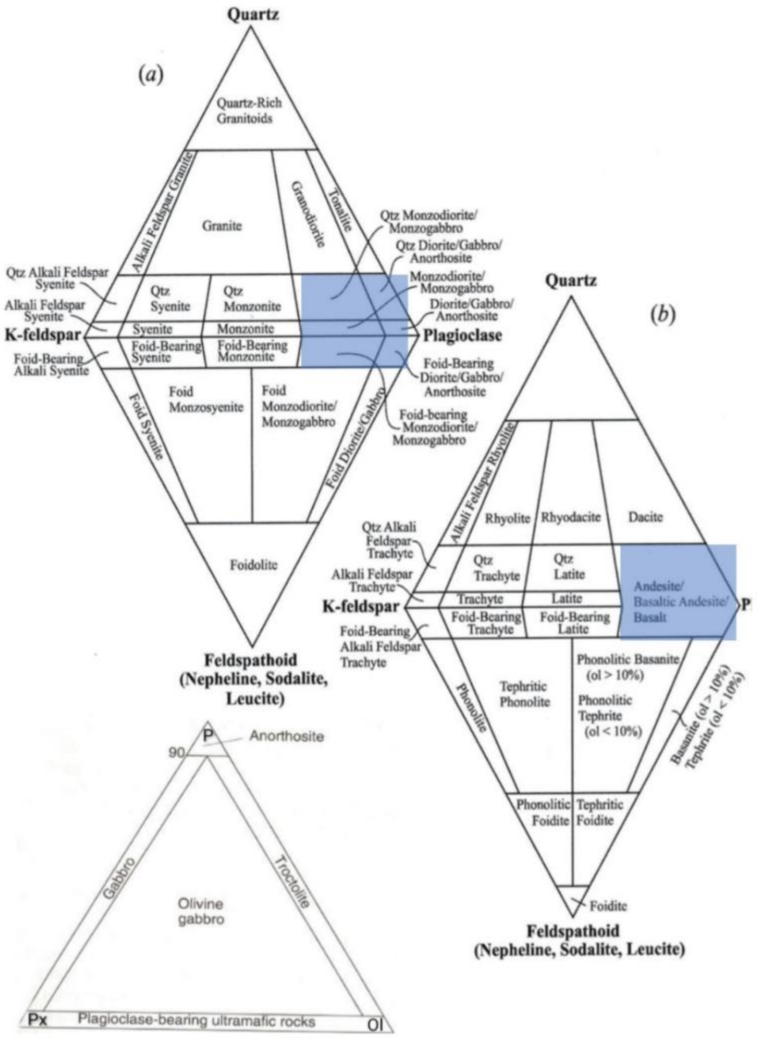
Result from gravitational settling

Layered gappro Structure

High color index & coarse grained

Moho boundary between gappro & UM rocks

4.6 Classification of oceanic rocks



- basalts have variation in K_2O oxide & classified based on this variation

TABLE 8-2 Representative chemical compositions of various basalts

Components	N-MORB[a]	E-MORB[a]	OIT[b]	OIAB[c]	IAT[d]	CFT
SiO_2	48.77	47.74	50.51	47.52	51.90	50.01
TiO_2	1.33	1.59	2.63	3.29	0.80	1.00
Al_2O_3	15.90	15.12	13.45	15.95	16.00	17.08
Fe_2O_3	1.33	2.31	1.78	7.16	—	—
FeO	8.62	9.74	9.59	5.30	9.56	10.01
MnO	0.17	0.20	0.17	0.19	0.17	0.14
MgO	9.67	8.99	7.41	5.18	6.77	7.84
CaO	11.16	11.61	11.18	8.96	11.80	11.01
Na_2O	2.43	2.04	2.28	3.56	2.42	2.44
K_2O	0.08	0.19	0.49	1.29	0.44	0.27
P_2O_5	0.09	0.18	0.28	0.64	0.11	0.19

N-MORB normal mid-oceanic ridge basalt
E-MORP enriched mid-oceanic ridge basalt
OIT ocean Island tholeiite
OIAB ocean Island alkali basalt (kohala, hawaii)
IAT Islands arcs tholeiite
CFT continental floods tholeiite

عندما تلتقي continental-continental بسبب ال subduction يغلق ال ocean وتحدث عملية Obduction وهي خروج جزء من ال oceanic crust & upper mantleال الى سطح ال continentalال وهذه العملية التي تسهل دراسة صخور ال mafic & ultramafic مثل ال Gappro وهو ما يسمى ophitic sequences مثل سمايل/عمان

- Vesicular texture in basalt
  - Center of basaltic flow → less vesicles لان الغاز يخرج وتمتلئ الفراغات بالصهير
  - Top of basaltic flow region → highly vesicles لان الغاز يخرج ويتصلب الصخر بسرعة فلا يمتلك وقت لملء الفراغات بالمادة المنصهرة (ينتج السكوريا)

Silica saturation	Key minerals indicators
Oversaturated	Quartz ± feldspars ± Mg-orthopyroxene
Saturated	Feldspars ± Mg-orthopyroxene only
Undersaturated	Feldspathoids (leucite, nepheline)±feldspar
Al-abundant	Al_2O_3 vs CaO, K_2O, Na_2O
Paraluminouse	$[Al_2O_3] > [CaO + K_2O + Na_2O] > [K_2O + Na_2O]$
Metaluminouse	$[CaO + K_2O + Na_2O] > [Al_2O_3] > [Na_2O + K_2O]$
Subluminouse	$[Al_2O_3] = [K_2O + Na_2O]$
Paralakaline	$[Al_2O_3] < [K_2O + Na_2O]$

4.7 character of primary magma

- only few magmas at MOR are of primary character
- High mg# reflecting high MgO content (10 - 11 %), which indicates that the olivine was not removed
- Highest concretions of Ca & Al (lack of fractionation of either augite or plagioclase)
- Only few magmas meet these requirements

4.8 Magma Vs Seawater

- Newly formed oceanic crust is susceptible to various kinds of interaction with seawater
- **A hydrothermal convection system is established in vicinity of submarine magmatism:** Seawater penetrates crust → heated by magma or hot rock → rises back to the surface
- Vents near the ridge crest emitting jets or plumes of very hot water (up to 350 °C)
- On contact with the cold seawater, the hot fluids rapidly precipitate dense concentrations of very small sulfide & oxide, thereby giving the plumes a smoky appearance (***black smoker or gray smoker***)

Blake or gray smoker: Stalagmite-like columns of sulfide mineral & colons of unique marine animals (surround vent)
Gyser هو اسم عمود الدخان
درجة حرارتها عالية وبالتالي قادرة على اذابة الصخور وحمل ال dissolved material ولهذا تكتسب اللون الاسود

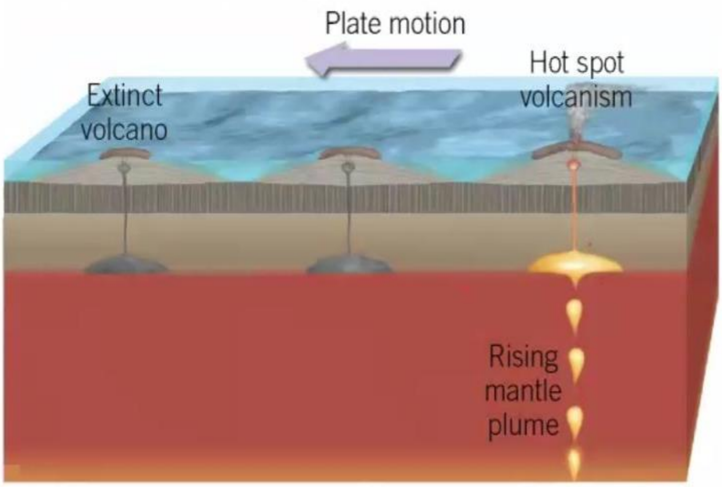
4.9 Tholeiitic Magma Series

- **A magma series**: is a chemically distinct range of a magma compositions that describes the evolution of a mafic magma into a more evolved (silica rich end member)
- There are 2 main magma series in igneous rocks
  1. **The tholeiitic magma series**: (after the German municipality of Tholey) classified as subalkaline (contain less K than other basalts)
  2. **calc-alkaline magma series**
- tholeiitic less oxidized & K_2O than calc alkaline

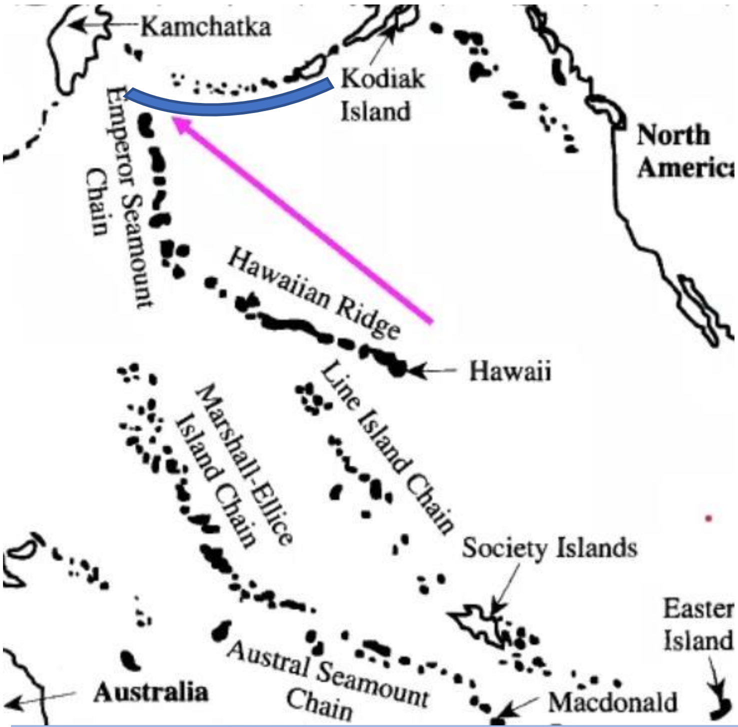
يحدث النشاط عند ال mid-oceanic ridge نتيجة حدوث decompression (partial melting) نتيجة انخفاض P لان ال magma تنتقل من مستوى لاخر فتكون ال mafic magma وتمتد على امتداد ال ridge حيث تبنى ال oceanic crust فتنشأ صخور بازلت تتميز بانخفاض نسب ال K_2O (tholeiitic)

4.10 Ocean Island basalts

- most of the volcanic activity in the oceans occurs at MOR, there are widely scattered occurrences of so-called ***intraplate volcanic activity*** (ascribed to hot spot) which produce ***linear arrangement of islands***
- The basalts produced by intraplate volcanic activity accounts for about $1/10^{th}$ of the activity at the MOR



- the position directly over the hotspot rising mantle melts to produce magma that erupt on the seafloor to building a ***volcanic island*** directly above hot spot
- As the ***lithospheric plate moves*** over the hot spot the volcano is cut off from its source of magma, & becomes ***extinct***, & a new volcano forms on the plate at location directly above the hot spot
- Volcanoes that have moved away from the hot spot eventually begin to erode until their elevations are reduced below sea level, At this point they are called ***seamounts***



Major linear Island trends in the Pacific Ocean

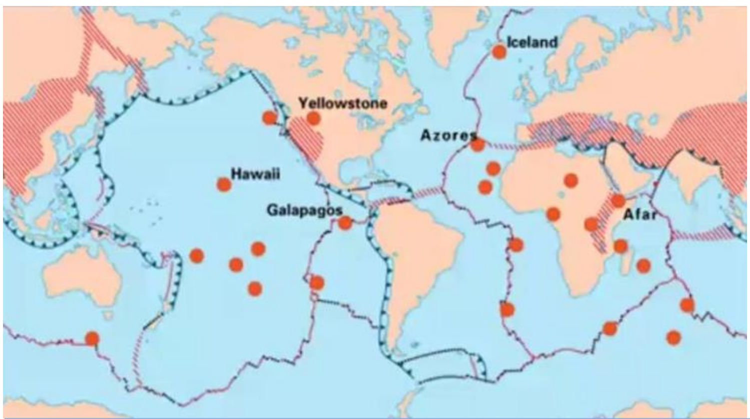
الذي يؤدي لعملية الانصهار هو ان ال rising magma حركتها اسرع من انتقال الحرارة (تحتفظ في درجة حرارة عالية اثناء انتقالها لمنطقة ضغط منخفض) وعندما تبدأ عملية الانصهار تتكون ال volcanic islands ما يكيز هذه الجزر هو اعمارها فالابعد عن ال hotspots هو الاقدم

Islands arc

تختلف عن ال volcanic بأنها تتكون نتيجة تصادم الصفائح subduction boundary وهي سلسلة براكين لها نفس العمر وممكن ان يتواجد اكثر من سلسلة باعمار مختلفة

هاواي حركتها سريعة جدا لان درجة حرارة ال magma عالية وال viscosity للبازلت متدنية فهي قل ما تكون pyroclastic materials

- سرعتها في المتوسط 8سم/سنة وبعض المناطق 16سم/سنة
- Range of T of Hawaii mafic magma 1070 - 1250, most of crystallization series were known from study of Hawaiian mafic magma



Distribution of hot spot

The differences between hot spot & mid-oceanic ridge: in the hot spot the source of magma deeper (150km,from mantle blume) & the degree of partial melting is less (<10%) so most of hot spot magma is alkaline (K_2O > 1%)

Questions

- **Q1 : Defined the following**
  - A. Mid-Oceanic Ridge
  - B. Rift valley
  - C. Hot spot
  - D. Sea-floor spreading
  - E. Foles
  - F. Island arc
  - G. Spreading rates
  - H. Mg number (Mg#)
  - I. Ophitic sequences
  - J. Gyser
  - K. A magma series
- **Q2 : Complete the following**
  - A. MORB formed by partial melting of ______ or ________ which undergoes significant degrees of melting which removed residual UM rock (Eg. Dunite, Harzburgite) in the upper mantle (Hint. Rock types)
  - B. The existence of residua UM rocks has been demonstrated by the presence of dunite & Harzburgite after partial melting as a/an ____________ in intraplate basalts
  - C. The Hawaiian Islands are the example of an occurrence of __________ basalt
  - D. In a triple junction, the angle between each 2 arms equal ______, & this due to ______
  - E. Under the east African rift system, the thickness of the crust constantly decreases as a result of repeated _______________
  - F. The first stage of the formation of oceanic crust is _______ & the first stage of the formation os continental crust is _______
  - G. There're different parts of the MOR system characterized by different __________
  - H. ____________ characterized by prominent rift valley (8-20km wide,1-2kmdeep)
  - I. _________ Ridges show a topographic high at the ridge axis, with a narrow axial trough that is only 5-40km deep & 40-250 m wide (axial summit)
  - J. _____ spreading ridge has Mg#<65, highly diffractiated, fractionalted, & evolved, with less Mg minerals (such as Ol & Px)
  - K. Thin sedimentary layers on the oceanic floor made mostly of _______
  - L. _______ is the two-thirds of the ocean crust (4.5-5.0km thick)
  - M. Pilow lavas & sheeted dikes (1.5-2.0km thick) are mostly made of ______
  - N. _______: Lava that solidified under water
  - O. Chilled margin found in all ____ sequences
  - P. __________ make up the thin cover of chert & pelagic limestone
  - Q. Pillow lavas show _____ "internal habit"
  - R. Tholeiitic basalts classified based on variation in _____ oxide
  - S. MORB with high MgO content (10 – 11)% represents high ______ continent, & MORB with high Ca & Al represent high _______ & ______ (Hint. Minerals)
  - T. Black-color of black smoker due to ______
  - U. Tholeiitic series is ______ than calc alkaline
  - V. Intraplate volcanic activity ascribed to ______, which produce linear arrangement of islands called _______
  - W. Volcanoes that have moved away from the hot spot eventually begin to erode until their elevations are reduced below sea level, At this point they are called _______
- **Q3: Explain the following**
  - A. OIB far less than MORB but But it's very important. Why?
  - B. Explain the intercontinental rift
  - C. Explain the formation of triple junction
  - D. The thin layer of sediment consist of chert rether than limestone, Why?
  - E. Explain how pillow lava originates
  - F. The borders near source of magma is finer than the far end of the dike (distinguished by the existence of Chilled on one side), Why?
  - G. Which has higher vesicles in the basalt magma that is located in the center of the basaltic flow or on the surface, & why?
  - H. Explain how the black smoker formed
  - I. Explain how the tholeiitic magma formed
- **Q4: Choose the correct answer**
  - A. The differences between MORB & OIB in (Hint. cannot be see in the hand species)
    1. chemical composition 2. structure
    3. Composition & structure 4. Non of them
  - B. Oceanic crust is made up almost entirely of
    1. Gappro 2. MORB 3. OIB 4. Chert
  - C. The source rock for MORB is
    1. Spinel lherzolite
    2. Garnet lherzolite
    3. Ultramafic lherzolite
    4. All of the above
  - D. The source of the MORB magmas
    1. Upper mantle 2. Oceanic lithosphere
    3. Asthenosphere 4. All of them

E. the compositional characteristics of magmas are indicative of
   1. Tectonic setting
   2. Equilibrium crystallization
   3. Differences in structure
   4. More than one parent magma
F. The 1st stage of the formation of the new oceanic crust is
   1. Mid-oceanic ridge 2. Intercontinental rift
   3. Back-arc basins 4. Volcanic islands
G. Red sea & Atlantic ridges are example of
   1. Slow spreading ridges 2. Axial rift valleys
   3. Axial volcanic ridges 4. All of them
H. Pacific ridge is an example of
   1. Slow spreading ridge
   2. Intermediate spreading ridge
   3. Fast spreading ridge
   4. All of them
I. Axial summit graben is
   1. Slow spreading ridge
   2. Intermediate spreading ridge
   3. Fast spreading ridge
   4. All of them
J. Called as Axial- or a center- rift valleys
   1. Slow spreading ridge
   2. Intermediate spreading ridge
   3. Fast spreading ridge
   4. All of them
K. Has higher Mg# (primary magma)
   1. Slow spreading ridge
   2. Intermediate spreading ridge
   3. Fast spreading ridge
   4. All of them
L. Near Mid-Oceanic Ridge, partial melting =
   1. 60% 2. > 40% 3. < 70% 4. < 40%
M. _______ is the region where the oceanic ridges can be seen on the continental crust
   1. Hawaii islands 2. Japan
   3. Iceland 4. Red sea & EARS
N. Tholeiitic basalt is
   1. MORB 2. OIB
   3. Alkali rich basalt 4. Basanite
O. Tabular body (sill, dike) below pillow lavas
   1. Sheeted dikes 2. Dolarite
   3. Diabase 4. All of them
P. Tabular body (sill, dike) below pillow lavas
   1. Sheeted dikes 2. Dolarite
   3. Diabase 4. All of them
Q. If the magma contain Feldspars ± Mg-orthopyroxene only, called
   1. Paraluminouse 2. Saturated
   3. Paralakaline 4. Undersaturated
R. If [Al_2O_3] > [CaO + K_2O + Na_2O] > [K_2O+ Na_2O], the rock is called
   1. Paraluminouse 2. Saturated
   3. Paralakaline 4. Undersaturated
S. Given that, mol proportion (MgO=23, FeO=20, Fe_2O_3= 15), calculate Mg#
   1. 2.52 2. 53.5
   3. 39.7 4. 1.89
T. In the question (S), this magma is
   1. Has high Olivine 2. Has high Ca
   3. Highly differentiated 4. Has high Al
U. In the question (S & T), this magma form in
   1. Slow ridges. 2. Intermediate ridges.
   3. Fast ridges. 4. Hot-spot.
V. Most magma in volcanic islands is
   1. Thioliitic basalt 2. Olivine gabbro
   3. Alkaline basalt 4. Spinel lherzolite
W. A corresponding depth of 25kbar =
   1. 72Km 2. 92Km
   3. 82Km 4. 62Km

- **Q5: T/F**

A. The correct path in the formation of new ocean is Upwarping, Transion →upwelling in brittle crust → break the crust into blocks → bloks sinks → mid-oceanic ridge & seafloor spreading
B. the 2nd major type of magmatic occur in oceanic lithosphere is MORB, After OIB
C. In the formation of a triple junction, there are 3 arms, all are active arm
D. Compositions of magmas erupted at MOR are similar, regardless of spreading rate
E. Mg# is proportional to the differentiation
F. Fast spreading ridge has Mg# < 65 due to Separating of Mg-minerals
G. Crustal mush is in molten form
H. Subalkaline magma series is calc alkaline
I. The basalts produced by intraplate volcanic activity accounts for about 1/10th of the activity at the MOR
J. What causes the formation of volcanic islands that the magma moves faster than thermal transmission

- **Q6: for each of the following**

A. principle magma type in oceanic crust?
B. Write 2 types of basalt rock
C. Write 2 techniques, that have been used to discover the MOR (during the WWII)
D. Write 2 main magma series in igneous rock
E. Hawaii's moving so fast, why?
F. What is the differences between hot spot & mid-oceanic ridge

CIPW norm calculation, for anhydrous minerals

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	oxide	wt%	mol.wt	Prop.	Ap	ilm	Or	Ab	An	Cm	Amc	Mt	Hm	Di	Opx	Qz
2	SiO2	57.3	60.08	0.9537			0.185	0.341	0.156					0.04	0.05	0.183
3	TiO2	1.02	79.88	0.0128		0.030										
4	Al2O3	16.9	101.96	0.1658			0.031	0.057	0.078							
5	Fe2O3	4.58	159.69	0.0287								0.023	0.01			
6	FeO	2.55	71.85	0.0355		0.013						0.023				
7	MnO	0.11	70.94	0.0016												
8	MgO	2.74	40.3	0.0680										0.02	0.05	
9	CaO	6.11	56.08	0.1090	0.010				0.078					0.02		
10	Na2O	3.52	61.98	0.0568				0.057								
11	K2O	2.91	94.2	0.0309			0.031									
12	P2O5	0.42	141.94	0.0030	0.003											
13	Mole prop. of normative mineral				0.003	0.013	0.031	0.057	0.078			0.023	0.01	0.02	0.05	0.183
14	Mol-to-wt conversion factor				336.2	151.7	556.6	524.6	278.2			231.5	160	217	100	60.1
15	Wt%normative mineral				1.0	1.9	17.2	29.8	21.7	0.0	0.0	5.3	1.0	4.6	4.7	11.0

Oxides in each mineral

Minerals	Formula	Oxides
Apatite(ap)	$2Ca_5(PO_4)_3(F,Cl,OH)$	$10CaO$, $3P_2O_5$
Ilmenite (ilm)	$FeTiO_3$	FeO, TiO_2
Orthoclase (or)	$2KAlSi_3O_8$	K_2O, Al_2O_3, $6SiO_2$
Albite(ab)	$2NaAlSi_3O_8$	Na_2O, Al_2O_3, $6SiO_2$
Anorthite(an)	$CaAl_2Si_2O_8$	CaO, Al_2O_3, $2SiO_2$
Corundum (cm)	Al_2O_3	Al_2O_3
Magnetite(mt)	$Fe_3O_4(Fe^{2+}O.Fe^{3+}{}_2O_3)$	$Fe^{2+}O$, $Fe^{3+}{}_2O_3$
Hematite(hm)	Fe_2O_3	$Fe^{3+}{}_2O_3$
Diopside(di)	$CaMgSi_2O_6$	CaO, MgO, $2SiO_2$
Hypersthene(hy)	$MgFeSi_2O_6$	FeO, MgO, $2SiO_2$
Quartz (qz)	SiO_2	SiO_2

Rules

Wt% : Experimentally (Vol%), ΣWt% ≈ 100%

Mole oxide: from periodic table (Mm_{oxide})

Limiting reactant: The oxide that has fewer moles

Mole proportion = *Wt% / Mole oxide*

Mol pro$_{\text{normative-mineral}}$ = mole prop.$_{\text{limiting reactant}}$

Mol-wt conversion factor = Mm$_{\text{mineral}}$

Wt%$_{\text{normative mineral}}$ = Mol pro$_{\text{normative}}$*Mol-wt$_{\text{conversion factor}}$

Terms

Silica saturation	Key minerals indicators
Oversaturated	Quartz ± feldspars ± Mg-orthopyroxene
Saturated	Feldspars ± Mg-orthopyroxene only
Undersaturated	Feldspathoids (leucite, nepheline)±feldspar
Al-abundant	Al_2O_3 vs CaO, K_2O, Na_2O
Paraluminouse	$[Al_2O_3] > [CaO + K_2O + Na_2O]$
Metaluminouse	$[CaO + K_2O + Na_2O] > [Al_2O_3] > [Na_2O + K_2O]$
Subluminouse	$[Al_2O_3] = [K_2O + Na_2O]$
Paralakaline	$[Al_2O_3] < [K_2O + Na_2O]$

Calculation

Apatite $2Ca_5(PO_4)_3F \rightarrow 2Ca_5P_3O_{12} \rightarrow 10CaO + 3P_2O_5$

Limiting reactant: diphosphate-oxide

$3molP_2O_5 \rightarrow 10molCaO$, $molP_2O_5 \rightarrow 3.3molCaO$

Mole proportion$_{P_2O_5}$ = 3.3 Mole proportion$_{CaO}$

Mole proportion$_{P_2O_5}$ = 0.0030

Mole proportion$_{CaO}$ = 0.0030 * 3.33 = 0.00999

Molpro $_{\text{mineral}}$ = Mole pro$_{P_2O_5}$ = 0.0030

Wt%$_{\text{apatite}}$ = 0.003 * 336.21 = 1.0

& in the same way as the rest of the minerals…

in the calculation of apatite, we took all the P-oxide, so P-oxide wasn't left to make another minerals that contains it, & also we took a portion of Ca-oxide, other minerals that contain Ca-oxide will consume the remaining Ca-oxide

For example anorthite contain CaO, Al_2O_3, & $2SiO_2$

Limiting reactant: Al-oxide (It's the lowest

$molAl_2O_3 \rightarrow molCaO \rightarrow 2molSiO_2$

Mole proportion$_{Al_2O_3}$ = remaining$_{Al_2O_3}$ = D - H - G

Mole proportion$_{CaO}$ = **Mole proportion$_{Al_2O_3}$**

Mole proportion$_{SiO_2}$ = **2*Mole proportion$_{Al_2O_3}$**

Molpro $_{\text{mineral}}$ = Mole pro$_{P_2O_5}$ = 0.0781

Wt%$_{\text{apatite}}$ = 0.0781 * 278.2 = 21.7

This rock is Oversaturated & Metaluminouse

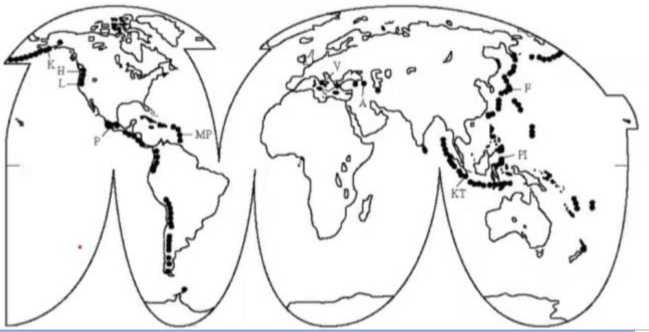
Oversaturated because there's remaining silica oxides which form quartz

Metaluminouse because $[Na_2O + K_2O] = 0.0877$ $[Na_2O+K_2O+CaO]=0.1967$, $[Al_2O_3] = 0.1658$ then $[CaO+K_2O+Na_2O] > [Al_2O_3] > [Na_2O + K_2O]$

CONVERGENT PLATE BOUNDARIES (SUBDUCTION ZONES)

5.1 convergent plate boundaries

- **Wilson's cycle:** ***continental drift*** → ***formation of the oceanic crust*** (at mid-oceanic ridge) & ***formation of volcanic arc*** (above hot spot) → ***formation of continental crust*** (near subduction zone where 2 oceanic or oceanic & continental crusts collides, forming islands arc which called a proto-continents) → ***collision of continental crust*** (mountains & close ocean crust forming ophiolite)
- regions of island arc is S- & N-America (ring of fire)



Worldwide distribution of subduction zones (active & recent volcanoes)

Called Ring Of Fire or Andesite Line

- **Convergent (active margins)** where lithospheric plates collide, are the most active parts of the Earth

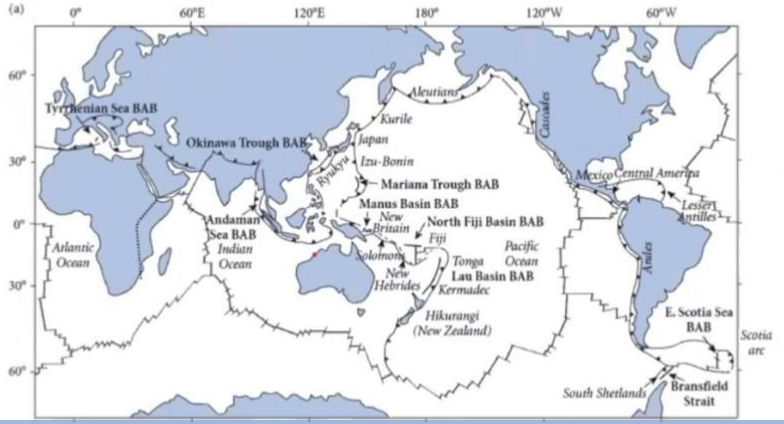
Convergent	Give rise to	Such as
Oceanic-oceanic	**Island arcs**	**Japanese, indonesian, aleutian**
Oceanic-Continental	**Volcanic arcs**	**Andes, rockies**
Continental-Continental	**No any subducted**	**Alps, & himalayas**

5.2 Volcanic arcs Vs Island arcs

- **Oceanic crust form often from** Tholeiitic basalt (near MOR), & alkali-basalt (above hotspot)
- **Continental crust formed by** all types of rocks from all categories but the dominant rock is granite rock

Arc	Location	Age & note	
Volcanic arcs	Hot spot (plume)	closest to the hotspot is the newest	
Island arcs	subduction zone	All have same age	first step to formation of the continent (proto-continents)

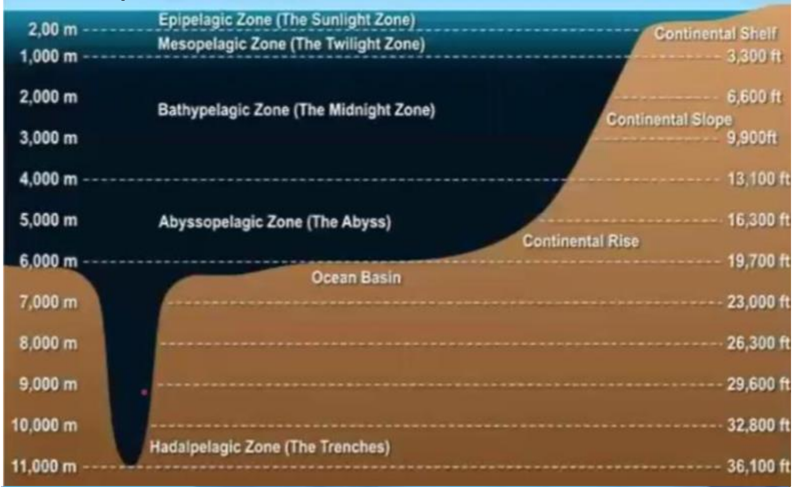
- **The reason that the island arcs take the arc-shape is** the curvature of the earth
- Most of earthquakes occur at subduction zone, because the plates that slide under each other are not smooth!



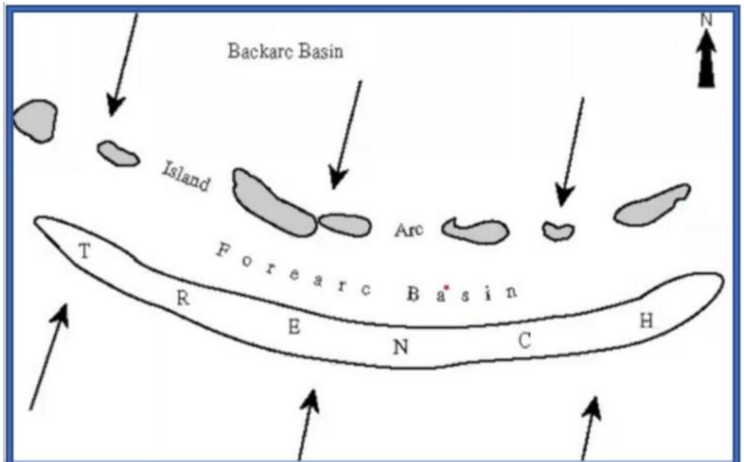
Worldwide distribution of subduction zones
The direction of the arrows is the direction of the subduction

5.3 Tranche

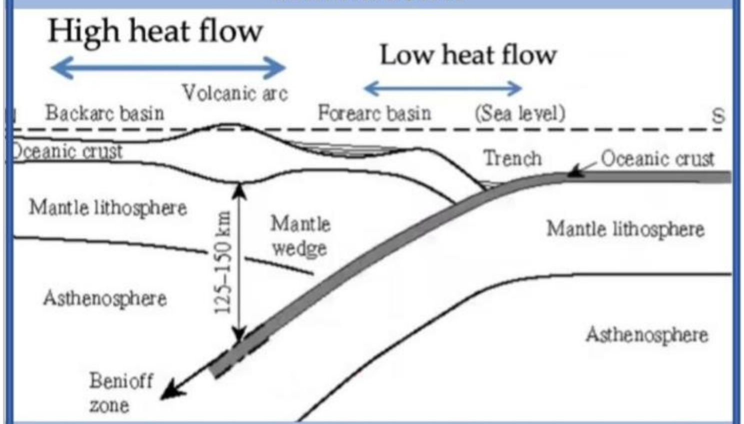
The deepest area is the tranche



An imaginary image of Mariana tranche, earthquakes occur due to the roughness of the sliding plates



Off shore Island arc (arrows is the direction of convergent) Volcanoes occur above the rises plate, & the magma within these volcanoes arises from the partial melting of the downward plate



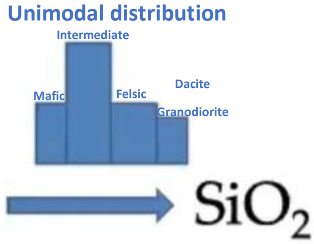
Cross-section view of an island arc

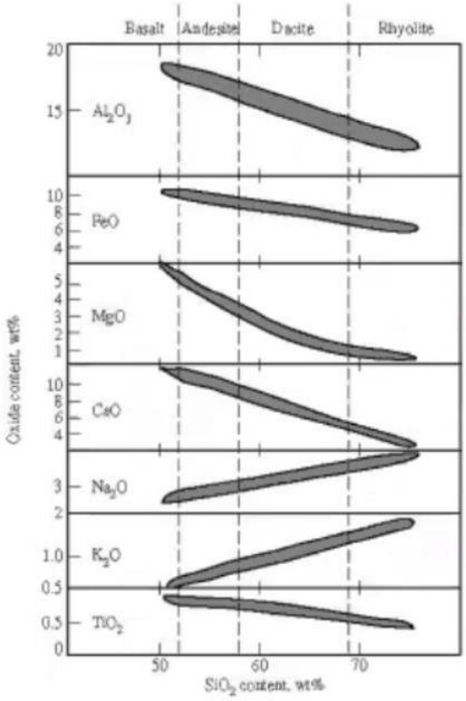
*** subducted plate : downward plate**
*** over riding plate : rises plate**

This island sits off the coast of Sumatra above the Sumatran-Andaman subduction zone.

5.4 Petrography of Island arc

- Andesites are by far the most abundant rock in the arcs like the Indonesian & Philippine arcs
- The rocks in these arcs vary from high Mg tholeiitic basalts to strongly differentiated dacite & granodiorite(basalt- andesite- rhyolite-association)
- Tholeiites here are different from the MOR by more Al (Al_2O_3 > 16%) "called high alumina basalt"
- Some andesite have high Mg#, it is agreed upon that these are derived from high Al basalts by fractional crystallization





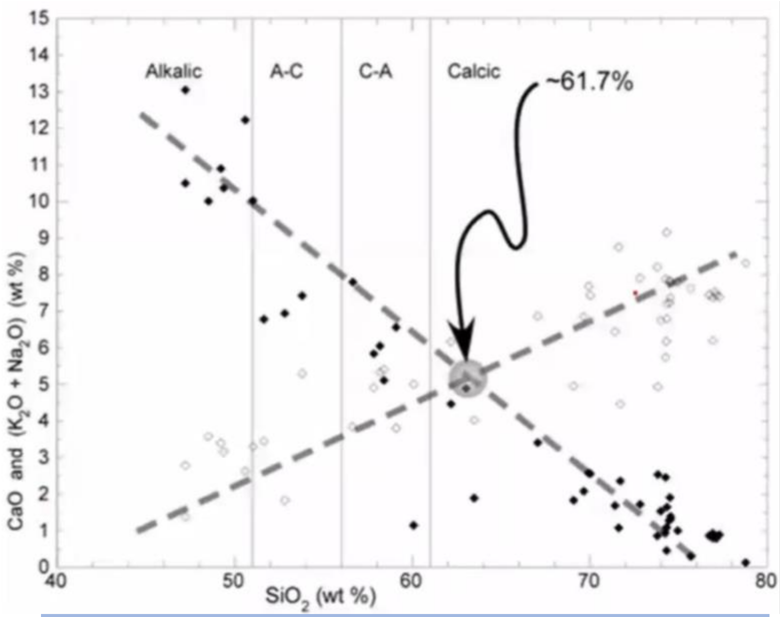
Harker variation diagrams for the common rocks of the subduction zones

تعتمد العلاقة على المعادن التي تتبلور اولا فمثلا في Al_2O_3 (in form of anorthite) يتبلور ال Al_2O_3 قبل ال SiO_2 (in form of quartz)

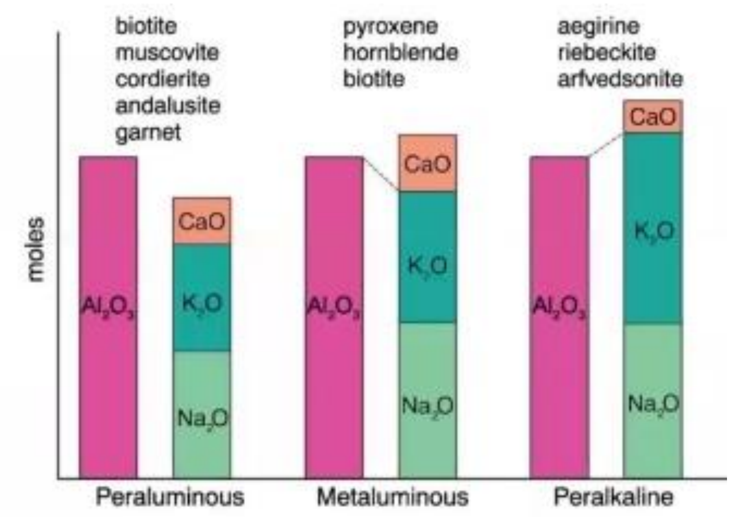
Suite : A group of igneous rocks associated with its origins (genitic relations)

Alkali-Lime Classification for Igneous rocks

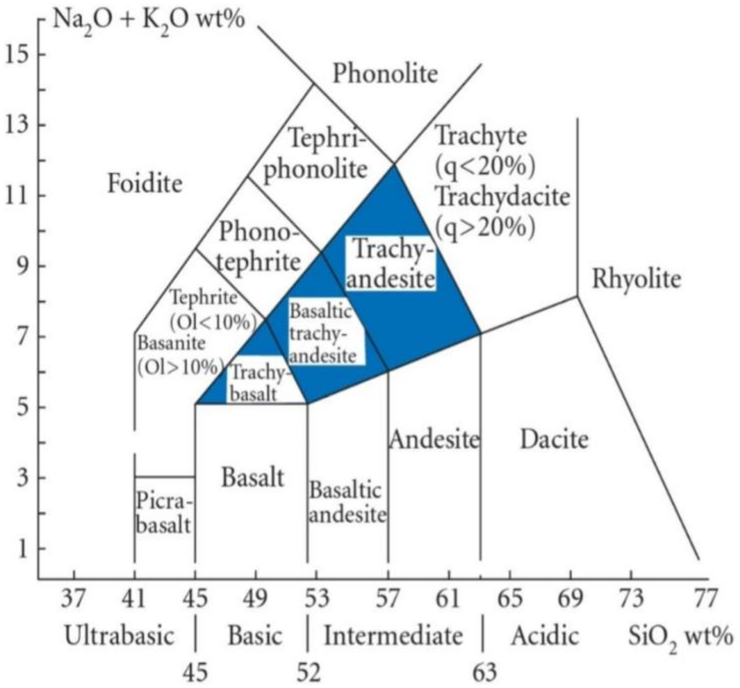
Alkali-Lime index (wt%SiO_2) where CaO = [K_2O + Na_2O]	Name
< 51%	Alkalic
51% – 56%	Alkali-Calcic
56% – 61%	Calc-Alkalic
> 61%	Calcic

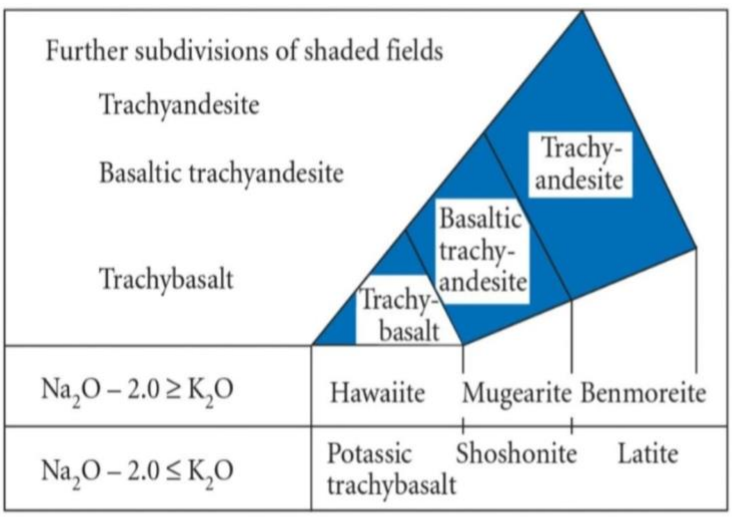


نقاط تقاطع ال Best fit هي التي تحدد ال Alkali-Lime index (wt%SiO_2) where CaO = [K_2O + Na_2O]
Calc alkaline found in subduction zone
Calcic (tholeiitic) found in the Mid-Oceanic ridge
Alkali calcic & alkalic found in the continental crust



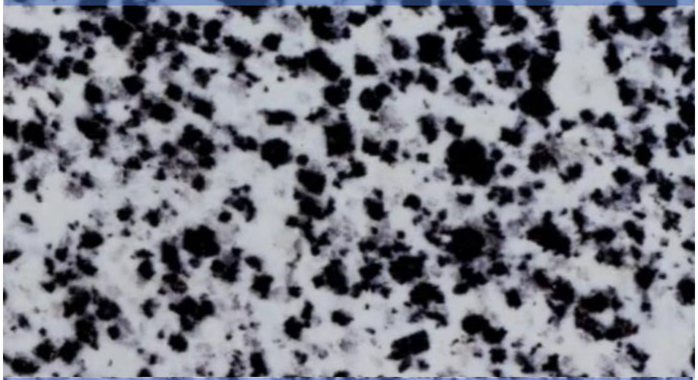
Alumina saturation index
Paraluminouse : high feldspar content
Paralakaline : high alpite, (within the continents)



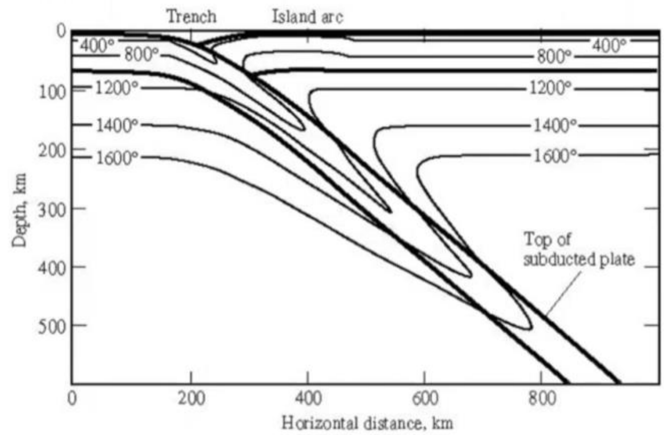


Classification of volcanic rocks
Intermediate volcanic rocks classified based on the variation in alkali oxides

Diorite: Andisine, ± quartz & K-feldspars

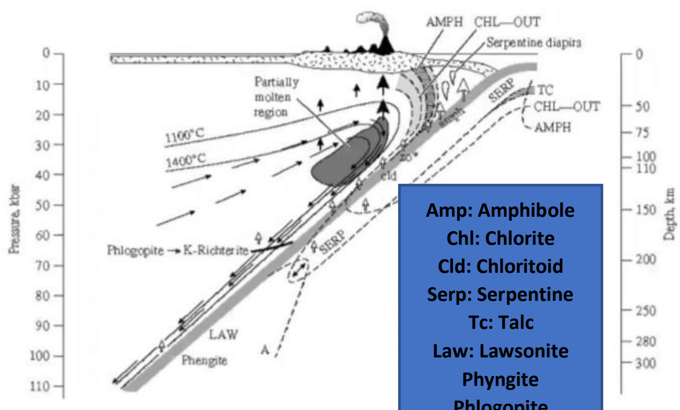


Monzonite, found in subduction zone
Plagioclase + orthoclase + biotite & hornblende



Thermal structure beneath offshore island arc
Subducted plate has T less than overriding plate because the subduction rate is faster than conduction (thermal movement which move in conduction or convection)
T are high in the Arc region due to volcanic activity

5.5 Subduction Zone & Related Rock

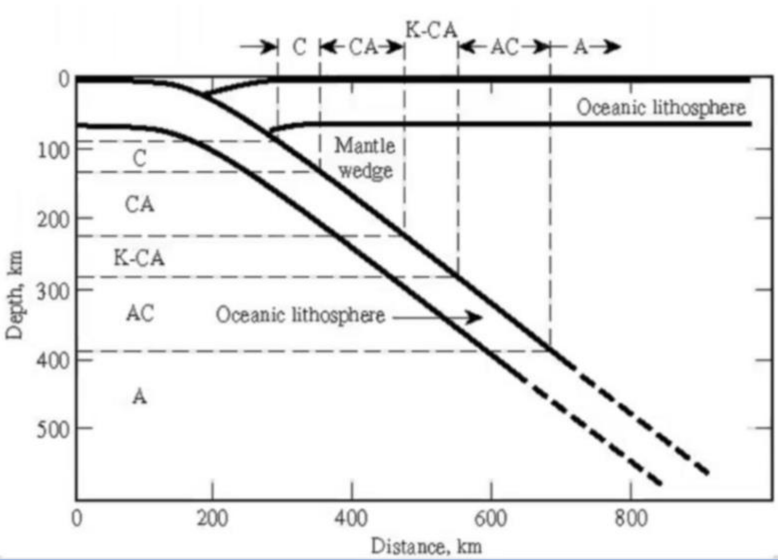


Amp: Amphibole
Chl: Chlorite
Cld: Chloritoid
Serp: Serpentine
Tc: Talc
Law: Lawsonite
Phyngite
Phlogopite

Features of subduction zones in an island arc setting

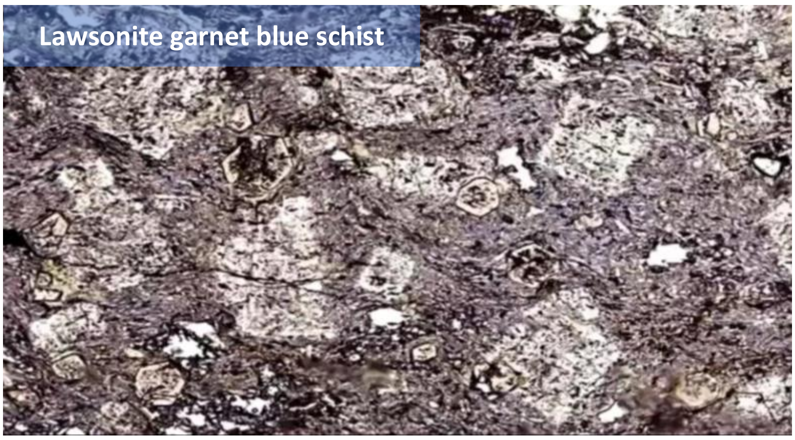
- Most of the granite & granodiorite rocks (batholiths) are located in subduction zones
- **Partial melting occurs in these areas as a result of** the production of the fluids by the dehydration reaction which penetrate the rocks & lower the melting point of these rocks to get partial melting of wedges, oceanic crust, metamorphic & sedimentary rocks, to get different types of magma (*different melting source → variation in rock type*)

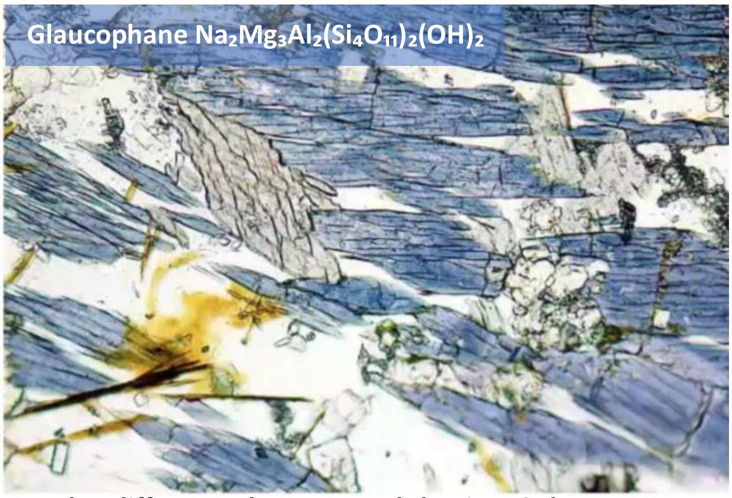
Magma	Sources
Mafic	Partially melting of a Mantel wedge Completely melting of oceanic crust
Intermediate	Melting of <40km within earth Partial melting of Oceanic crust Partial melting of mantle wedge
Granitic (felsic)	Partial melting of shell (Clay minerals) → quartz & feldspar melting to produce magma (batholiths)



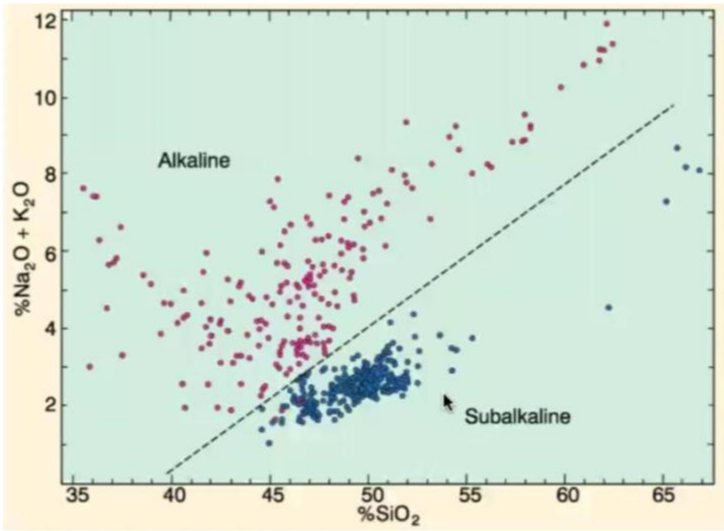
Relationship between depth of melting to the location of various igneous rock types

- subduction zones are characterized by rocks that formed at low T & high P & contain Glaucophane (blue), lawsonite, & geodite (green), such as blue schist & ophitic rocks

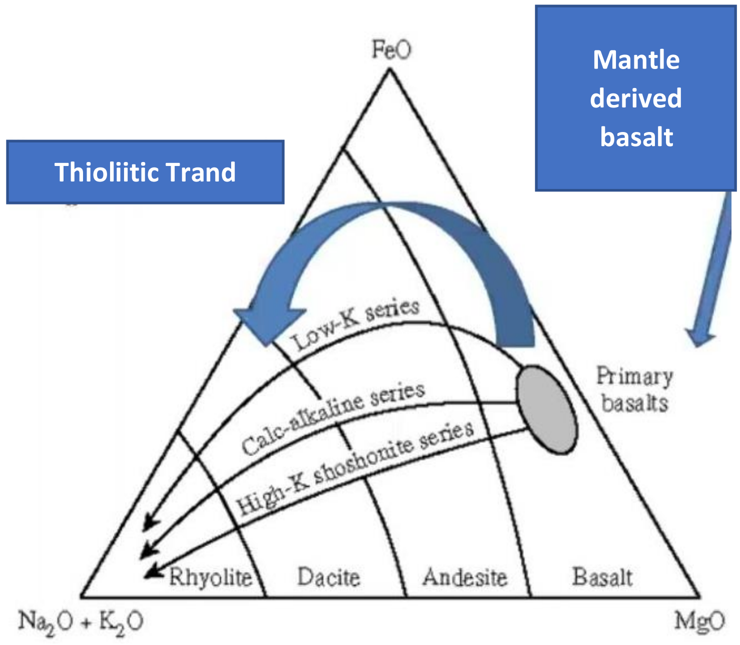




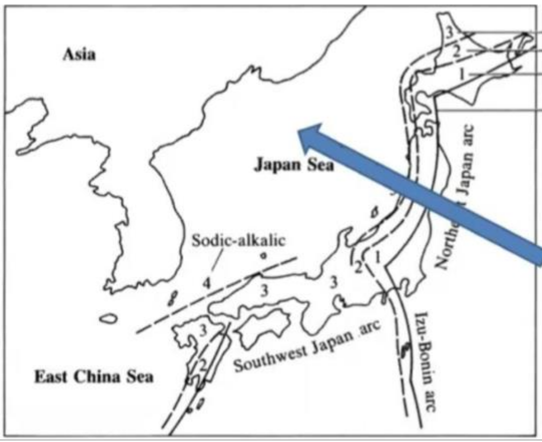
- **The difference between subduction & hotspots** cause of partial melting
  - ➢ In subduction zone due to ***hydrothermal fluids***
  - ➢ In hotspot due to ***decomposition*** (lowering P)



Classification of igneous rocks into alkaline & subalkaline



Classification of subalkaline rocks



Boninite
Asnukitoid
Adakites

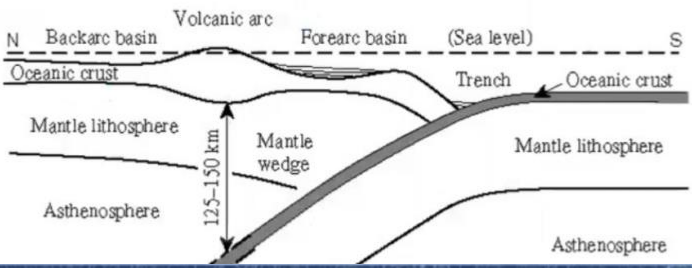
Intermediate rocks has high Mg# & SiO_2

5.6 rocks of the continental Margin

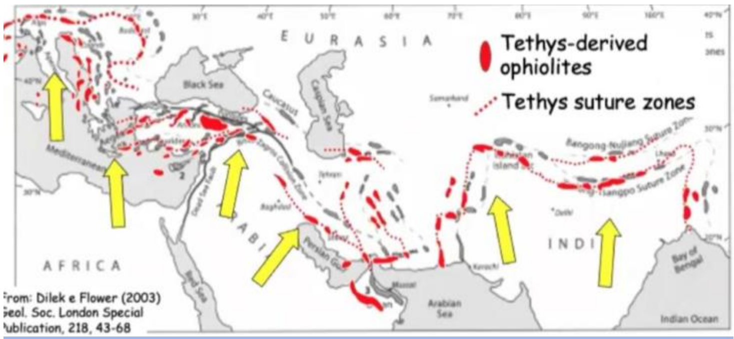
- **Continental margin:** is the site of sediments accumulation, metamorphism, & magmatism
  - ➢ Places of continental accretion
- 2 type of margin : Passive & Active Margins
  - ➢ **Passive margins:** such as Americas-atlantic margins, normal fault without trench
  - ➢ **Active margins:** such as Pacific-Americas, with active subduction
- There are similarities with island arc magmatism, & differences arise from the crust mantle interaction in the case of the latter

5.7 Ophiolite Sequences

- **Suite:** A different rocks linked to the same source of formation (genetic relation)
- **Ophiolite**: a peculiar assemblage of ultramafic rocks, gabbroic rocks, sheeted dikes & pillow lavas overlain by a thin cover of sediments
- **An ophiolite**: section of oceanic crust & upper mantle that uplifted & exposed to the surface
- Most of ophiolite rocks have superficial texture
- Ophiolites formed in the back arc basins above subduction

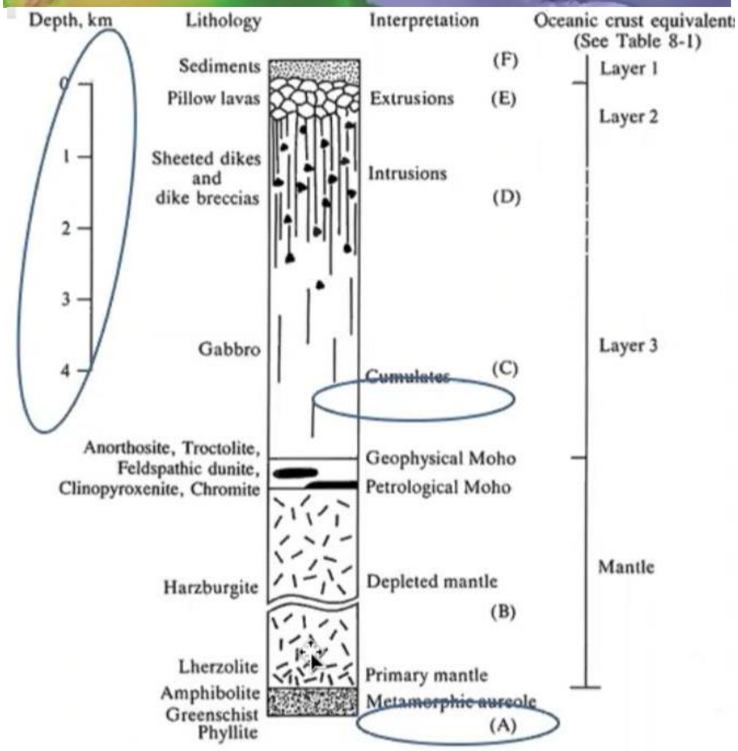


Melage: mixed zone of fractured & deformed rock formed in subduction zone due to compressional



Alpite-Himalayas Collision System

3 oceanic subduction zones in the Mediterranean area



Sequence of rocks found in the island ophitic

5.8 Turbidities

- **Turbidities:** are syntectonic sedimentary deposits originated by deep submarine turbidity currents, especially in foreland basins, in tectonic setting of convergent margin (active)
- **Turbidite**: is a sequence of layers that consist of a grano-classified set of sandstone strata/pelitic sediments, generally in fining-upward that were deposited by turbidity currents & covered by hemi-pelagic pelites containing deep-water fossils
- alternation of calcareous clay & marl are classic example of Flysch, i.e. classical turbidite sediments

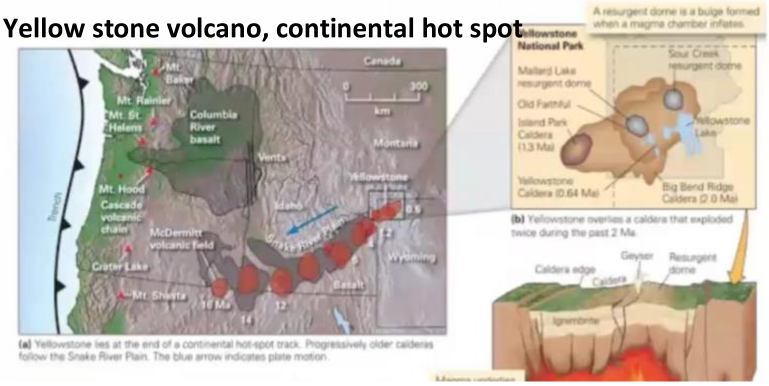
5.9 Continental intraplate magmatism (magmatic Arcs)

- Huge batholithic provinces of Earth occur on the continental side of the subduction zone at the so-called Andean-type margins
- Magma generation in these areas are almost similar to the islands but the differences is:
  1. interaction & magma differentiation is more complex due to the interaction with the continent (i.e. magma mixing, assimilation etc)
  2. more complex diversity
  3. plutons more abundant
  4. Thickness of continental crust varies
- Continental intraplate magmatism & volcanism produce:
  1. Continental flood basalts, such as حرة الشام
  2. Continental rift assemblages
  3. Bimodal volcanism, most important feature
  4. Layered basic & ultrabasic intrusions
  5. Ultrabasic suites: include komatiite, kimberlite
  6. unusual array of alkaline & anorogenic granites
- Why is there a Bimodal activity?

تندفع mantle blume تحت ال asthenosphere ما يؤدي لارتفاعه فيحدث extension للقارة مثل east African rift system (EARS) يحدث normal fault يتسبب في هبوط ال crust وحدوث partial melting فتنتج mafic magma ويصاحب عملية التبلور exothermal process وهذه الحرارة تعمل على تسخين منطقة ال lower crust والتي بدورها تتعرض لعملية partial melting وتنشأ منها felsic magma (وممكن ان تكون carbonatites magma) في المحصلة ينشأ تحت القارة mafic magma والبراكين تكون felsic

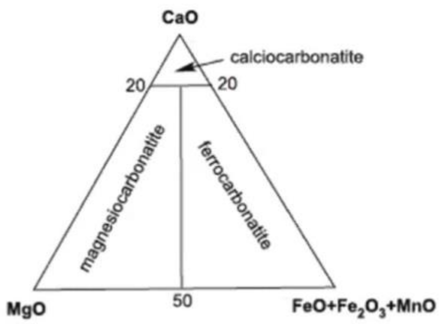
- **Carbonatites magma**: Formed due to liquid-liquid impeccability, & it's the coldest type of magma (500 – 600)°C, There is an active carbonatite volcano in Tanzania/Africa

Yellow stone volcano, continental hot spot



Carbonates	Sulfides
Calcite	Pyrrhotite
Dolomite	Pyrite
Ankerite	Galena
Siderite	Sphalerite
Strontanite	**Oxides-Hydroxides**
Bastnäsite $((Ce,La)FCO_3)$	Magnetite
* Nyerereite $((Na,K)_2Ca(CO_3)_2)$	Pyrochlore
* Gregoryite $((Na,K)_2CO_3)$	Perovskite
Silicates	Hematite
Pyroxene	Ilmenite
Aegirine-augite	Rutile
Diopside	Baddeleyite
Augite	Pyrolusite
Olivine	**Halides**
Monticellite	Fluorite
Alkali amphibole	**Phosphates**
Allanite	Apatite
Andradite	Monazite
Phlogopite	
Zircon	

Carbonate magma composition & classification



Carbonate magma with Pohoehoe structure

Questions

- **Q1 : Defined the following**
  - A. Oceanic Tranche
  - B. Suite
  - C. Continental margin
  - D. Ophiolite sequence
  - E. Turbidities
- **Q2 : Complete the following**
  - A. _______ the most active parts of the Earth
  - B. No any subducted (such as Alps, & himalayas mountains) are example of ____
  - C. ________ crust formed by all types of rocks from all categories but the dominant rock is granite rock
  - D. The deepest area in the oceanic floor is ___
  - E. _______ are by far the most abundant rock in the arcs (e.g.Indonesian & Philippine)
  - F. Tje Andisitite rocks that have high Mg# (found in island arc) are produced by ___________ from _____________ basalt
  - G. Intermediate volcanic rocks classified based on the variation in ________ oxides
  - H. Most of the granite & granodiorite rocks (batholiths) are located in _____________
  - I. Partially melting of a Mantel wedges or Completely melting of oceanic crust produce _______ magma
  - J. Partially melting of <40km within earth, or of Oceanic crust or of mantle wedges produce _______ magma
  - K. Partial melting of shell (Clay minerals) → quartz & feldspar melting to produce ____
  - L. Subduction zones are characterized by rocks that formed at ___ T & ___ P
  - M. Subduction zones are characterized by rocks that contain _________, ________, & _________ (Hint. Minerals)
  - N. Subduction zones are characterized by rocks such as ___________ & __________
  - O. Most of ophiolite rocks have _____texture
  - P. syntectonic sedimentary deposits originated by deep submarine turbidity current, in _________, & _________
  - Q. Alternation of _____ are classic example of Flysch, i.e. classical turbidite sediments
- **Q3: Explain the following**
  - A. Wilson's cycle
  - B. differences between island & volcanic arcs
  - C. The island arcs take the arc-shape, Why?
  - D. earthquakes occur at subduction zone
  - E. The major source of magma in volcanoes near subduction zones
  - F. Subducted plate has T < overriding plate
  - G. T are high in the Arc region, Why?
  - H. Partial melting occur in subduction zones
  - I. There are different types if rocks near subduction zones, Why?
- **Q4: Choose the correct answer**
  - A. The regions of island arc is
    1. WN-America 2. WS-America
    2. Andisitite line 4. Ring of fire
    5. All of the above
  - B. Island arcs such as Japanese, indonesian, aleutian, are example if
    1. Oceanic-oceanic convergent
    2. Oceanic-continental convergent
    3. Continental-continental convergent
    4. Any subduction zone
  - C. Oceanic crust form mainly from ______ basalt (near MOR), & ____ (above hotspot)
    1. Calc-alkaline, tholeiitic
    2. Tholeiitic, alkaline
    3. Alkaline, Tholeiitic
    4. Non of the above
  - D. First step in formation of continental crust
    1. Hot spots activity
    2. Mantle plumes activity
    3. Volcanic islands arc
    4. Island arcs
  - E. Tholeiites basalt in island arc are different from the MORB by
    1. More Al (Al_2O_3>16)"high alumina basalt"
    2. More CaO
    3. More Alkali elements
    4. All of the above
  - F. diagrams for the common rocks of the subduction zones is called
    1. James Hutton 2. Harker variation
    3. Plutonic 4. Volcanic
  - G. Rock contain (51 – 56) wt%SiO_2 where CaO = [K_2O + Na_2O], classified as
    1. Alkalic 2. Alkali-Calcic
    3. Calc alkaline 4. Calcic
  - H. found in subduction zone
    1. Alkalic 2. Alkali-Calcic
    3. Calc alkaline 4. Calcic
  - I. Found in the Mid-Oceanic ridge
    1. Alkalic 2. Alkali-Calcic
    3. Calc alkaline 4. Calcic
  - J. Have high feldspar contents
    1. Paraluminouse 2. Subluminouse
    3. Paraalkaline 4. Matalumiuse

K. Ophiolites formed in the ___________
    1. back arc basins above subduction
    2. For arc basins below subduction
    3. Above hot spot
    4. All of the above
L. Carbonatites magma Formed by
    1. Gravitational settling
    2. Filter pressing
    3. Fractional crystallization
    4. liquid-liquid impeccability

- **Q5: T/F**
    A. Convergent Plate Boundaries (active margin) where 2 lithospheric plates collide
    B. Volcanic arcs (e.g. Andes, & rocky mountains) are example of continental-continental convergent
    C. Volcanic arc farthest from hot spot is the newest island
    D. Island arc farthest from subduction zone is the oldest island
    E. In the subduction zone, volcanoes occur above subducted plate
    F. High heat flow is the region of for arc basins (toward tranche)
    G. The rocks in island arcs vary from high Mg tholeiitic basalts to strongly differentiated dacite & granodiorite
    H. The graph of distribution of rock type in island arc is bimodal
    I. Alkali calcic & alkalic found in the continental crust
    J. Carbonatites magma is the coldest type of magma (500 – 600)°C, There is an active carbonatite volcano in Tanzania/Africa
- **Q6: for each of the following**
    A. Write the most abundant rocks in island arc (From the most to the least)
    B. The major difference between subduction & hotspots is
    C. 2 types of continental margins
    D. Magma generation in intraplate areas are similar to the islands but the differences is
    E. Continental intraplate magmatism & volcanism produce
    F. Why is there a Bimodal activity?

Chapter one	
Q1	
A	Is the study of rocks, or explanation or understanding of rocks & Their formation
B	Naturally occurring, mechanically formed aggregates of minerals or mineraloids, some with interstitial fluids, & most consist of several different minerals
C	molten or partially molten material, most of them consist of minerals, rock fragments, fluids, & gases
D	Fine-grained borders against rocks, producing because the rock near dike or cell are cooler than dike, so the rocks cooling rapidly at borders & slowly in the center
E	Loose materials accumulate in layers to produce sedimentary rocks
F	Huge igneous body, most of the batholiths have granitic composition
G	Transitional rock between igneous & sedimentary rocks, such as Tuffs (volcanic sediments) that classified as igneous rocks but consist of layers
H	Transitional rock between metamorphic & igneous rocks, outcrop-scale mixture of light & dark rocks, represent the onset of melting in crust at high-grade metamorphism
I	Rock that formed by solidification of magma
J	Rock that formed by consolidation of sediments & accumulation in layers
K	Formed by preexisting rocks by changing mineralogy, structure, or chemical composition of rock in response to marked changes in T, P, sharing stress, or chemical environments below the zone of weathring & cementation
L	Machanically formed fragments of older rocks that has transported from their source & precipitated in water
M	Rocks formed by precipitation in solution
N	Rock consist of organic remains, from organism that lived in the past (animal, plant)
O	Transitional zone, Rock exist in one or another of the categories due to historical precedence or the bais whim of the classifier

Q2	
A. Geosphere (litho…)	B. Magma
C. Aqueous	D. Igneous, sedimentary
E. 200°C – 700°C	F. Migmatite,Pyroclastic
G. Layering or stratification	

Q3	
A	If the magma reach the surface, it cools fast, & there's no time for it's ions to be formed in a regular order to make crystals, But it hardens randomly to produce glass (solidified)
B	Because we study geosphere which consist of minerals & rocks, petrology occupies central position between earth's science
C	Limestone & marble composed of Ca-carbonate, in the simple composition the ions rearrange during metamorphism to produced rock with same composition but with larger crystals so limestone metamorphosed to marble (coarser) with same composition
D	Granitic magma have higher viscosity
E	Regional metamorphism (high-grade metam.) occur near subduction zone where different plate move in different direction, so the stress isn't equal in all direction

Q4					
A. 2	B. 1	C. 1	D. 2	E. 3	F. 2

Q5	
A. T	B. F (increase)
C. T	D. F (structure, texture)
E. T	F. T
G. F (Basaltic at ridge, & granitic in the continentals)	

Q6	
A	1. Characteristic shape: dike, veins, stock, batholith, laccolith, laccolith, lava,volcanoes 2. Lack of fossils or stratification except for pyroclastic rocks 3. Chilled : fine-grained borders against rocks 4. Thermal effects on adjacent rocks 5. Found in Precambrian & orogenic terranes 6. Cross-cutting relationships
B	1. Sorting & stratification 2. Characteristic shapes : mud-cracks, ripple marks, cross-beds 3. Wed spread & interbedded with known sediments 4. May be consolidated or unconsolidated 5. The shape may be characteristic form delta, river, drainage systems
C	1. Distorted pebbles, fossils, or crystals 2. Parallelism of planar, & elongate grains 3. Located adjacent to igneous, occasionally 5. Rock cleavage related to regional structures 6. Progressive change in mineralogy 7. Some rocks composed of interlocking grains
D	Porphyritic, glassy, vesicular, amygdaloidal, graphic, pyroclastic, interlocking aggregate
E	Fragmental, fossiliferous, oolitic, pisolitic, stratified, interlocking aggregate
F	Brecciated, granulated, crystalloblastic, hornfels
J	Bowns series (olivine, pyroxene, Amphibole, biotite, muscovite, anorthite, Labradorite, andisine, oligoclase, alpite, Sanadine, microcline, orthoclase, anorthocalse) & peldspethoids (Leucite, & Nepheline) & related minerals
H	Quartz, chert, clays, carbonates (calcite & dolomite), Anhydrite, Halite, Gypsum
I	Amphibole, Andalusite, Epidote, Feldspar, Garnet, Graphite, Kyanite, Sillimanite, Micas

Chapter Two

Q1	
A	Adding new components (mass) to the earth by meteorites bombardment
B	The boundary between 2 earth's layers such as moho boundary between crust & mantle
C	Law velocity zone, below the lithosphere, major source of mgma, & consist of UM rocks & have little volume of interstitial melt
D	Is the igneous body, move from the hot outer core by currents (from lower to a higher level) & originating near core-mantle boundary
E	Is the cycling of magma in mantle toward the surface as cooler mantle sinks, is the primary mechanism by which heat is transported from the interior of Earth to the exterior
F	Changing in T with depth (3.3°C/Km)
G	Part of the oceanic lithosphere Rich surface by abduction process

Q2	
A	Asthenosphere (mantle), lower continental crust(lithosphere), 640Km discontinuity
B	Meteorites bombardment
C	Xenolith, Xenocrystals
D	Moho boundary
E	50Km – 100Km, 250Km depth
F	2.8g/cm^3
G	Moho boundary
H	250 km (the crust & upper mantle)
I	Liquid
J	P-wave
K	A-olivine, β-Mg_2SiO_4 (wadsleyite), spinel, MgO + perovskite
L	Linearly, exponentially
M	Convection currents (mantle convection)
N	670km depth
O	Mantel Plume
P	Volcanic islands
Q	Decreases pressure, extension process
R	Granitic (batholiths)
S	Mineralogical Transitional Zone

Q3	
A	
B	Due to little volume of interstitial melt
C	1.Seismic evidence shows that at least some subducted slabs probably sink to the vicinity of the core-mantle boundary 2.Mantle plumes are originating in this area
D	Magmatic processes result in move of the large cation from the mantle into a crust, so crust are rich in the radioactive elements that increasing T
E	The outer core composed of other elements than Fe & Ni such as S & Si which decreasing melting point of the solution
F	Because granitic magma consist of low T mineral like quartz (unstable in the mantle)
G	Basaltic magma has the same ρ as surrounding rock at depths 100 – 150 km (30-45kbar)

Q4					
A. 1	B. 2	C. 1	D. 2	E. 1	F. 2

Q5	
A	T
B	T
C	F –> liquid state (melt)
D	F –> solid & liquid
E	F –> higher than continental lithosphere
F	T
G	F –> mafic magma
H	T
I	T
J	F –> norite composed of Opx, & gaproo Cpx

Q6	
A	1. Geophysical measurement (gravity, magnetization, seismic wave) 2. Study of the meteoric composition 3. Experimental petrology 4. Study of the cross section in the lab 5. Study of the xenolith & xenocrystals 6. New techniques: computer Simulation
B	1. Heat that stored in Earth by accretion (adding nwe components to the earth by meteorites bombardment) from 4.5Ga 2. LAIL (large ions lithofile element): radioactive elements 3. Fractional heat generate
C	1. Mid-oceanic ridge 2. Subduction zones 3. Hot spots (&mantle plumes
D	SiO_2 45.2%, FeO 8.48%, & MgO 37.48%, (91.2)
E	1. Increasing in fluid such as H_2O, & CO_2 2. Decreasing load pressures

Q7	
A. Peridotite (>40%Ol)	G.olivineorthopyroxenite
B. Pyroxenite (<40%Ol)	H. Websterite
C. Dunite (>90%Ol)	I. Olivine Websterite
D. Clinopyroxenite	J. Lherzolite
E. Orthopyroxenite	K. Wherlite
F.olivineclinopyroxenite	L. Harzburgite

Q8

$GG_{oce(500 - 1000)}$ = (1000-500)/(100-25) = 6.67°C/km
$GG_{con(500 - 1000)}$ = (1000-500)/(120-35) = 5.90°C/km
$GG_{oce(1000 - 1500)}$ = (1500-1000)/(420-100) = 1.6°C/km
$GG_{con(1000 - 1500)}$ = (1500-1000)/(420-120) = 1.7°C/km

Q9

Norite (Pl, Ol, pyroxene), harzburgite (Ol, Opx)

Q10

Moho boundary, becouse the upper rock is felsic (granitic, continental crust) & the lower is ultramafic (composed of Ol & Pyroxene)

Chapter Three	
Q1	
A	Equilibrium relationships of minerals & melts described graphically by phase diagram (Homogeneous part of a system, that can be mechanically separate from another, & can have either a fixed composition or a variable)
B	Number of decreasing in freedom, the max. number of variables of a given system which can be changed independently without changing the state of the system
C	Rule that Relates number of components to the number of phases to T-P variation
D	A geologic system (rock or magma) is in state where there is no driving force for change
E	Verticalline on diagram represent composition
F	Horizontal line on the pinary diagram represent Temperature
G	The point where 2 liquidus line intersect with solidus line (represent min. crystallization T)
H	Called reaction points, liquid can leave it as cooling proceeds, moving down the liquidus to the eutectic point, where we have Icongruently melt
I	The early formed mineral phases separated from the magma & the remaining magma enriched in the low T minerals due to preferential cooling of the boundaries of the magma chamber: roof, side wall, & floor
J	Fundamental tools used by any scientist deals with molten materials to illustrate crystallization & melting
K	Is the process by which particulates rise to the bottom of a magma due to gravity, important operation in many applications, such as mining (Ores are formed by separating minerals)
L	Fluids that transported & milting some rock, & carry ions, & when the T of fluids decreases precipitate the ions to form rocks, such as water & carbon dioxide
M	We can get different rocks or magma composition from parent magma
N	Separation of crystals from melt, lead to magma differentiation
O	2 melts controlling mineralogical of the crystallization of the magma, is the process responsible for the production of rare magma such as carbonite & sulfate magma
P	By Hutton, the present is the key to the past
Q	Composition at any given time
Q2	
A	Plutonists
B	Komatite
C	J. Hutton
D	800°C – 1200°C
E	Fine-grained, coarse-grained
F	Olivine
G	$Si^{4+} + Na^{+} \leftrightarrow Al^{3+} + Ca^{2+}$
H	Physical condition(T,P), new equilibrium state
I	Components
J	Phases
K	A spontaneous attainment
L	Components
M	Metastable
N	Pressure, Temperature
O	1.5%VolH_2O, 3%VolH_2O, 6%VolH_2O
P	Isothermal, isobars diagram
Q	Filter pressing
R	Garnet & amphibole, phlogopite
S	Phlogopite
Q3	
A	Due to presence of several different minerals
B	T of lower continental crust is > oceanic
C	Due to solid solution series (substitution)

Q4

A	B	C	D	E	F	G	H	I	J	K	L	M
4	4	2	1	4	1	1	1	2	3	4	1	2

Q5

A. F: basalt is mafic	B. T
C. T	D. F: each mineral phase
E. F: less than or equal	F. F
G. T	H. F: fractional melting
I. F: you can see	

Q6	
A	Study of Oldest rocks, & active volcanoes
B	1. observations in field (mineralogy, texture) 2.laboratory studies (thinsections, minerals) 3.analyses of chemical compositio
C	1. Load P (lithostatic) : P of rock, increase B.P 2. Fluid P (H_2O, CO_2) : decreases Boiling poin
D	Fractional crystallization, Liquid impeccability, Rock assimilation, Magma mixing, & Degree of partial meltin
E	1. Water goes deep into earth, heated by GG 2. Water that separates from the magma during magma differentatio
F	1.Enstatite($Mg_2Si_2O_4$)-Forsterite (Mg_2SiO_2) 2.Quartz-feldspathoid (leucite, nepheline)
G	1. Eutectic point (min. crystallization point) 2. Peritectic point (reaction point
H	Marginal accretion, Gravitational settling, Convection flow, Filter pressing
I	**Density** There is no differences in densities between minerals in felsic rocks **Viscosity** granitic rocks has very high viscosity
Q7	
1	Binary congruent system, no
2	liquidus line, A & B
3	C
4	G: solid, E & F : solid + melts

5	1510°C, 1247°C
6	Start at H, & end at J
7	Mafic or intermediate because pyroxene, Ca-plagioclase is intermediate or mafic minerals
8	3 phases (An, Di, An + Di)
9	The solidus T (or eutectic point temperature)
10	1 kbar, 1410°C, 2 phase 27.8%solid (100%An) & 72.2%melt (90%An, & 10%Di)

Q8

1	Binary congruent system, yes
2	A. Melt, B. Melt&crystal,C.Homogenies crystal
3	$F = C - \Phi + 1 = 1 - 2 + 1 = 0$
4	1500°C, 80%An + 20%Ab
5	Olivine & pyroxene systems
6	1 homogenies mineral (plagioclase)
7	$Al^{3+} + Ca^{2+} \leftrightarrow Na^{+} + Si^{4+}$

Q9

1	$Mg^{2+} \leftrightarrow Fe^{2+}$ Perfect substitution, because Mg & Fe have nearly same atomic volume, charge & electronegativity
2	Becouse olivine is stable in mantle
3	لان ذلك يتطلب صهر جزء من الستار بنسبة 100٪
4	Due ro type of substitution

Q10

1	عند اضافة الماء تنخفض خطوط ال solidus وتتقاطع مع خط ال solvus وتتحول ال minimum crystallization point الى eutectic فلا يتكون معدن متجانس وانما تنفصل بلورات ال anorthite & alpite عن بعضها البعض في اطر وتشكل zoning واذا كان ال anorthite في هذه الاطر يتناقص تناقصا منتظما نسميه normal zoning اما اذا كان غير منتظم نسميه oscillatory اما في حالة وجود كمية كبيرة من الماء ستنخفض الخطوط كثيرا وسينتج صخر ل granitic bigmatite هو very coarse grained granite وهو اخر ما يتبلور من ال granitic لذا تكون به نسبة ال fluids عالية ما يؤدي لتسريع حركة الايونات فتتكون بلورات كبيرة
2	Granite: because consist of K-feldspar (orthoclase) & Na-feldspar (albite)
3	Minimum crystallization point, at this point melt + homogenies solid exist, but at eutectic point eutectic melt + 2different solid exist
4	The line between homogeneous crystals (subsolvuse) & heterogeneous (hypersolvuse)
5	Perthitic texture
6	Antiperthitic texture
7	اذا وجدنا granite يوجد به 2 feldspar نستنتج ان كمية fluid كانت به كبيرة اي انه كان مصدرا hydrothermal solution التي تتميز بحملها لمعادن لا مكان لها في المعادن الرئيسية مثل gemstones, silver, gold..

Q11

1	Peritectic point, Eutectic point
2	50%VolFo (solid) 50%Vol peritectic melt (rich in silica) with composition 37%Qz + 63%Fo
3	Enstatite (Opx) ↔ Forsterite (Ol) + Quartz $Mg_2Si_2O_6 \rightarrow Mg_2SiO_4 + SiO_2$
4	1880°C

Q12

Ox	An	Di	Degree of partial melting (for melt)			
			1st solid	17%	35%	100%
SiO_2	43.2	55.5	44.43	49.7	46.6	44.4
Al_2O_3	36.7	0.00	32.99	17.2	26.9	33.0
CaO	20.2	25.9	20.73	23.2	21.8	20.7
MgO	0.00	18.6	1.860	9.87	5.12	1.86

Q13

O	E	F	F1	F2
46.6	47.8	49.8	46.1	45.9
10.5	10.8	18.5	61.9	68.5
23.8	23.2	15.8	24.1	22.6
19.1	18.4	16.0	19.4	19.3

Q14

Filter pressing: The early formed mineral phases separated from the magma & the remaining magma enriched in the low T minerals

Due to preferential cooling of the boundaries of the magma chamber: roof, side wall, & floor

Q15

1	F: liquidus, G:Solidus
2	P: Perthitic, E: Eutectic
3	If we heat sample that tack place in D, result is homogenies liquid composed of silica & Fo, &If we cool this sample at the solidus another liquid (eutectic) & a solid will be created If we heat the sample that tack place in E the result is homogenies liquid composed of silica & forsterite, & If we cool this sample solid mineral will be created, with same composition
4	A_2: 25.9%solid(100%Fo) + 74.1%Peritectic melt (80%En+20%Fo), A_3: there's one solid phase only 100%solid with comp. (60%En, 40%Fo)
5	T = 1757°C
6	71.0%SiO_2, 29.0%MgO
7	45.5%SiO_2, 54.5%MgO
8	The composition start to change by changing T (melt & solid proportion changes & composition of melt change)
9	T = 1900°C (T of melting pure forsterite)

Q16

kind of layer: Rhythmic layers

name of complex: Bushveld complex

name of rock: komatite-Anorthite (intrusive rocks)

processes led to layer: 2 possess, 1st gravitational settling (separation of minerals depend on Δρ) & the 2nd is filter pressing (separation by preferential cooling of the boundaries of the magma chamber)

where did it originate: within the earth (intrusive)

Chapter Four

Q1

A	Elevated areas in the oceanic floor characteristic by high heat flow & volcanism
B	Is the deep-down-faulted structure near the axis of some ridge
C	Is the area of volcanism, high heat flow, & crustal uplift, related to mantle plume OR are volcanic regions underlying mantle that is very hot compared to the surrounding
D	Basaltic magma constantly added to the oceanic floor at MOR & then transported away from ridge until return to the mantle at trench
E	Is the magma Chanel, near intercontinental rift, produced by P generated from partial melting at the surface of mantle blume
F	Made of OIB, formed due to rising magma from blume, & transported away from hot spot due to drifting of plates forming arc-shaped islands
G	Rate at which the plates move away from ridge
H	Is the chemical parameter, used to distinguish between basalt types
I	At the subduction zone, the ocean is closed due to abduction (the process of exiting part of the Mantel & the oceanic crust over the continent) & this process facilitates the study of the M & UM rocks, called ophitic sequence such as سمايل/عمان
J	Called Blake smoker, Stalagmite-like columns of sulfide & unique marine animals (surround vent)
K	Chemically distinct range of magma compositions that describes the evolution of a mafic magma into a more evolved (silica rich end member)

Q2

A	Garnet lherzolite, serphentine lherzolite
B	Xenoliths
C	OIB
D	120°, same P in all directions (or tension f)
E	Normal Fault
F	Intercontinental rift, back-are basin
J	Spreading rates
H	Slow spreading ridge
I	Fast spreading ridge
J	Fast
K	Chert (microcrystalline quartz)
L	Gabbro
M	Alkali basalt or tholeiitic basalt
N	Pillow lavas
O	Ophitic
P	Shells of microorganisms (radiolaria, foraminifera
Q	Radial cracks
R	K_2O
S	Olivine, Augite (Cpx) & plagioclase (anorthite)
T	Dissolved ions (such as oxides & sulfides)
U	Less oxidized
V	Hotspots, Volcanic islands
W	Seamountains

Q3

A	information about high P melting process
B	As plume originate at the Mantel-Core boundary, the confining P decreases which result in partial melting (Upwelling), & melting produce P under continental crust which upwarping, & thinning, & Finally divided into 2 crust which move away from each other forming new ocean (in between) such as red see & EARS
C	plume originate P below new oceanic lithosphere & P is equal in all directions, so the crust is exposed to equal tension forces that lead to formation of triple junction, The Domal structure will formed due to rising magma
D	Limestone ($CaCO_3$) is stable at high Ph (> 7.8), but deep in ocean (below CCL), the Ph is < 7.8 (Alkali)
E	The upper part of magma chamber is molten & the lower is Mush, Gappro crystallizes from it & part move to the oceanic crust via dikes forming lava عند وصولها للسطح تتوقف نتيجة ملامستها للماء فيتصلب سطحها الخارجي ويتكون Chilled وتبقى الmagma تندفع بها وتفصل الىsheets اي ان الصهير ستخرج منها ويشكل pillow
F	Because the border near source of magma crystals more slowly than at the far end
G	Center of basaltic flow → less vesicles
H	Seawater penetrates oceanic crust → heated by magma or hot rock → dissolve surrounding rocks & carry ions → as the water return to ocean form smoke
I	عند انتقال الصهير من مستوى لاخر يقل P فيحدث decomposition ما يؤدي لنشوء thioliitic magma على طول ال ridge والتي تتميز في انها تحتوي كمية K_2O قليلة وانها less oxidized

Q4

A. 1	**B. 1**	**C. 1**	**D. 4**	**E. 1**	**F. 2**	**G. 4**	**H. 3**
I. 2	**J. 1**	**K. 1**	**L. 4**	**M. 3**	**N. 3**	**O. 4**	**P. 1**
Q. 2	**R. 1**	**S. 3**	**T. 3**	**U. 3**	**V. 3**	**W. 3**	

Q5

A.T	B. F (1st major type)
C. F (one isn't active)	D. T
E. F (inverse proportion)	F. T
G. F (solid + magma)	H. F (Tholeiitic series)
I. T	J. T

Q6

A	Gappro, & then Basalt (in form of MORB)
B	**MORB:** Formed near mid-oceanic ridge **OIB:** partial melting in the upper surface of a blum
C	Remote sensing & depth sounding instruments
D	Tholeiitic magma series, & Calc-alkaline series
E	High T of magma, & the viscosity is very law
F	In hot spot 1. Source of a magma is deeper (150km,blume) 2. the degree of partial melting is less (<10%) 3. most of hot spot magma alkaline (K_2O > 1%)

Chapter Five

Q1

A	Is the deepest area in the oceanic floor, formed by Oceanic-oceanic convergent
B	A group of igneous rocks associated with its origins (genitic relations)
C	site of sediments accumulation, metamorphism, & magmatism (Places of continental accretion)
D	a peculiar assemblage of UM rocks, gabbro, pillow lavas, & sheeted dikes overlain by a thin cover of sediments, as uplifted & exposed to the surface
E	is a sequence of layers that consist of a grano-classified set of sandstone strata/pelitic sediments, generally in fining-upward that were deposited by turbidity currents & covered by hemi-pelagic pelites containing deep-water fossils

Q2

A. Active margins	B.Continental-Continental
C. Continental crust	D. Oceanic tranche
E. Andesites	F. FC, mantle basalt
G. Alkaline	H. subduction zones
I. Mafic	J. Intermediate
K. Felsic (granitic)	L. low, high
M. Glaucophane (blue), lawsonite, geodite (green)	N. blue schist & ophitic rocks
O. superficial	P. forarc, & active margin
Q. calcareous clay & marl	R.

Q3

<table>
<tr><td>A</td><td>Continental drift → formation of the oceanic crust (at MOR) & volcanic arc (hot spot) → formation of continental crust (subduction zone) & islands arc (proto-continents) → collision of continental crust (mountains & close ocean crust forming ophiolite)</td></tr>
<tr><td>B</td><td><table>
<tr><th>Arc</th><th>Location</th><th colspan="2">Age & note</th></tr>
<tr><td>Volcanic arcs</td><td>Hot spot (plume)</td><td colspan="2">closest to the hotspot is the newest</td></tr>
<tr><td>Island arcs</td><td>subduction zone</td><td>All have same age</td><td>first step to formation of the continent (proto-continents)</td></tr>
</table></td></tr>
<tr><td>C</td><td>Due to the curvature of the earth</td></tr>
<tr><td>D</td><td>Due to the roughness of a plates that slide under each other (not smooth)</td></tr>
<tr><td>E</td><td>subducted plate partially melted to produce magma in the volcanoes above overriding plate</td></tr>
<tr><td>F</td><td>subduction rate is faster than conduction (thermal movement)</td></tr>
<tr><td>G</td><td>T are high in the Arc region due to volcanic activity</td></tr>
<tr><td>H</td><td>the production of the fluids by the dehydration reaction which penetrate the rocks & lower the melting point of these rocks to get partial melting of wedges, oceanic crust, metamorphic & sedimentary rocks</td></tr>
<tr><td>I</td><td>Due to different melting source (mantle wedges, oceanic crust, metamorphic & sedimentary rocks)</td></tr>
</table>

Q4

A. 5	B. 1	C. 2	D. 4	E. 1	F. 2
G. 2	H. 3	I. 4	J. 1	K. 1	L. 4

Q5

A. T	B. F (oceanic-continental)
C. F (oldest)	D. F (all have same age)
E. F (overriding plate)	F. F (back arc basins)
G. T	H. F (Unimodal)
I.T	J. T

Q6

A	Intermediate > mafic > felsic > dacite, granodiorite
B	cause of partial melting 1. In subduction zone due to hydrothermal fluids 2. In hotspot due to decomposition (lowering P)
C	1. Passive margins: such as Americas-atlantic margins, normal fault without trench 2. Active margins: such as Pacific-Americas, with active subduction
D	1. interaction & magma differentiation is more complex due to the interaction with the continent (i.e. magma mixing, assimilation etc) 2. more complex diversity 3. plutons more abundant 4. Thickness of continental crust varies
E	1. Continental flood basalts, such as حرة الشام 2. Continental rift assemblages 3. Bimodal volcanism, most important feature 4. Layered basic & ultrabasic intrusions 5. Ultrabasic suites: include komatiite, kimberlite 6. unusual array of alkaline & anorogenic granites
F	تندفع mantle blume تحت ال asthenosphere ما يؤدي لارتفاعه فيحدث extension للقارة مثل east African rift system (EARS) يحدث normal fault يتسبب في هبوط ال crust وحدوث partial melting فتنتج mafic magma ويصاحب عملية التبلور exothermal process وهذه الحرارة تعمل على تسخين منطقة ال lower crust والتي بدورها تتعرض لعملية partial melting وتنشأ منها felsic magma (وممكن ان تكون carbonatites magma

Q7

Q8

Q9

Q10

Q11

Q12

Q13

Q14

PART 2
SEDIMENTARY ROCKS

WEATHERING & SOILS

6.1 Introduction

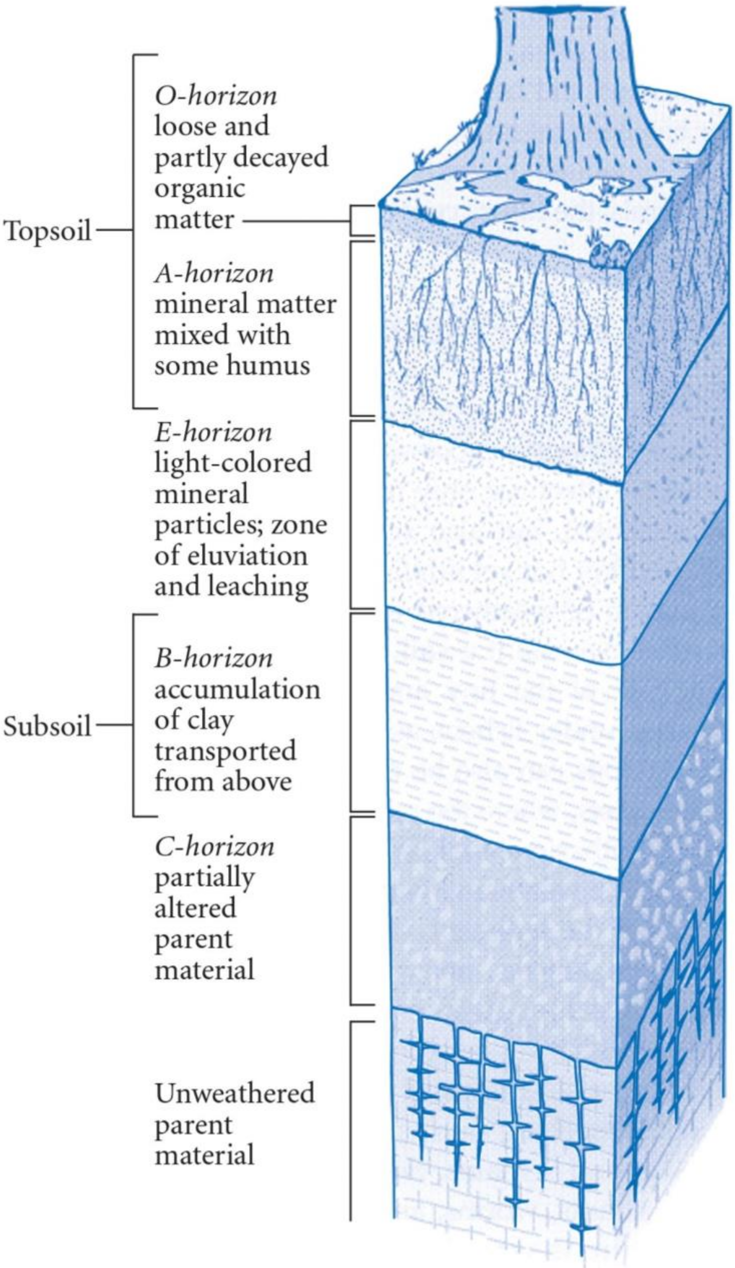
Mechanical Weathering
Exfoliation: as the batholiths rises to the surface, P decreases so they are cracks parallel of their surfaces
اذا حدثت هذه العملية لاجسام اصغر حجما **small scale** تكون اسم الظاهرة **spheroidal weathering** وهي تحويل القطع المربعة الى دائرية ومحاطة في طبقات رقيقة
هذه الصخور التي تتكون تكون **metastable** (تحتاج الى طاقة تنشيط لتتحول من شكل لاخر)

- **Exfoliation term** used to describe sheet joints that resemble the curved surface of an onion
- **Weathering:** is the breakdown of rock materials into smaller pieces
  - ➢ important in generation of soil, & sedimentary rocks which cover > 80% of surface

6.2 Soils & Sediments

- Sediment originate as detrital particles & dissolved solid which produced during weathering, then eroded & dispersed by water, wind, glaciers, & mass flows across surface to be deposited as detrital, & biochemical to produced soils

- **Soils:** one of the major product of the chemical weathering & important in the liking inorganic with organic world (lithosphere with Biosphere)
- **Soil horizons & profiles**

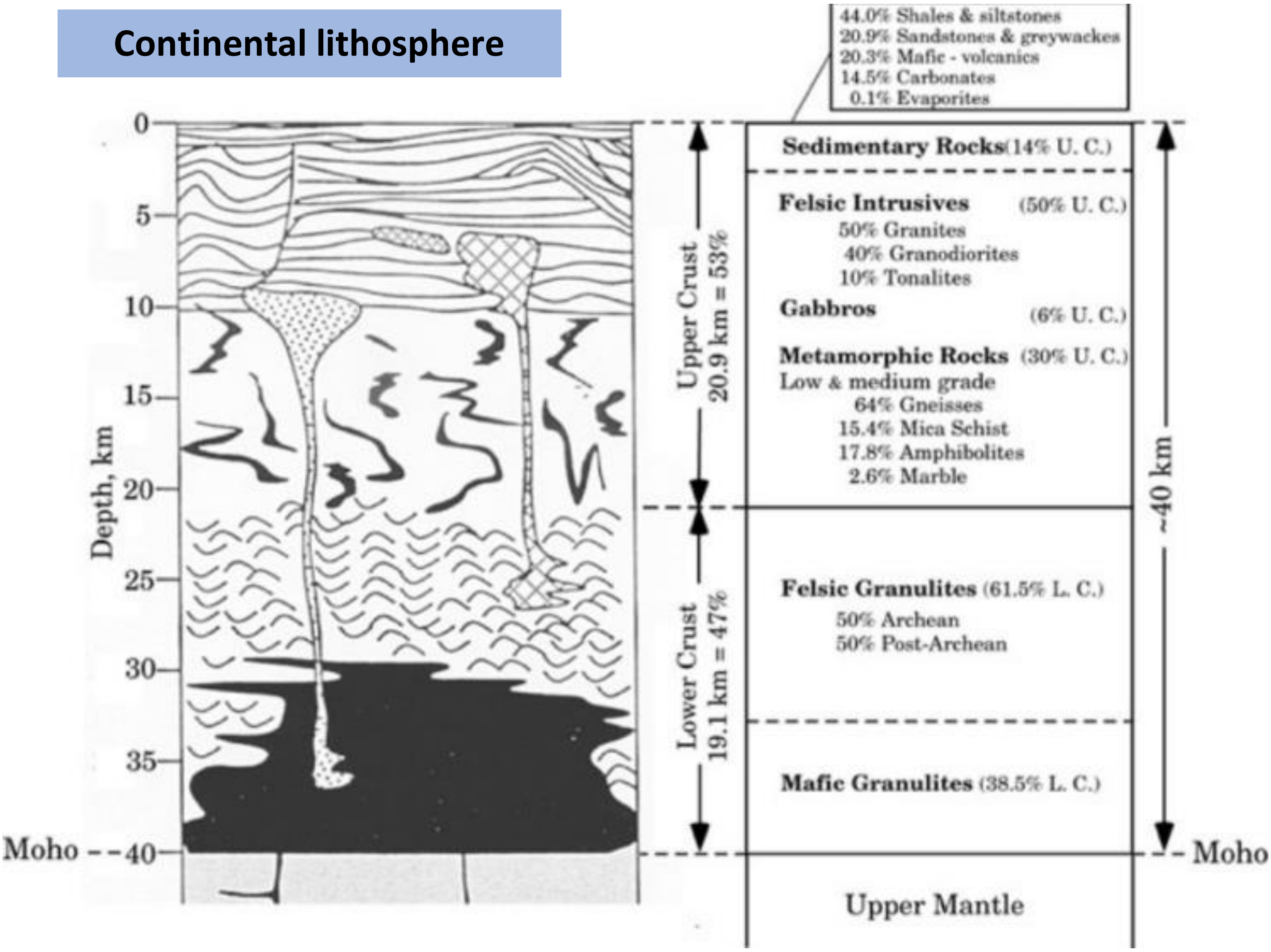


- **Horizons:** Layers of soils produced by weathering
- **O-horizon** upper portion of soil, characterized by organic material
- **B-horizon (zone of accumulation / illuviation)**
- **C-horizon:** is the interaction regions, moderate weathered, slightly altered materials

6.3 distribution of rocks

- Sedimentary rock make up 14% of continental rock
- The most abundant component of the continental crust is the granite (55%)

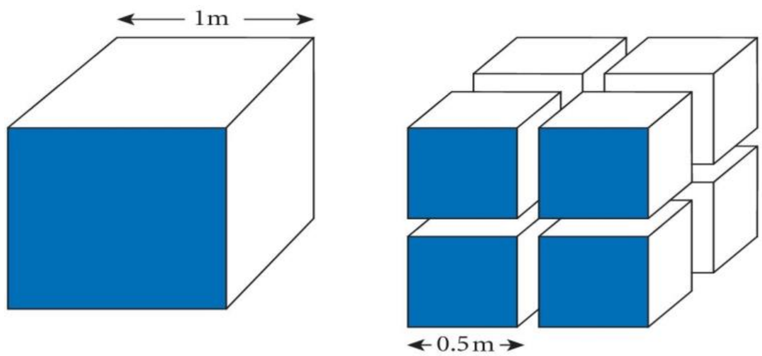
Continental lithosphere



- **Basalt rocks don't exist because they rise to the surface & produce lava flow (due to low viscosity)**

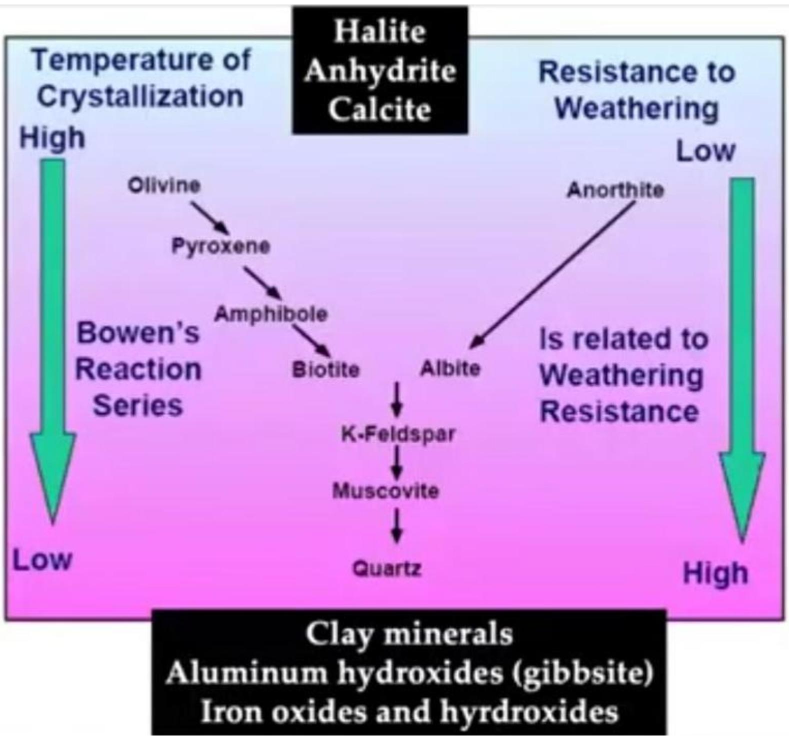
6.4 Weathering

- **Weathering Vs Erosion:** weathering involve the breakdown of rock material in particular location, erosion is the removal of rock material from a location & transportation to another location
- **Differential weathering**: different rock material weather (or altered) at different rates
- **Weathering processes** subdivided into disintegration & decomposition processes
- **Disintegration (machanical Weathering)** breakdown of large , & more coherent rock into smaller fragment with same composition
  - ➢ generates an increased surface area for chemical weathering
- **Decomposition (chemical Weathering)** breakdown of rock, with changes in composition
- Disintegration more prevalent in cold & dry climate
- decomposition dominate in warme, wetter climate



Disintegration enhance decomposition by increasing the surface area of rock fragments

- **Factors controlling rate of chemical alteration**
  1. **Chemical composition:** (Goldlich's series) Compounds with covalent bonding are less soluble in water than those with ionic
  2. **Structural integrity:** smaller grain size, & presence fractures facilitate chemical attack
  3. **Crystallinity**: Crystals lacking any defects are more stable (K-feldspar more stable than perthites, amorphous solids are easily dissolved in water than crystalline silica)



- High stability of quartz is one of the reasons why it's the most abundant in sandstones & gravelstones (conglomerates & breccias)
- High stability of clay helps to explain why they are the major constituents of mudrocks (shale)
- High susceptibility of olivine to altration explain why they are not found on Earth surface

6.5 Alteration & Decomposition

- Silicate minerals are less stable in acidic environments & less stable at higher T
- Soils in semi arid climates tend to be basic, with calcite accumulation in the B horizon, Those in more humid climates are acidic because of the growth & decay of organic matter (organic acids)

Ions in solution			
	Radius A°*100	Ionic Potential Z/r	Ions in solution
K^+	133	0.75	$K^+_{(aq)}$
Na^+	97	1.0	$Na^+_{(aq)}$
Ca^{2+}	99	2.0	$Ca^{2+}_{(aq)}$
Mn^{2+}	80	2.5	$Mn^{2+}_{(aq)}$
Fe^{2+}	74	2.7	$Fe^{2+}_{(aq)}$
Mg^{2+}	66	3.0	$Mg^{2+}_{(aq)}$
B^{3+}	23	13.0	$BO_3^{3-}{}_{(aq)}$
P^{5+}	35	14.3	$PO_4^{3-}{}_{(aq)}$
S^{4+}	30	20.0	$SO_4^{2-}{}_{(aq)}$
C^{4+}	16	25.0	$CO_3^{2-}{}_{(aq)}$
Fe^{3+}	64	4.7	$Fe(OH)_3$, $Fe_2O_{3(s)}$
Al^{3+}	51	5.9	$Al(OH)_{3(s)}$
Mn^{4+}	60	6.7	$Mn(OH)_4$,$MnO_{2(s)}$
Si^{4+}	42	9.5	$Si(OH)_4$, $H_4SiO_{2(s)}$

- **Ionic Potential = charge of ion/radius** (Directly proportional to the strength of chemical bonds, ion that has more IP, goes to the structure first)

Major Product Of Chemical Weathering	
Mineral	Weathering Products
Quartz	Quartz as sand grains
Feldspar	Clay (Kaolonite) + K, Na, or Ca
Biotite	Chlorite + Fe, or Mg
amphibol	Chlorite + Fe, or Mg
Pyroxene	Serpentine + Fe, or Mg
Olivine	Serpentine + Fe, or Mg
Calcite	Carbonate + Ca
Pyrite	Iron oxide + Fe + sulphuric acid

➢ **Kaolonite $Al_2Si_2O_5(OH)_4$**: major product of weathering of feldspar, major mineral in shale

لموازنة معادلات التجوية الكيميائية:

1. نثبت ال immobile elements مثل Al في الطرفين (اذا كان بلاجيوكليز فأن من اهم نتائجه الكاولونايت)
2. نكتب الايونات التي تتواجد في المحاليل المائية بشكل حر
3. نوازن ال Si في $Si(OH)_4(s)$
4. نوازن ال O في H_2O ثم نوازن ال H باضافة H^+

Orthoclase → Muscovite + dissolved silica

$$3KAlSi_3O_8+2H^++12H_2O \rightarrow KAl_3Si_3O_{10}(OH)_2+6H_4SiO_4+2K$$

Muscovite → kaolonite

$$2KAl_3Si_3O_{10}(OH)_2 + 3H_2O + 2H^+ \rightarrow 3Al_2Si_2O_5(OH)_4 + 2K^+$$

Kaolonite → Gibbsite + dissolved silica

$$Al_2Si_2O_5 + 9H_2O + 4H^+ \rightarrow 2Al(OH)_3 + 2H_4SiO_4$$

Albite → kaolonite + dissolved silica

$$2NaAlSi_3O_8+2H+9H_2O \rightarrow Al_2Si_2O_5(OH)_4+H_4SiO_4+2Na^+$$

Ferromagnesian minerals → hematite or goethite

$$2Fe(OH)_3 \rightarrow Fe_2O_3 + 3H_2O \text{ or } FeOOH + H_2O$$

$$Mg_2SiO_4 + 4H^+ \rightarrow Si(OH)_4 + Mg^{2+}$$
$$Mn_2SiO_4 + H_2O \rightarrow Mn(OH)_2 + H_4SiO_4$$
$$2Fe^{2+}{}_2SiO_4 + 4H_2O + O_2 \rightarrow 2Fe^{3+}{}_2O_3 + 2H_4SiO_4$$
$$Mn^{2+}{}_2SiO_3 + 4H_2O + O_2 \rightarrow 2Mn^{3+}O_2 + 2H_4SiO_4$$
$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow [HCO_3]^- + H^+$$
$$[HCO_3]^- \rightarrow [CO_3]^{2-} + H^+$$

Halite: $NaCl + H_2O \rightarrow Na^+_{(aq)} + Cl^-_{(aq)} + H_2O$

Calcite: $3H_2O + 3CO_2 \rightarrow 3H_2CO_{3(aq)}$

$$3H_2CO_{3(aq)} + CaCO_3 \rightarrow Ca^{2+}_{(aq)} + 2(HCO_3)^{1-}$$

لحساب عدد الجرامات : $m = nMm$

قريبا من خط الاستواء تحدث تفاعلات endothermic وهي تفاعلات تحتاج الى طاقة (حرارة)

Ferromagnesian minerals altered to chlorite (green, stable to up 500°C)

Chert are produced from calcic acid (dissolved silica)

Sandstone & Conglomerates make up 30% of the sedimentary rocks

Shales is most abundant sedimentary rocks

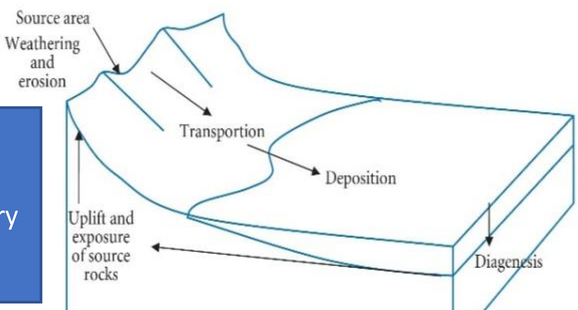
SEDIMENTARY CYCLE

7.1 Sediments & Sedimentary Rocks

- Sedimentary materials including soils, sediments & sedimentary rocks, cover > 80% of earth's surface
- Contain most of the fluid resources such as groundwater, gas, petroleum
- Sediments are classified genetically, according to the processes involved in their formation:
  1) **Detrital sediment:** solid product of weathering include gravel, sand, & mud
  2) **Organic sediment:** solid products of organic synthesis & precipitation
  3) **Chemical sediment:** solid product of inorganic precipitated from solution (mineral crystals)
  4) **Biochemical sediments:** Chemical + Organic
- **Lithification**: set of processes that converte unconsolidated sediments to sedimentary rock

7.2 Sedimentary Cycle & Deposition

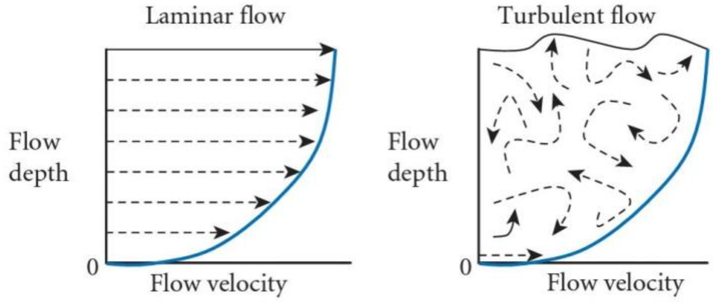
A simple model of sedimentary cycle.



Weathering & uplifting → Erosion & Transportation → deposition → Diagenesis & lithification

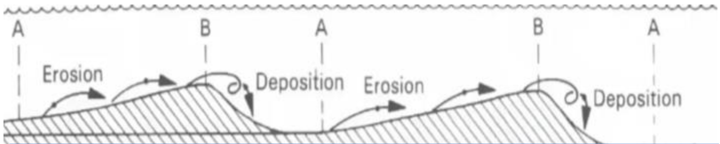
- **Deposition**: accumulate of sediments on surface
- **Diagenesis** encompasses suite of low T processes, affect sediments after accumulation (after burial)
  - Include **lithification** compaction& cementation
- **Stratification** layering of sediments & sedimentary rocks, One of the most striking feature
- **Strata** layers of deposited sediments
- السبب في وجود الطبقات هو اختلاف بيئة الترسيب
- Thick strata (>1cm thick) are called **beds**
- Thin strata (< 1cm) called **laminations** or **laminae**
- Strata form when sediments come to rest on flat surfaces (horizontal so at the time they form)

- **laminar** parcels of flow move parallel to each other in a well pattern, with negligible mixing
- **Turbulent flow** adjacent parcels of the flow move in chaotic patterns, with random mixing

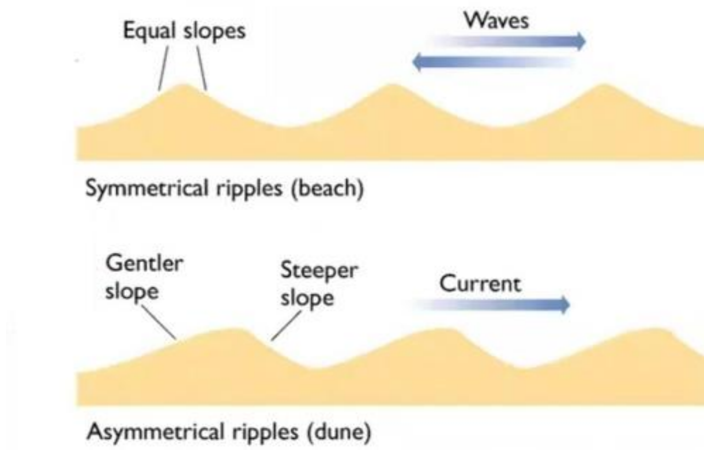


7.3 Type of bedding structures

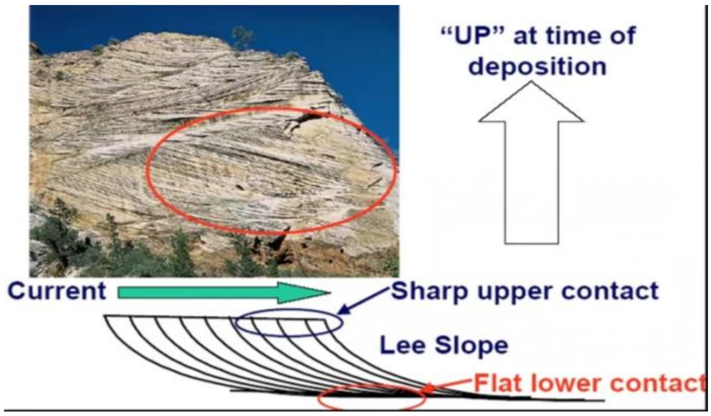
- **Ripple Marks:** oblique layer, produced by water current (dune, Asymmetrical layers) or oscillatory movement of wind (on beach area, Symmetrical layers) prior to Lithification



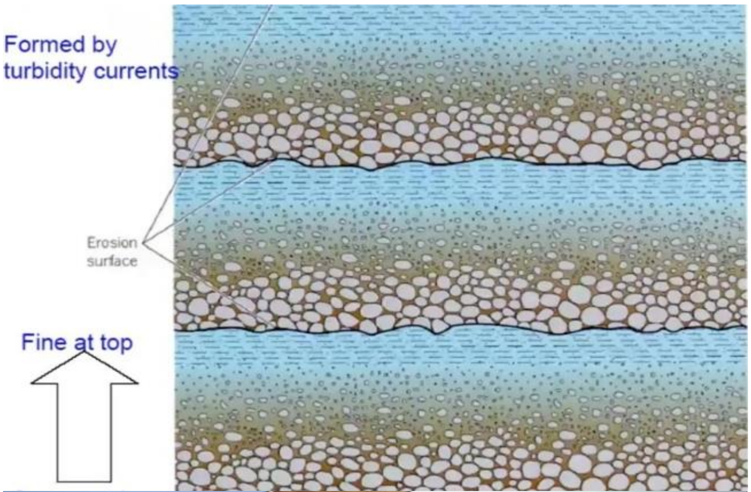
Ripples: Gentle slope in the direction of upstream & steep slope in the direction of down stream



- **Cross-bedding:** strata inclined at an angle to the main bed (wind or water), tangential layering



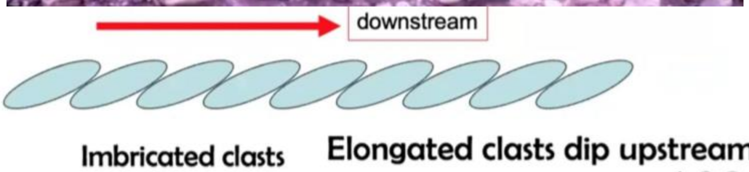
- **Graded bedding**: particle size changes from coarser to finer, produced by Turbidity currents, Rhythmic layers



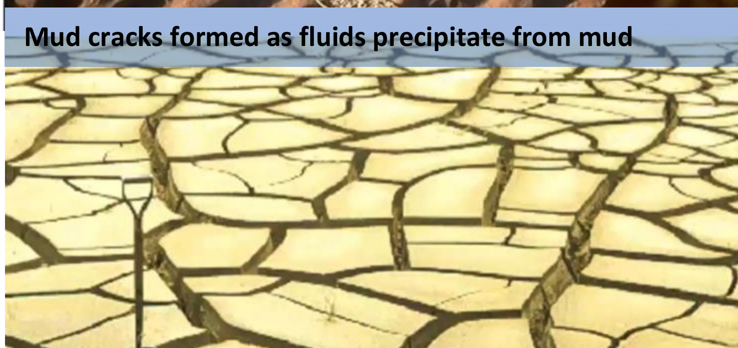

Cross beds


Cross beds


Ripple marks




Symmetrical Ripple marks

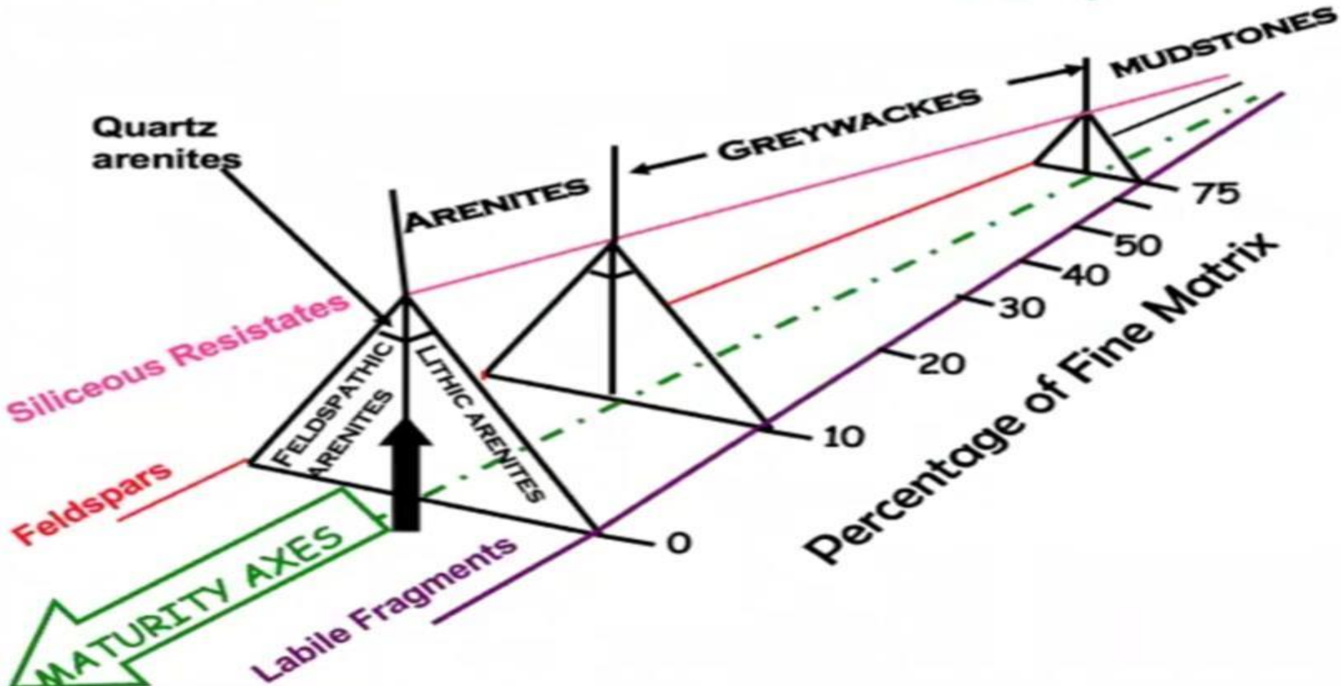

Mud cracks formed as fluids precipitate from mud


Faling mud cracks in the bed of overlying strata

DETRITAL SEDIMENTARY ROCKS

Detrital Sedimentary Rocks

Texture (particle size)		Sediment Name	Rock Name
Coarse (over 2 mm)		Gravel (Rounded particles)	**Conglomerate**
		Gravel (Angular particles)	**Breccia**
Medium (1/16 to 2 mm)		Sand (If abundant feldspar is present the rock is called **Arkose**)	**Sandstone**
Fine (1/16 to 1/256 mm)		Mud	**Siltstone**
Very fine (less than 1/256 mm)		Mud	**Shale**



	Name	Millimeters	Micrometers	φ
GRAVEL		4096		−12
	Boulder			
		256		−8
	Cobble			
		64		−6
	Pebble			
		4		−2
	Granule			
		2	———	−1
SAND	Very coarse sand			
		1		0
	Coarse sand			
		0.5	500	1
	Medium sand			
		0.25	250	2
	Fine sand			
		0.125	125	3
	Very fine sand			
		0.062	———	4
SILT	Coarse silt			
		0.031	31	5
	Medium silt			
		0.016	16	6
	Fine silt			
		0.008	8	7
	Very fine silt			
		0.004	———	8
	Clay	↓	↓	↓

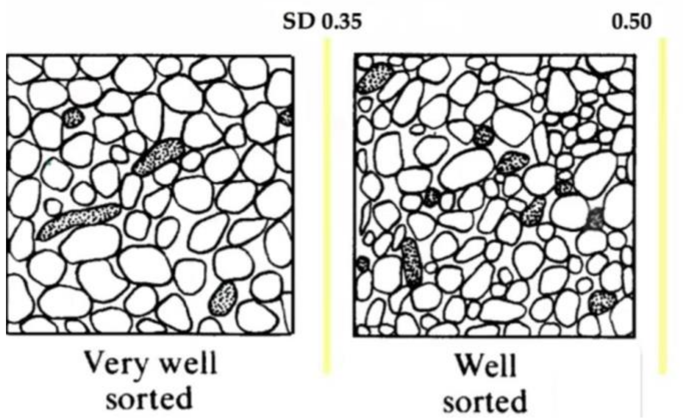
$\Phi = -\log_2^{(\text{size in mm})}$ يعتمد مقياس Φ للدراسة الاحصائية لتوزيع الحبيبات لان لها مؤشرات بيئية

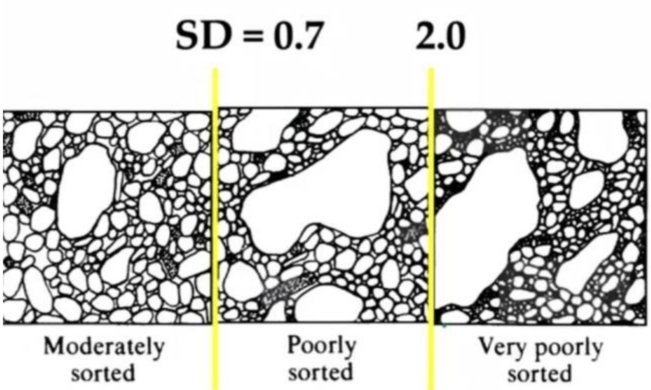
ال mud يشكل 70٪ ينتج من granitic الذي يحتوي plagioclase والذي يتجوى الى kaolonite ويتحول ال mud الى shells وهو most common rock

- The solid, inorganic components of residual soils are detrital sediments
- **mineral fragments depends on:**
  1) Mineral composition of source bedrock
  2) Erosion, Transportation, & Deposition rates

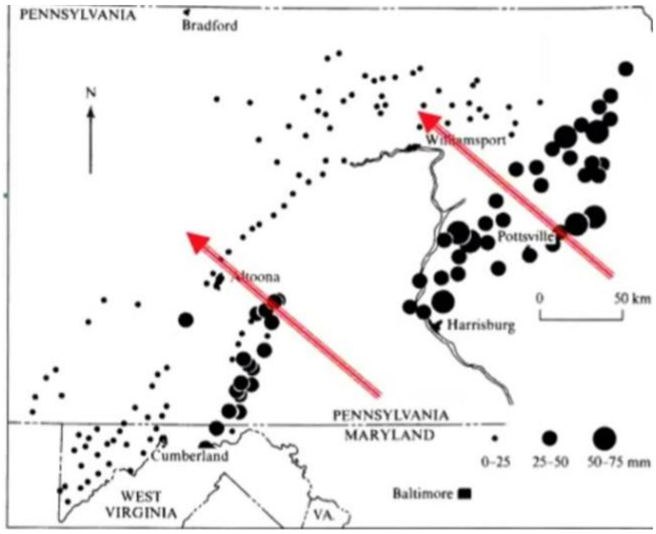
8.2 Gravel Size Rocks

- **Fermability**: rate of fluid movement in the rock, conglomerate has higher fermability & mud lower
- **Sorting:** the variation in a grain size in a given rocks





- Sorting Depending on the standard diviation (S)
    1. Lower S → Well-Sorting
    2. Higher S → Poorly-Sorting
  - ⅔ of a grains have size [1.5 - 2.5]Φ, so S =½
  - S is accepted as a measure of the SORTING
  - Very poorly sorted formed by glaciers (لان الجليد يتحرك ببطء، وقادر على نقل الرسوبيات بنفس السرعة)
- Transpiration of sediments



- The amount of erosion is a function of relief & climate 1000cm/ka years
  - Alps & Himalayas 100 cm/ka years
  - average erosion in world high relief areas 50cm/ka in low lands cm/ka
- **Stream competence:** the ability of the stream to transport large particles
- **Oligomictic (monomictic) conglomerate** consists almost exclusively of one type of fragments
- **Polymictic conglomerates** consists of a set of fragment types
- The composition of gravel (conglomerate) is a function of several factors:
  1. **Lithology & climate of the area**
  2. **Initial size of the fragments**
  3. **Transport distance**
  4. **Grain size of gravel particles in conglomerate**
- To have a rock fragment in the conglomerate, the rock should be exposed **upstream!**

- Weathering type may affect the proportions of the minerals in the source
- The initial size of fragments depends on:
  1. **the type of the source rocks**
  2. **thickness of bedding**
  3. **spacing of joints**
- Metaquartzite, cherts, & rhyolites are highly durable during transport to the contrary of limestones, schists, & shales
- **Conglomerates are very useful in determining Provenance (source area)**
- The conglomerates in orogenic terranes (e.g. Alps) contain components have low resistance to weathering & transportation such as schist, granites, limestones … etc

Polymictic Saramuj Conglomerate

A reworked sedimentary clast from a previous

Monomictic congl.

Polymictic

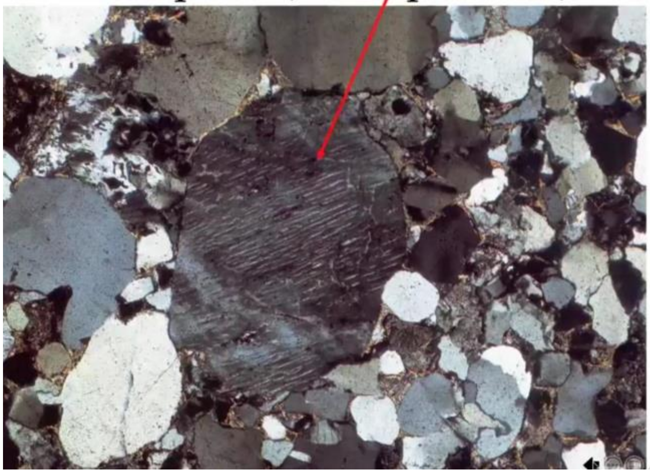
Monomictic (rhyolite clasts)

BRECCIA

8.3 Sand Size Rocks (Sand Stones)

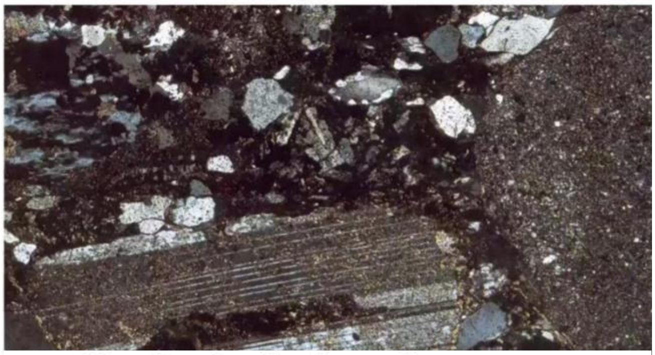
- Sandstones are at least one order (10times) of magnitude more abundant than conglomerates
- Mostly used rocks for provenance studies
- provenance studies are useful for reconstruction of paleogeographic maps which show the outcrop distribution of past like the present day geologic

Feldspars (microperthite)

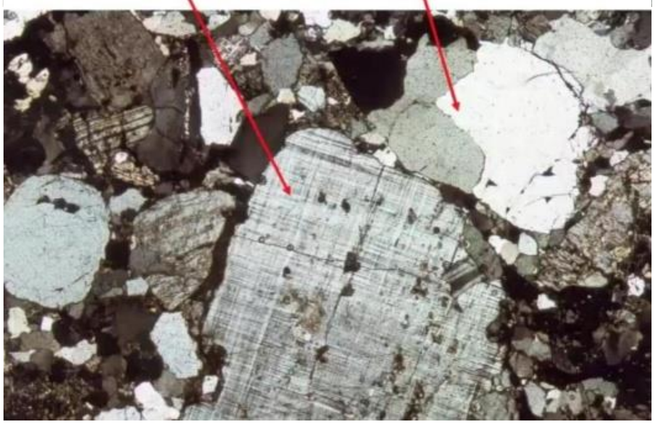


- 2/3 of the detrital fraction of a sandtones:
  1. **Monocrystalline grains** (one crystalline)
  2. **Polycrystalline grains** (> grain) are considered as lithic fragments
- Sandstones properties:
  1. **Undulatory extinction**
  2. **Elongate structure** (metamorphic origin)
  3. **Grain size** depending on grain size of source rock (particular as source isn't far from basin)
  4. Monocrystalline grains are coarse grained (which formed by granites)
  5. can consist alot of components depending on the rock type in the source area

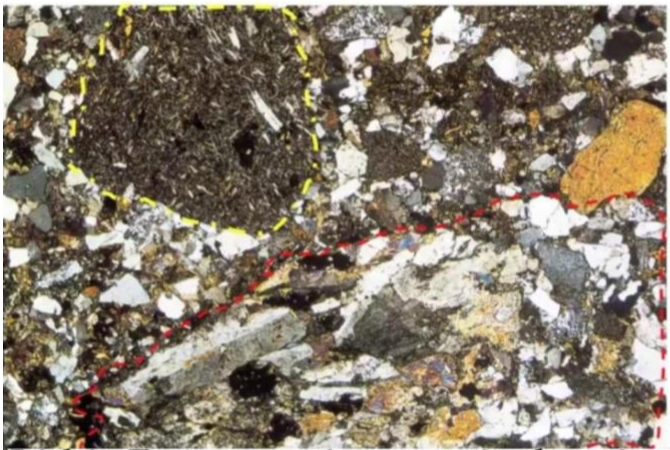
Plagioclase with albite and carlsbad twins
(the high birefringent grains are sericites



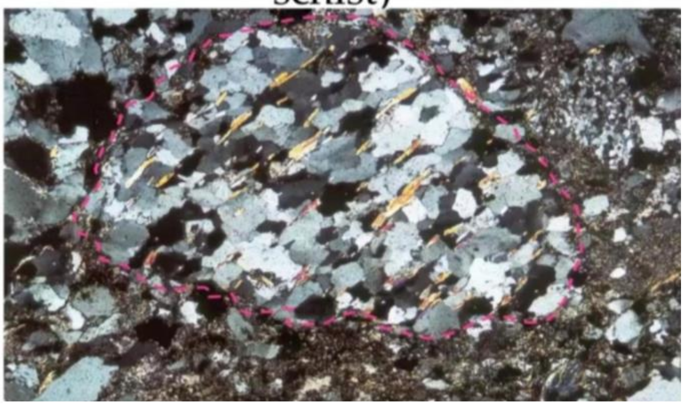
Microcline clast & polycrystalline quartz



Fine grained volcanic basic rock Coarse grained plutonic fragment

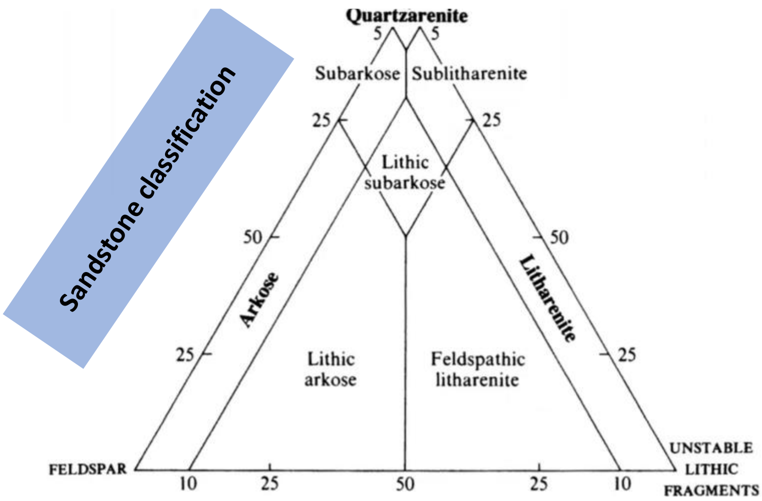


Lithic Fragment (muscovite bearing schist)

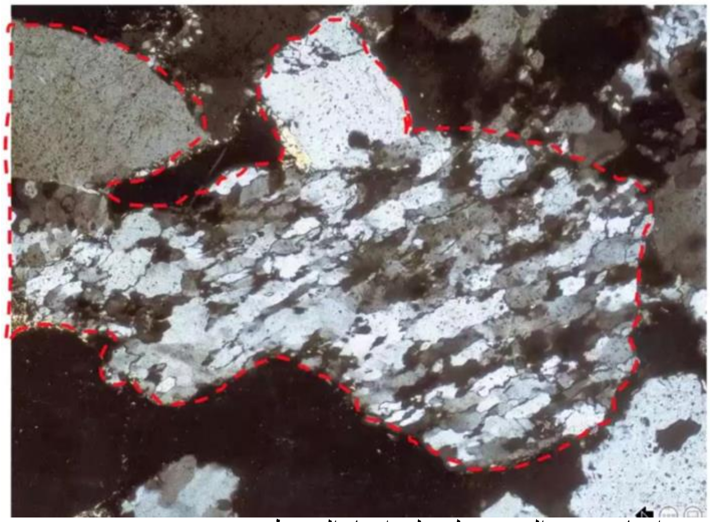


Common accessory minerals in sandstone	
Sources	**Common accessory minerals**
Igneous	Aegerine, Augite, Ilmenite, Chromite, Topaz
Metamorphic	Actinolite, Andalusite, Chloritoid, Cordierite, Diopside, Rutile, Kyanite, Epidote, Garnet, Glaucophane, Sillimanite, Staurolite, Tremolite
Indeterminate	Enstatite, hornblende, Hypersthene, Magnetite, Sphene, Tourmaline, Zircon

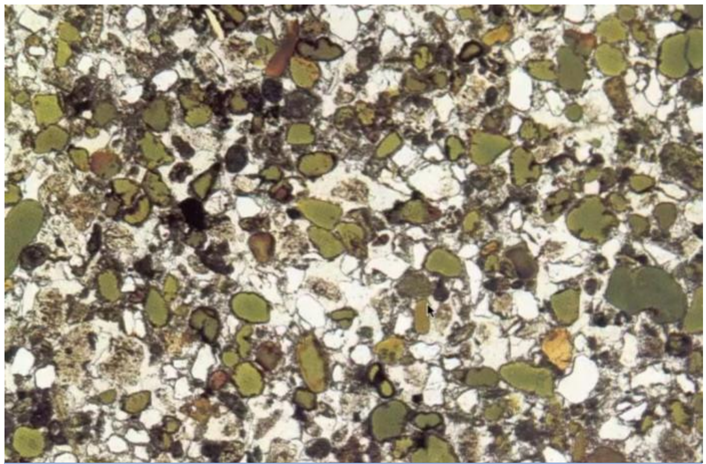
Range in densities of accessories found in sandstones is 3.0 to 5.2 in contrast to quartz & feldspars (2.56-2.76), so these minerals are heavy mineral



Elongated quartz in a polycrystalline clast



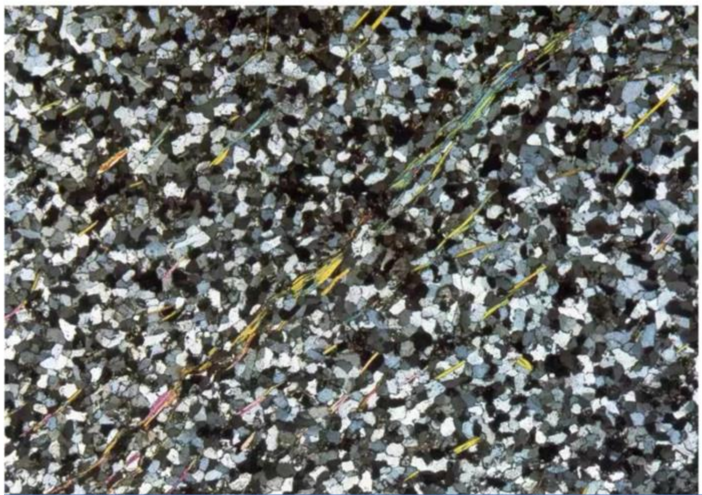
اتجاه ترتيب المعدن يدل على اتجاه الضغط



المعدن الاخضر هو **gloconite** يتميز بأنه يتكون في نفس مكان بيئة الترسيب لذا فأنه يستخدم لتحديد اعمار ال **sandstone**

Glauconite: distinctive sand-size, granular material, green structureless near-spheres (peloids)

White mica (muscovite) in Ss



Mica arranged when sandstone precipitation under gravity in a solution (by settling)

بلورات ال **mica** تكون **tabular** عندما يحدث لها هبوط تستقر على السطح الاوسع (لا علاقة له بالضغط)

Related to shape of the grains (elongate or tabular)

CHEMICAL & BIOCHEMICAL ROCKS

8.1 Limestone & Dolostone

- Form 10-15 % of the sedimentary rocks
- Limestones are more abundant than dolostones
- Carbonate rocks are normally free of impurities, & contains < 5% clays & fine-grained quartz
- Limestones are recognized in the field by its relative softness & by reactivity with diluted HCl

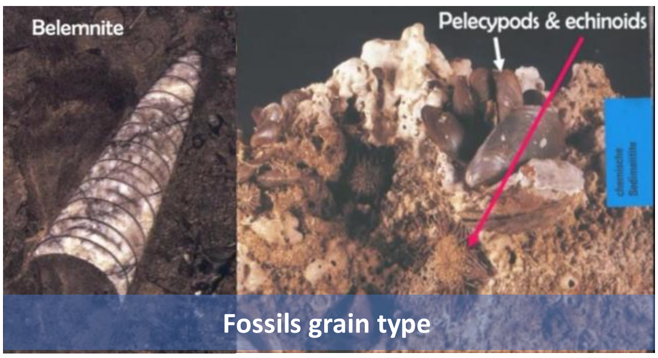
  $CaCO_3 + 2HCl \rightarrow Ca^{2+} + 2Cl^{-} + CO_2 + H_2O$
- Dolostone reacts visibly with HCl when powdered
- Dolostones commonly weather to dull brownish material due to the presence of some iron
- The textures of limestone are quite variable due to the complex origins of these rocks
  - ➢ Textures of detrital rock, chemical precipitates, & characteristic of growth habits of organisms
- Most of them are formed by:
  1. biochemical processes
  2. diagenesis (recrystallization, compaction, & cementation at T up to 200°C)
- Mineralogy
  - ➢ Calcite $CaCO_3$ (rhombohedral)

    Low-Mg (<4Mg)

    High-Mg (>4%)
  - ➢ Aragonite $CaCO_3$ (orthorhombic)
  - ➢ Dolomite $CaMg(CO_3)_2$

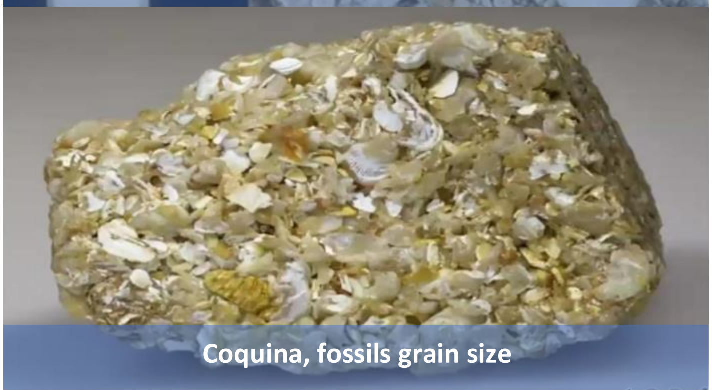
8.2 Grains (allochemical, allochem)

- gravel-, sand-, & coarse silt-size carbonate particles >30 microns that form the framework in mechanically deposited limestone
- 4 grain type : Fossils, ooids, peloids, & limeclasts

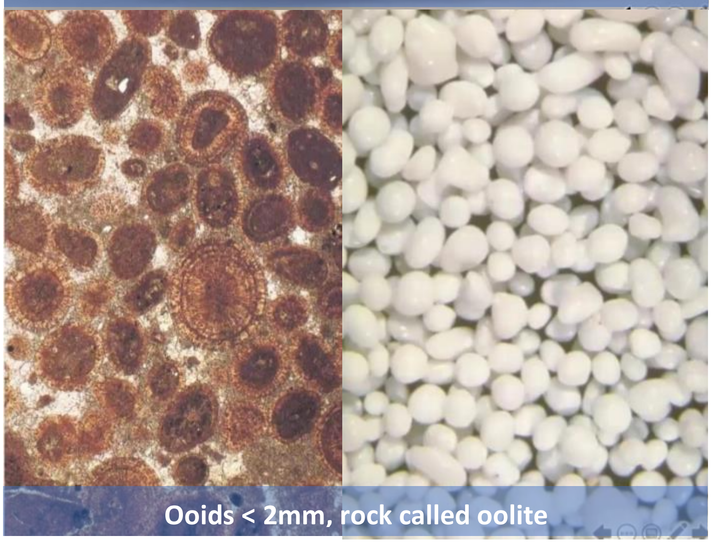


Fossils grain type

Bioclasts, fossils grain size

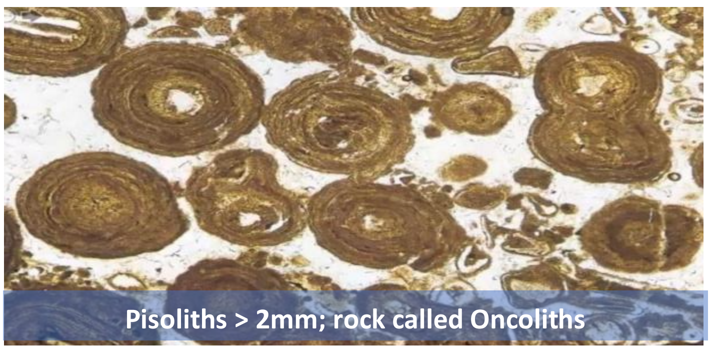


Coquina, fossils grain size



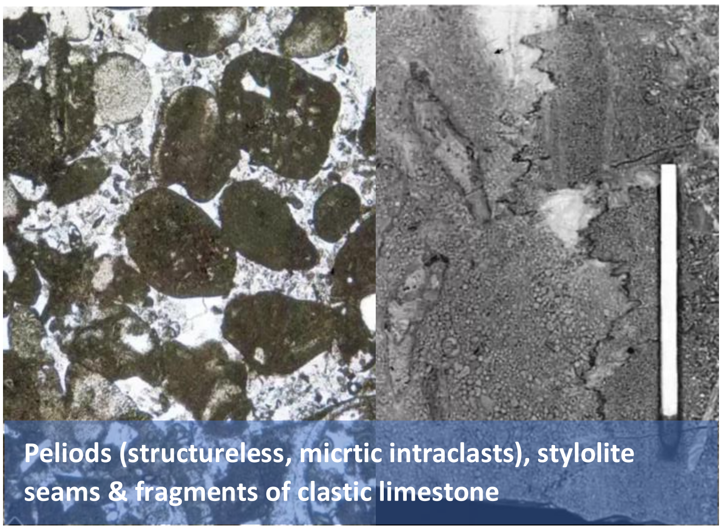
Ooids < 2mm, rock called oolite

- **Ooids (<2mm)**: Spherical, polycrystalline carbonate grains of sand size that have a concentric radial structure
  - ➢ have quartz or carbonate fragments as nuclei
  - ➢ Oolitic limestone form in agitated shallow marine waters & commonly have cross beds



Pisoliths > 2mm; rock called Oncoliths

- Pisoliths have organic origin, & differ from ooids by grain size (larger than ooids)

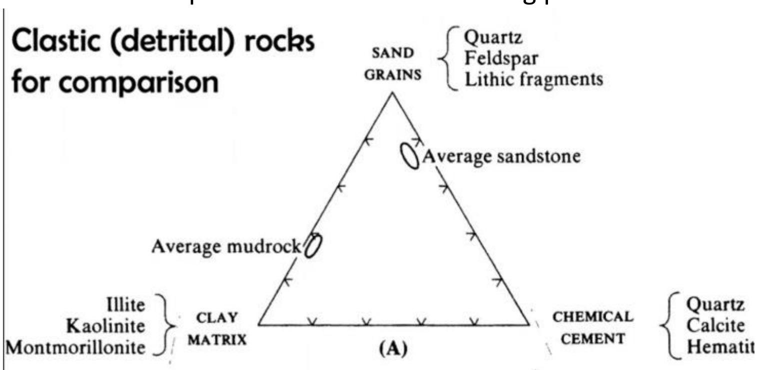


Peliods (structureless, micrtic intraclasts), stylolite seams & fragments of clastic limestone

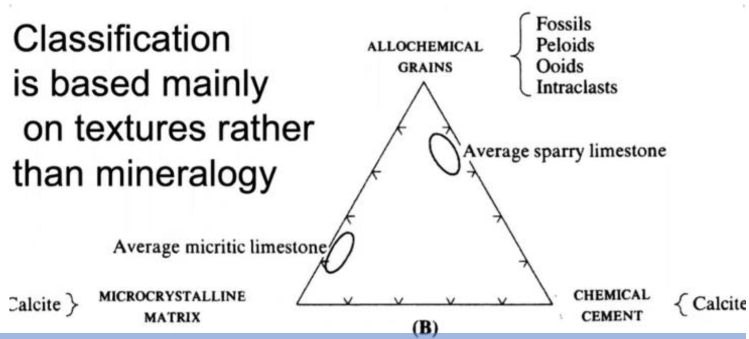
- Peloids are silt to sand-sized of microcrystalline calcite that lacks internal structure, elliptical to spherical in shape
  - ➢ Many believe that these represent fecal pellets because they contain organic matter
- **Limeclasts:** Fragments of earlier formed limestone or partially lithified carbonate sediment
  - ➢ Most are intraclasts pieces of penecon-temporaneous partially lithified carbonate sediment from within the basin of deposition

8.3 Limestone Classification

- **The matrix in limestones**
  1. **mud (micrite):** the Ca-carbonate mud (1-5 microns) that binds the allochemical grains, represents low energy environments
  - ➢ **Microspar** 5-15 µm, recrystallization of micrite
  - ➢ **Sparry** calcite cement > 20 microns
- **Insoluble residues**: chert, clay, detrital quartz
  - ➢ shells of radiolarian & diatom (consist of silica)
  - ➢ The silica is present in the form of nodular form parallel to limestone bedding planes



Classification of a sandtones

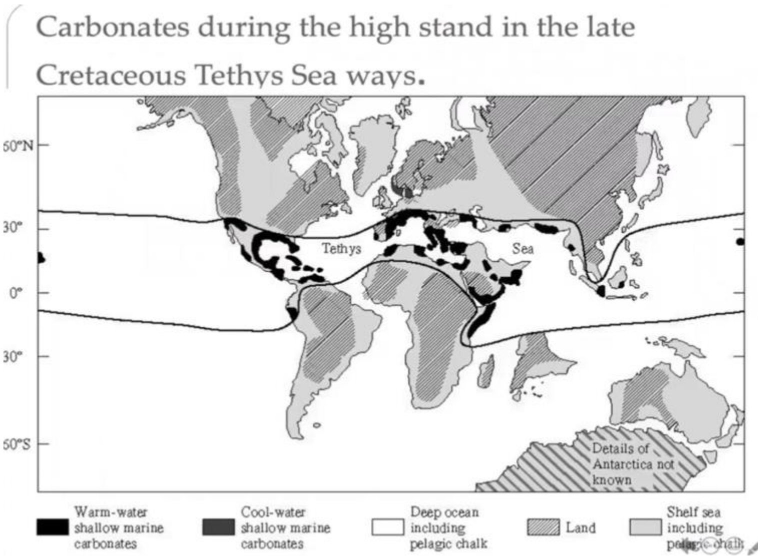


Classification of limestones

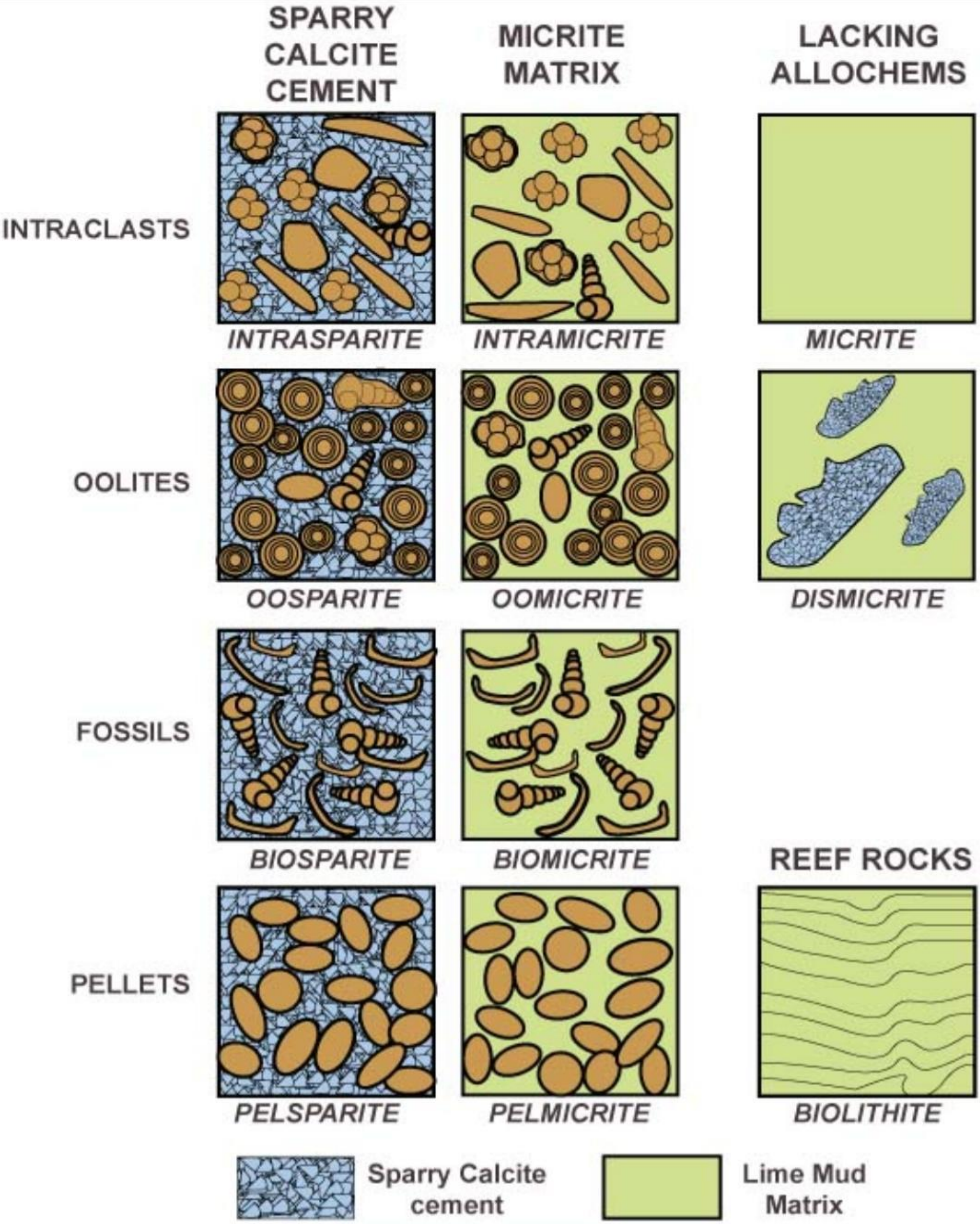
8.4 Stromatolites & Corals Reefs

Stromatolites, limestones formed by cyanobacteria
Very important as a Water & oil tank duo to vesicles

- هذا الصخر يشبه صخر chemically وهو Travertine الذي ينشأ في مناطق ال hotspring عند خروج المياه الايونية الى السطح يخرج منها ال CO_2 فينخفض الضغط مما يؤدي لترسيب كاربونات الكالسيوم لتكوين ال Travertine



تتركز ال cyanobacteria و ال coral reefs غالبا في مناطق خط الاستواء لانها مناطق دافئة (30° شمالا، 30° جنوبا)

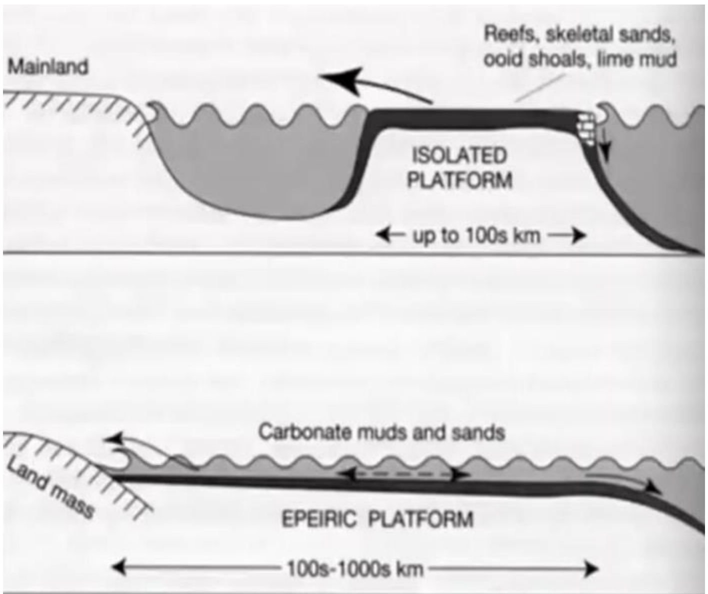

SPARRY CALCITE CEMENT
MICRITE MATRIX
LACKING ALLOCHEMS
INTRACLASTS
INTRASPARITE
INTRAMICRITE
MICRITE
OOLITES
OOSPARITE
OOMICRITE
DISMICRITE
FOSSILS
BIOSPARITE
BIOMICRITE
REEF ROCKS
PELLETS
PELSPARITE
PELMICRITE
BIOLITHITE
Sparry Calcite cement
Lime Mud Matrix

- **Organic reefy** Carbonate buildups of local origin that are laterally restricted
- Reefs originate almost entirely in low latitudes in shallow marine waters
- The carbonate sediments are produced by a variety of frame-building organisms: corals, sponges, algae, bryozoas, rudist pelecypods

Distribution of reefs

8.5 Ca-Carbonate Depositional sites

- Warm T necessary to cause supersaturation of waters with respect to $CaCO_3$ (abundance & growth of calcareous-shelled organism)
- Calcareous-shelled organism are mostly marine & need light, constant salinity, clear & warm waters
- Water must be very shallow & far from large rivers which cause a drop in salinity
- Modern reef-building organisms (corals) contain blue- green algae which needs light to thrive

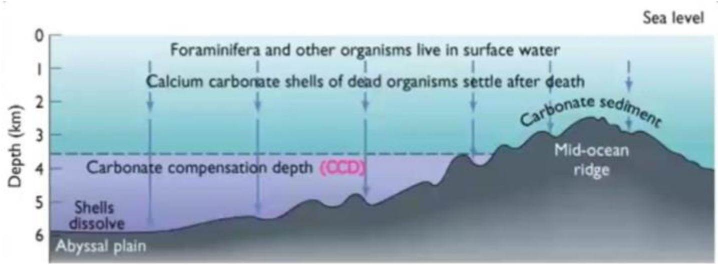


ال active margin مكان غير مناسب لوجود ال carbonate بسبب وجود ال detrial sediment و Tranche
في passive عندما تخرج المياه للرصيف القاري ترسب ال $CaCO_3$

جميع ال $CaCO_3$ الذي يترسب في قاع المحيط يكون aragonite ولكنه metastable لذا يتحول الى calcite

8.6 Carbonates Compensation level

- Carbonates Compensation level (CCL) is deeper in equatorial regions because carbonate formation is larger in warmer water
- CCL is a pelagic carbonates, 4km in open ocean (photic zone)
- Carbonate secreting planktonics didn't evolve until the Jurassic Period, microbiomicrite of pre-Jurassic didn't exist



- Under CCL, T decreases so solubility of $CaCO_3$ increases to produce H_2CO_3 which controlling the solubility of limestone (unstable in acidic environments, & stable in alkali environment)
- pH on the surface (7.9 – 8.1) & as the concentration of H_2CO_3 increases under CCDL pH became (7.8) limestone at this pH disintegrates (limestone fense : pH = 7.8)
- The limestone can be formed over the bridge because it's a high area & under CCL it melts & chert is more stable (cryptocrystalline quartz)
- chert is formed as a result of the sink of the shells to the oceanic floor, which build their shells from quartz or $CaCO_3$, whose shells are built from quartz (e.g. idolaria & diatomes) forms pelagic silica (chert, melts at pH 8.5)

8.7 Solubility

- **Lacustrine Carbonate:** lake deposits & commonly associated with other evaporites
- During late spring & early summer the surface waters of many lakes turn white as T increase & the removal of CO_2 from surface waters is at maximum as a result of active photosynthesis by microscopic plants called charophytes

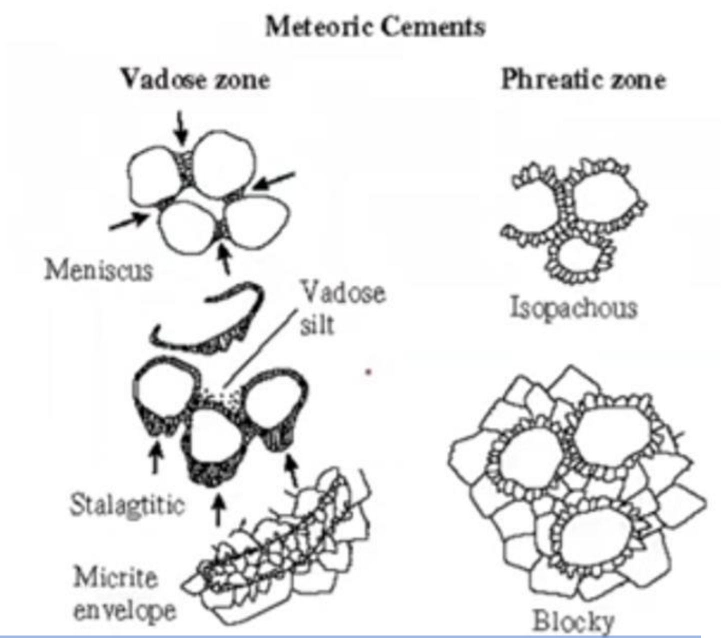
$CO_2 + H_2O \leftrightarrow H_2CO_3$ **$K_{25} = 10^{-1.47}$**
$H_2CO_3 \leftrightarrow HCO_3^- + H^+$ **$K_{25} = 10^{-6.40}$**
$HCO_3^- \leftrightarrow CO_3^{2-} + H^+$ **$K_{25} = 10^{-10.33}$**
$CaCO_3 \leftrightarrow Ca^{2+} + CO_3^{2-}$ **$K_{25} = 10^{-8.48}$ (calcite)**
$CaCO_3 \leftrightarrow Ca^{2+} + CO_3^{2-}$ **$K_{25} = 10^{-8.43}$ (aragonite)**
Net result: $CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2H^+ + CO_3^{2-}$

عند pH 4.6 توجد ال carbonate على شكل HCO_3^- وعند 10.33 على شكل CO_3^{2-}

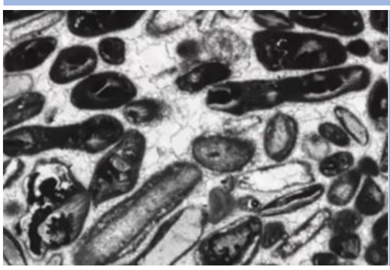
ال aragonite ذائبيته اكبر من ال calcite (Ksp اكبر)

8.8 IAP & Diagenesis

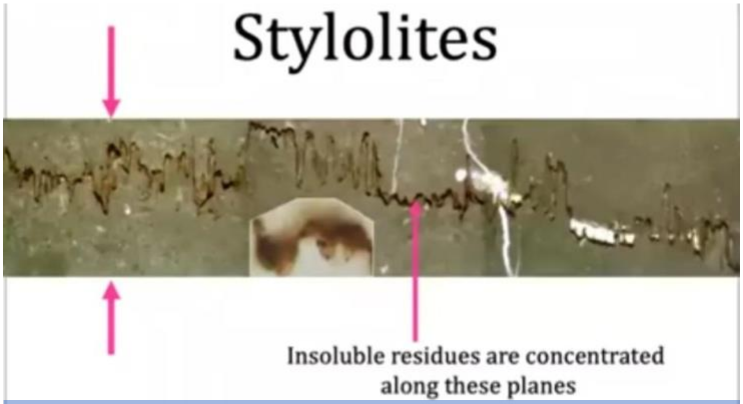
- The IAP (ion activity product) in river 10^{-85}-10^{-9}, (undersaturated with respect to carbonates)
- For seawater IAP = $1.7x10^{-8}$, supersatured with respect to both calcite & aragonite
- Several natural processes stimulate the rapid formation of carbonates in seawater:
  2. Increased T & salinity
  3. Organic activity, photosynthesis during the day takes CO_2 away & triggers $CaCO_3$ formation
  4. Organic CO_2 production in the soil: The soil is enriched in CO_2 relative to the atmosphere due to the decay of plant tissue
- **Diagenesis**: all process that contributes to solidification of sediments into a sedimentary rock include cementation, compaction, Lithification
  - start after deposition of skeletal carbonates
  - A large variety of organisms can be involved in the process
  - **Cementation** by production of hardground on the shelf carbonates or beach rocks (Meteoric water cementation)
  - Mechanical compaction & Chemical cementation (including P solution)



Phreatic zone: under water table (saturated in water)
Vadose zone (reaction zone): from Earth's surface to the water table (undersaturated, water + air)



Skeletal grainstone with sparite cement

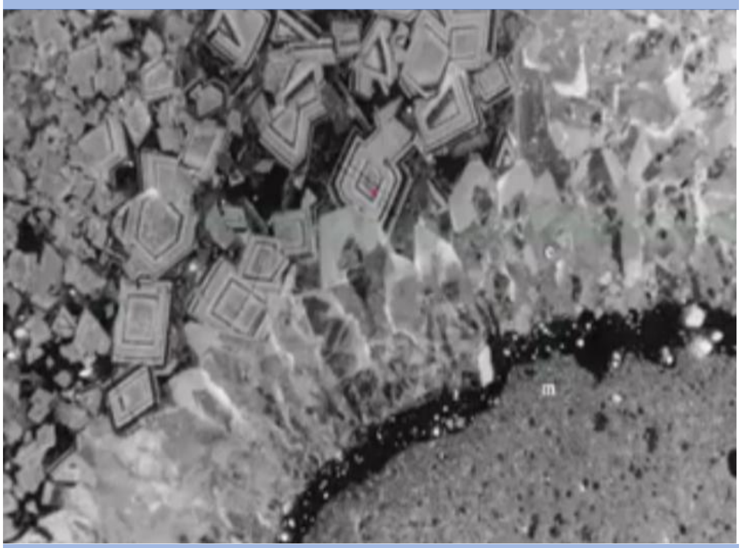


Stylolites limestone:structure formed by P solution due to
1. Deposition of a new layer of limestones
2. Tectonic Compression: limestone dissolution

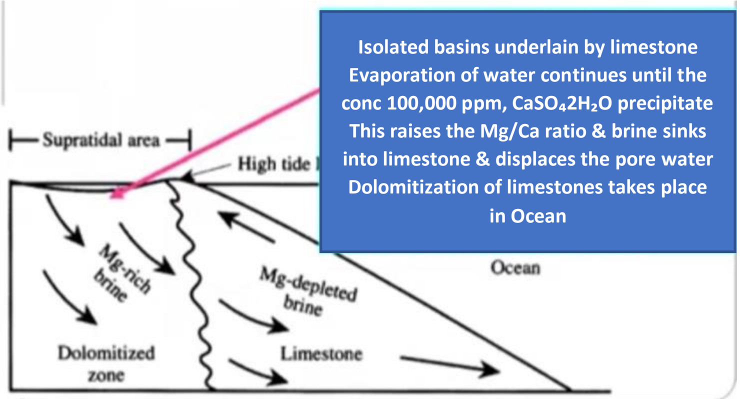
8.9 Dolostones

- **Dolostones** impure carbonate rock formed by one or 2 mechanisms (Evaporative reflux or mixing of a fresh & marine water)

Dolostones (composed of dolomite)
Is a chemically rocks forms by dolomitization (change a limestone into a dolomite) in arid climates



Dolostones thinsection
We can distinguish dolomites from calcites in thinsection by staining (staining of calcite)



Isolated basins underlain by limestone
Evaporation of water continues until the conc 100,000 ppm, $CaSO_4 2H_2O$ precipitate
This raises the Mg/Ca ratio & brine sinks into limestone & displaces the pore water
Dolomitization of limestones takes place in Ocean

The formation of dolomite described chemically as:

$$CaMg(CO_3)_2 \leftrightarrow Ca^{2+} + Mg^{2+} + 2CO_3^{2-}$$

Equilibrium constant $K_{25} = [Ca^{2+}][Mg^{2+}][CO_3^{2-}]^2 = 10^{-18.06}$

IAP for seawater is 10^{-46}**, supersaturated with respect to dolomite (theoretically)**

8.10 Other rocks (Evaporates)

- Evaporate rock formed chemically by evaporation
- Minerals produced from saline solution as a result of extensive evaporation

عندما تتبخر المحاليل المائية تبدأ عملية ترسيب الايونات بسبب زيادة تركيز الايونات IAP فتتكون هذه الصخور، اي عندما تصل IPA الى Ksp لاي ملح يصبح المحلول supersaturated ويبدأ الترسيب

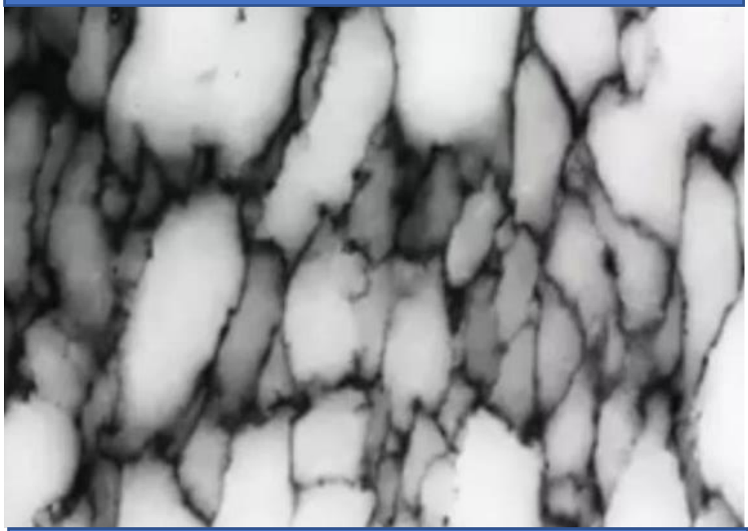
Major minerals in marine evaporate deposits	
Chlorides	Halite NaCl, Sylvite KCl Carnellite $KMgCl_3.6H_2O$
Sulfates	Anhydrite $CaSO_4$ Langbenite $K_2Mg_2(SO_4)_3$ Polyhalite $K_2Ca_2Mg(SO_4)_4.2H_2O$ Keiserite $MgSO_4.H_2O$ Gypsum $CaSO_4.H_2O$ Kainite $KMg(SO_4)Cl.3H_2O$

Salt deposits in the stratigraphic column

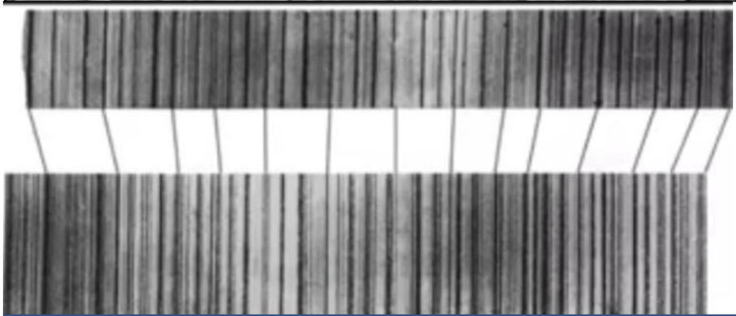
المناطق الغامقة رسوبيات ملحية، ولانها تتكون بالقرب من خط الاستواء فان موقعها الحالي يشير الى انجراف القارات المسؤول عن وجودها في البحر الابيض المتوسط هو اغلاق المحيط

Salt crust, dead sea Boulders

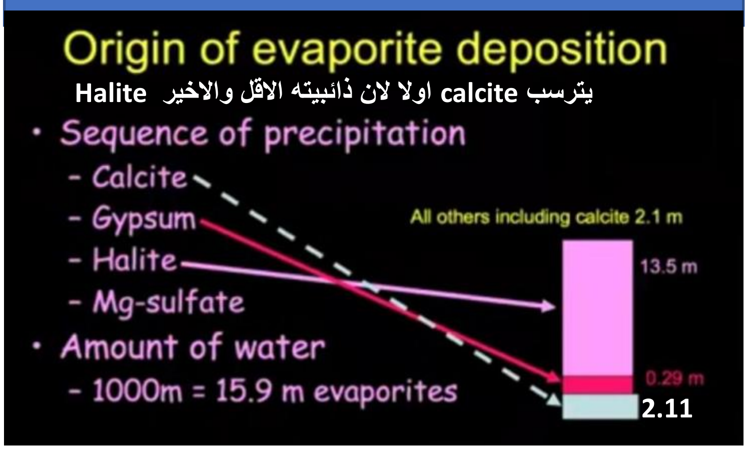
Chicken-wire structure in anhydrite deposits



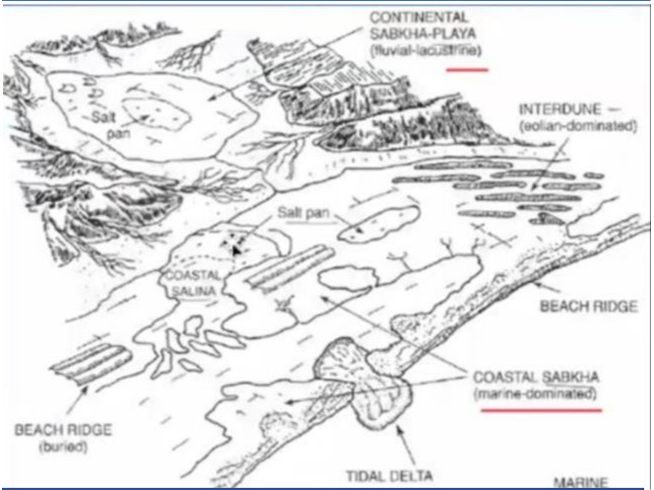
Laminated evaporates, one of the most common structure of evaporates (Rhythmic layers)



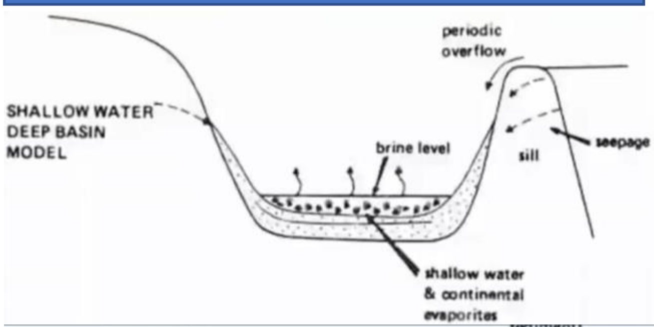
Laminated evaporates sequence (calcite-anhydrite)

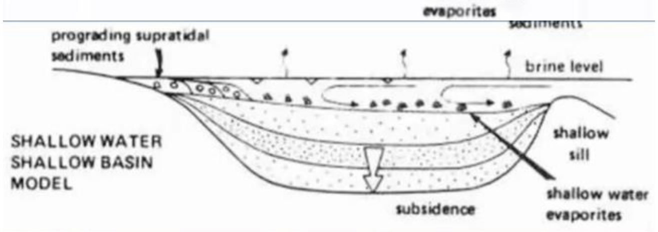


amounts of dissolved constituents in seawater		
Dissolved species	Molarity	Percentage
Cl^-	0.535	48.72
Na^+	0.459	41.80
Mg^{2+}	0.052	4.740
SO_4^{2-}	0.028	2.500
Ca^{2+}	0.010	0.910
Other	0.014	1.330
Total	1.098	100.0
يتشكل ملح الطعام Halite بشكل اكبر لان تركيز ايوناته هو الاكثر		



Environments of evaporates formation
Sabkha, Marine, & Playa Lack





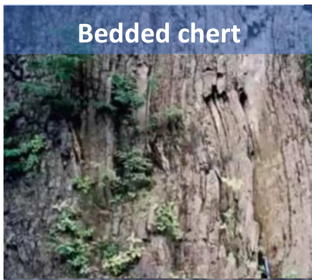
Marine models
عندما ترتفع مياه البحر تدخل الماء الى basin قريب عند ازدياد درجة حرارتها تبدأ عملية ال evaporation فيزداد تركيز الايونات بها وتبدأ عملية الترسيب (ترسب ال evaporates)

8.11 Siliceous Deposits (Cherts)

- Mineralogy & texture:
  - ➢ Microcrystalline quartz (1-5 microns)
  - ➢ Chalcedonic quartz (5-20 microns,chalcedony)
  - ➢ Megacrystaline quartz (> 20 microns)
- Mineralogical transformations
  - ➢ Opal-A ($SiO_2.H_2O$, amorphous)
  - ➢ Opal-CT (SiO_2, Cristobalite, Tridymite, Quartz)


Fibrous quartz, PPL

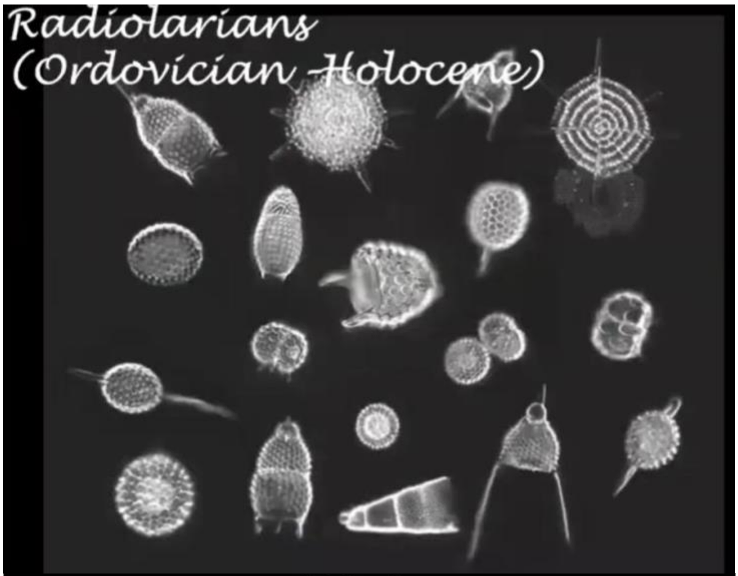
- **Chert Types**: Jasper, Flint, Agate, Bedded, Nodular


Bedded chert


Flint


Nodular chert in limestone

تتابع لطبقات chert & Limestone
Marl is a limestone + clay, commonly found in area where landslides occur
Concretion: eleptucal body found in limestone (by changing mud into a limestone



Most of chart are formed biochemically by accumulation of a Nanoplankton on the oceanic floor

- **Siliceous Ooze:** mud formed by hard part of an organism & from those the chert formed (stable in any part in ocean)
- Calcareous Ooze: stable above CCD

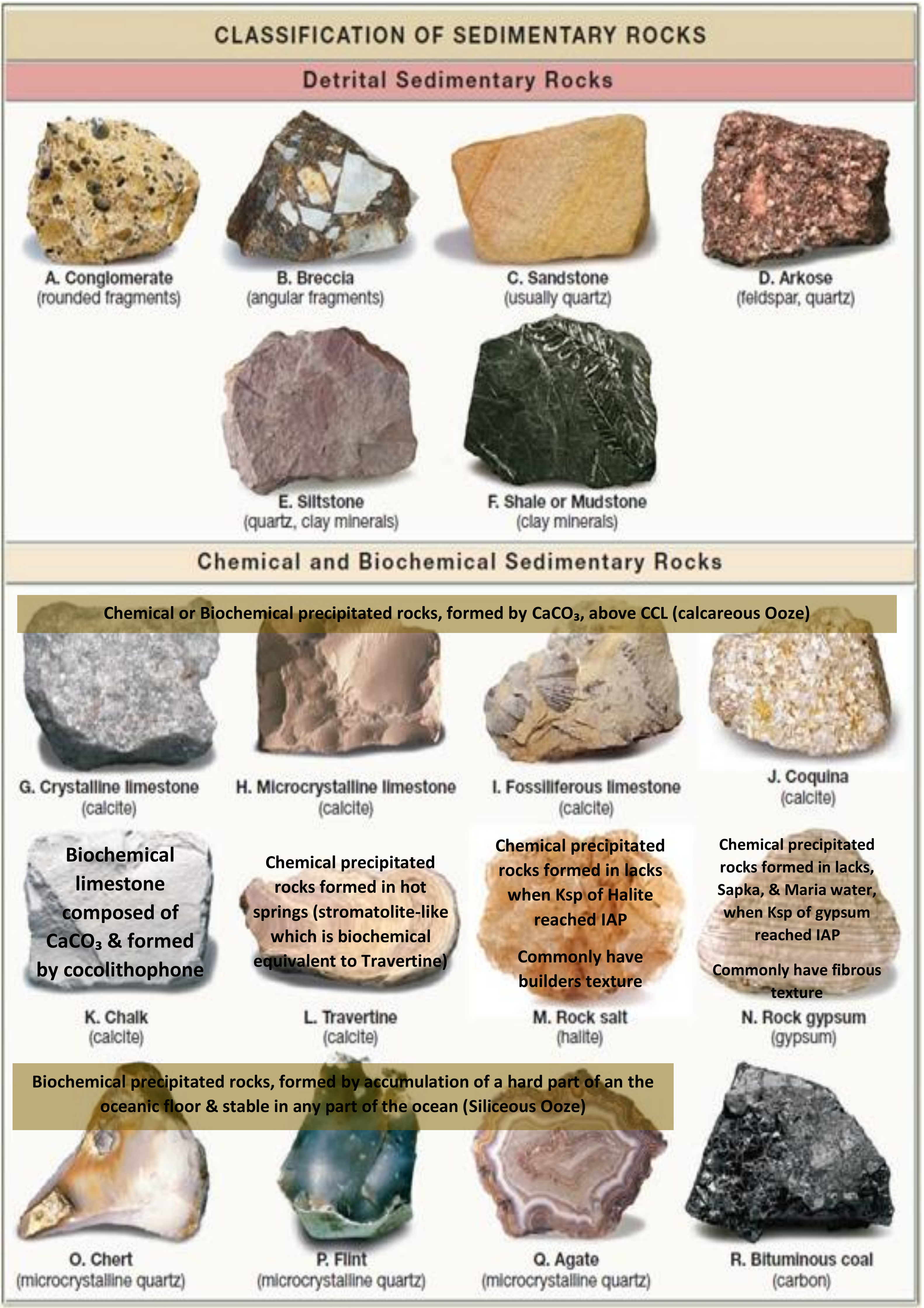
8.12 Banded-Iron Formation (BIF)

- Chemically precipitated iron
- Is an iron ore (>15%Fe)
- Iron oxidized during what we known as great oxidation level (3.5Ga), by photosynthesis, & during neo-proterozoic by snow Ball earth
- the BIF metamorphosed (at 600°C) into a Fayalite olivine Fe_2SiO_4: $2Fe^{2+} + O_2 + H_2O \rightarrow Fe_2O_3 + 2H^+$

The red is hematite (Fe_2O_3) & Magnetite (Fe_3O_4) Others are silica SiO_2

8.13 Chalk

- Biochemical limestone, composed of $CaCO_3$, & formed by Cocolithophones


CLASSIFICATION OF SEDIMENTARY ROCKS
Detrital Sedimentary Rocks
A. Conglomerate
(rounded fragments)
B. Breccia
(angular fragments)
C. Sandstone
(usually quartz)
D. Arkose
(feldspar, quartz)
E. Siltstone
(quartz, clay minerals)
F. Shale or Mudstone
(clay minerals)
Chemical and Biochemical Sedimentary Rocks
Chemical or Biochemical precipitated rocks, formed by $CaCO_3$, above CCL (calcareous Ooze)
G. Crystalline limestone
(calcite)
H. Microcrystalline limestone
(calcite)
I. Fossiliferous limestone
(calcite)
J. Coquina
(calcite)
Biochemical limestone composed of $CaCO_3$ & formed by cocolithophone
K. Chalk
(calcite)
Chemical precipitated rocks formed in hot springs (stromatolite-like which is biochemical equivalent to Travertine)
L. Travertine
(calcite)
Chemical precipitated rocks formed in lacks when Ksp of Halite reached IAP
Commonly have builders texture
M. Rock salt
(halite)
Chemical precipitated rocks formed in lacks, Sapka, & Maria water, when Ksp of gypsum reached IAP
Commonly have fibrous texture
N. Rock gypsum
(gypsum)
Biochemical precipitated rocks, formed by accumulation of a hard part of an the oceanic floor & stable in any part of the ocean (Siliceous Ooze)
O. Chert
(microcrystalline quartz)
P. Flint
(microcrystalline quartz)
Q. Agate
(microcrystalline quartz)
R. Bituminous coal
(carbon)

PART THREE

METAMORPHIC ROCKS

METAMORPHIC ROCKS

9.1 Introduction

- **Metamorphism:** occur when *sedimentary (in most case)* or *volcanic rocks* are subjected to elevated T &/or P within the crust & change in mineralogy or structure or both
- Rarely plutonic rocks may be metamorphism because these rocks are formed in high T & P

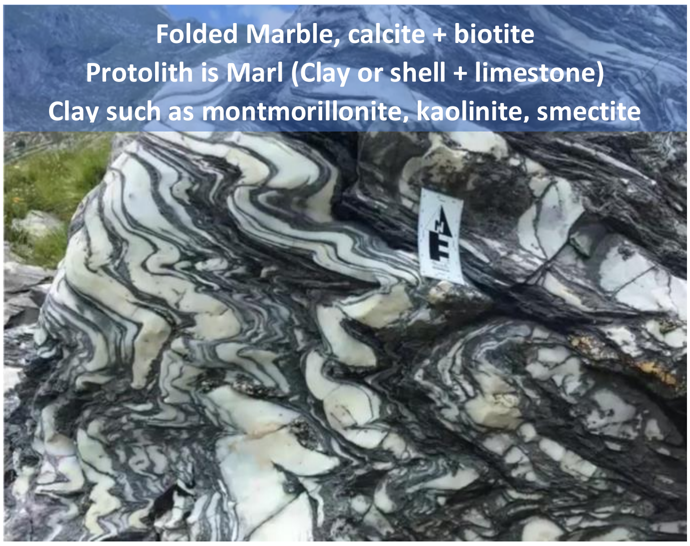
الصخور الجوفية ستتحول إذا تعرضت الى compressional stress
في ال subduction zones وتتميز هذه الصخور بوجود foliation

Sodalite granitic gneiss

A word "granitic" is an evidence for protolith

Migmatites rock, oldest rocks in Jordan (787-620)Ma

- **Folding**: most common character of metamorphic rocks, but not all metamorphic rocks are folded because require high T & P (200° - 700°), regional

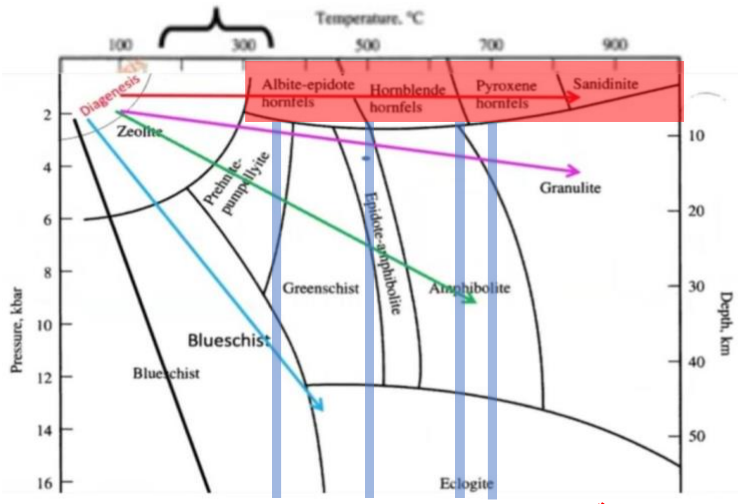


Folded Marble, calcite + biotite
Protolith is Marl (Clay or shell + limestone)
Clay such as montmorillonite, kaolinite, smectite

- **Calcsilicate** class of metamorphic rocks which formed by limestone & silicate such as marble
- **Pelitic or argilliceous:** shale protolith
- **Protolith**: is a rock which is suggested to the metamorphism
- Grain size increases with increasing grade of metamorphism (intensity of metamorphism)
- **In a shallow crust (e.g. 5km depth)** There's no metamorphism process because T is very low
- **Metamorphism occur because** Rocks & their minerals reach new chemical equilibrium, or physical or chemical environment

9.2 Classification of metamorphism

- **Retrograde (or retrogressive):** is a change from a higher grade to a lower grade
- **Prograde (or progressive):** is a change from lower grade to higher grade of metamorphism



المنطقة الحمراء هي contact metamorphism
الخطوط الطولية هي grade of metamorphism
الاسهم القطرية هي geothermal-gradant والfields هي facies

Classification according to grade of metamorphism

- **The Grade of metamorphism** is the intense of metamorphism
- Metamorphic range 200 – 750°C
- **Isograde**: equal metamorphic grade &separated by zone

T [°C]	Grade
<200	Transitional
200- 350	Very low
350 - 500	Low
500 - 630	Medium
630 - 700	High
700	Very high
> 700	Transitional

- equivalent metamorphic grade does not imply equal values of the environmental variables (P, T, & fluid P or composition)

Classification according to the facies

- **Metamorphic facies**: regions of T-P characterized by particular metamorphic assemblages or paragenesis (Facies = T & P)

- The term facies used also in sedimentary rocks
- e.g. **Green-schist facies:** foliated rocks, with a green color, characterized by chlorite, biotite, muscovite, epidote, & Alpite plagioclase
- e.g **Amphibolite facies** = medium grade

ليس بالضرورة ان اي صخر تعرض لل amphibolite facies او medium ان يحتوي hornblende اي ان المقصود هنا T-P

- Oceanic crust (mafic rocks) is the best rock that give Amphibolite facies

Mafic→subduction zone→Greenschist→Amphibolite

- The upper limit of metamorphism is a boundary between igneous & metamorphism processes (metamorphism in a solid-state)
- Mudrock compositions melting at T < 650°C, mafic & some aluminous quartzofeldspathic (Arkose) continue to undergo solid-state reactions, without melting at T > 800°C

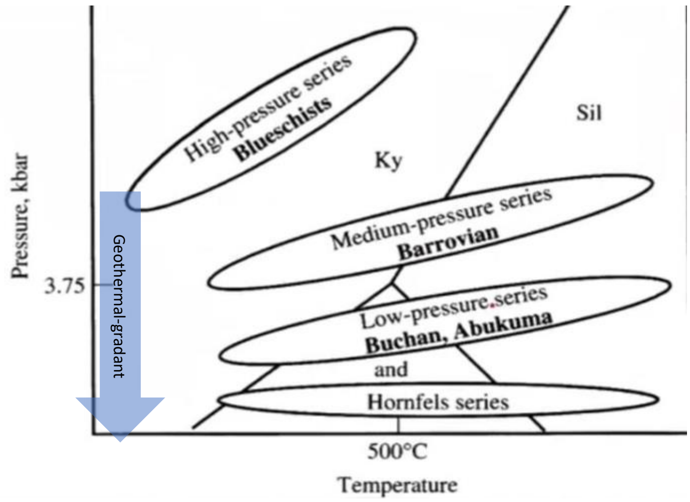
Classification according to the geothermal gradant

- Contact metamorphism called Hornfels
- Geothermal-gradant: is the change in T with h

$$dT/dh = \Delta T/\Delta h$$

Classification according to the pressures type

- **Facies Series**: P-T gradients aren't geotherms, nor actual P-path taken during metamorphism
- They are simply lines connecting the recorded & T of the individual rocks across each terrene

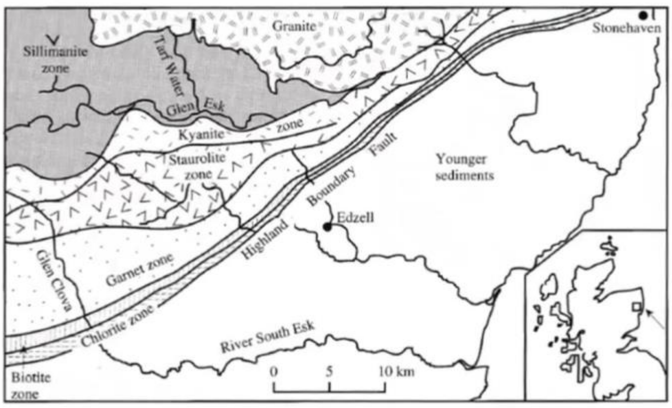


Al_2SiO_5 diagram

Hornfels → P negligible → lack of foliation → contact
Low P → Buchan or Abukuma, Sillimanite & Andalusite
Medium P → Barrovian facies, Kyanite & Sillimanite
High→ Ky, Glaucophane, Jadeite, Lowsonite, Aragonite

9.3 Index Minerals

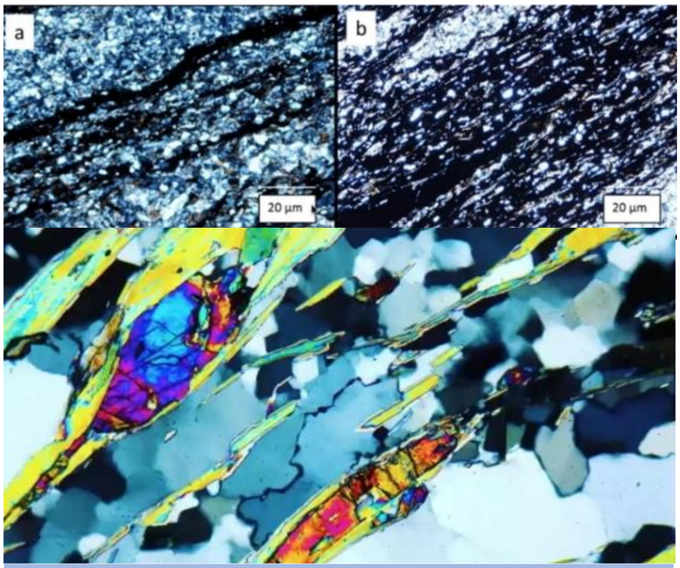
- isograds → idea of metamorphic zones
- **metamorphic zones:** zone of metamorphism characteristic by certain minerals
- **Outcrop:** where the rock appears on the surface of the earth (striking lines)



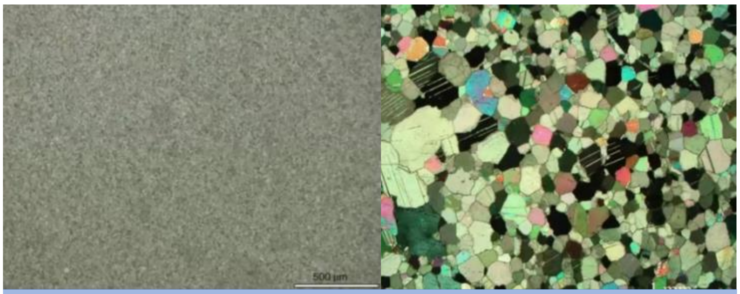
Transition between zone is a gradual change
Zone is a mapable (can be down in a map)
Metamorphic zone are mapable which characterized by index minerals
Protolith here is shale or pelitic sedimentary rock

T	zone	Typical mineral assemblages
200	Chlorite	Qz, chlorite, muscovite, albite
400	Biotite	Qz, chlorite, mica(bi,mu), albite
500	Garnet	Qz, mica, garnet, sodic plagioclase
630	Staurolite	Qz,mica,garnet,plagioclase,staurolite
700	Kyanite	Qz, mica, garnet, plagioclase, staurolite, Kyanite
750	Sillimanite	Qz,mica,garnet,plagioclase,Sillimanite

- **Chlorite**: Formed by weathering of ferromagnesian
- **Granulite facies** contains Opx (from biotite)
- **Blue schist** contains blue amphibole (Glucophane)
- **Zeolite** formed by chemical weathering of volcanic ash (have a lot of cavities which contain water) & can be form in early Stage of metamorphism
- **index mineral**: is a mineral used to determine the degree of metamorphism a rock, Depending on the protolith composition, P, T, & the chemical reactions between minerals in the solid state

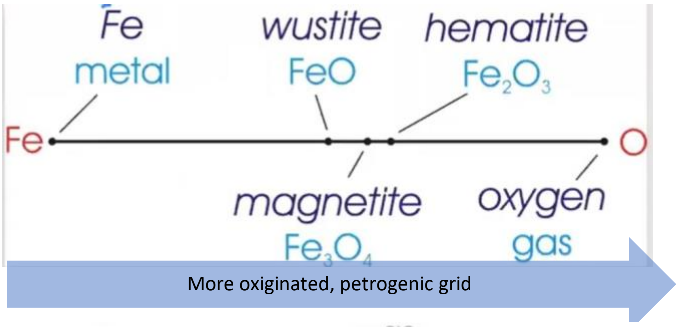


Shale or siltstones before & after metamorphism (grain size increase with metamorphism)
There are textural & mineralogical changes

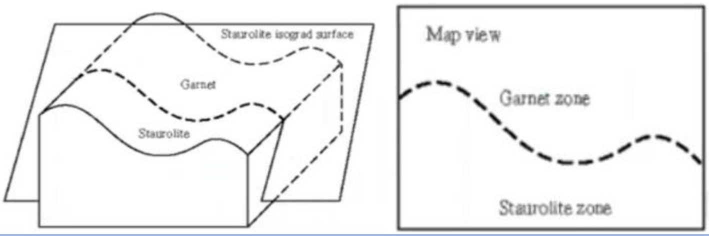


Micrtic limestone which metamorphosed to marble
Both consist of $CaCO_3$ but grain size is larger in marble

e.g. Bar diagram

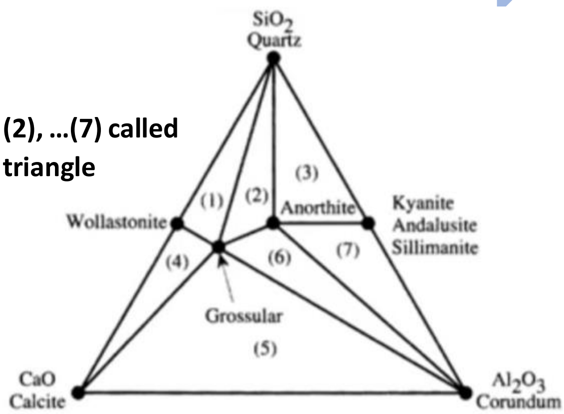


9.4 Graphical Representation



3D schematic illustration showing a dipping planar isograd surface intersecting the ground surface to create a curved isograd as a metamorphic map

Regions (1) , (2), …(7) called combatable triangle

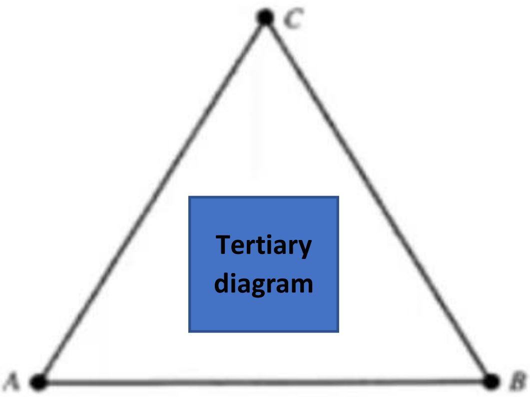


Ternary diagrams for unhydrus system

depend on mol proportion: $CaO.SiO_2.Al_2O_3$

- Kyanite, Andalusite, & Sillimanite has the same composition ($Al_2SiO_5 \rightarrow 1Al_2O_3 + 1SiO_2$) so occur in In the center between 2 oxides (50%for each one)
- Wollastonite: $CaSiO_3 \rightarrow CaO + SiO_2$
- Calcite: $CaCO_3 \rightarrow CaO + CO_2$ (CO_2 not represented)
- Grossular: $Ca_3Al_2(SiO_4)_3 \rightarrow 3CaO + Al_2O_3 + 3SiO_2$
  Mole proportion: CaO = 3/7, Al_2O_3 = 1/7, SiO_2 = 3/7

Bar diagram



Tertiary diagram

Oxide	Wt%	Proportion
SiO_2	54.06	0.900
Al_2O_3	13.64	0.134
Fe_2O_3	03.28	0.021
FeO	08.88	0.124
MgO	03.48	0.086
CaO	06.95	0.124
Na_2O	03.27	0.055
K_2O	01.69	0.018
TiO_2	02.24	0.028
P_2O_5	00.36	0.003
MnO	00.18	0.003
CO_2	00.03	0.001

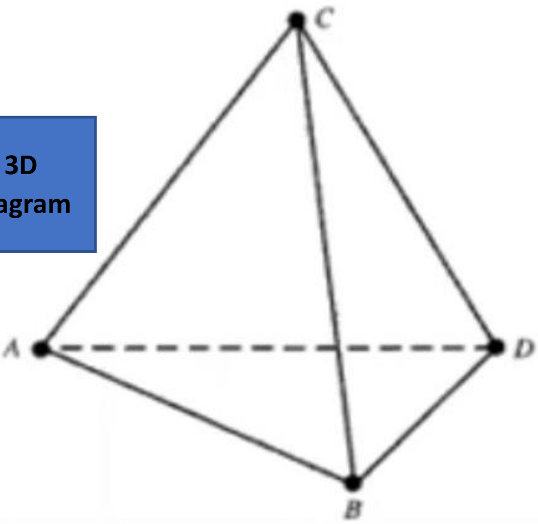
A = mol prop. (Al_2O_3+Fe_2O_3-Na_2O-K_2O) = 0.054

C = mol prop. (CaO-P_2O_5-CO_2) = 0.113

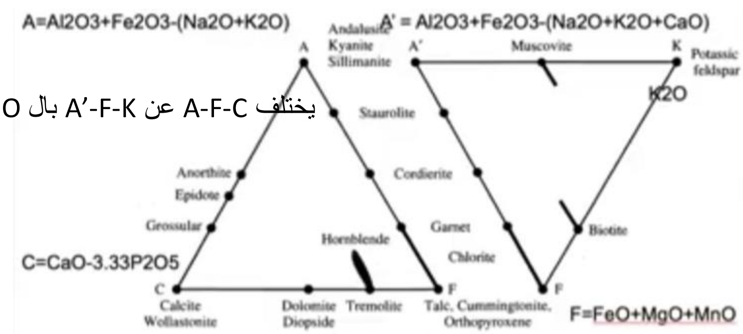
F = prop. (FeO+ MgO+MnO) = 0.164

A%= 23.3%
C%= 31.3%
F% = 45.4%

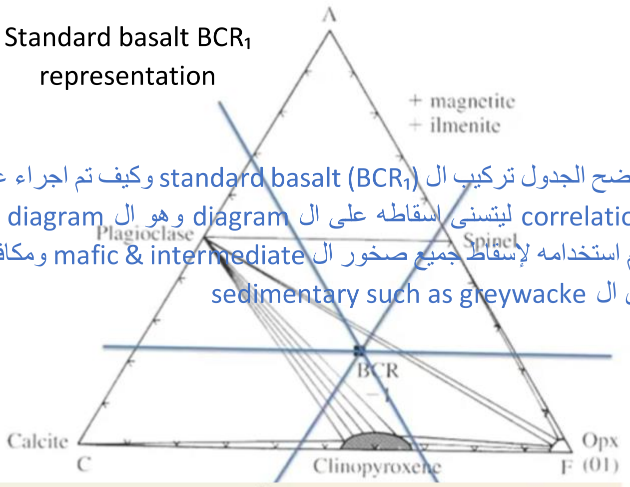
3D diagram



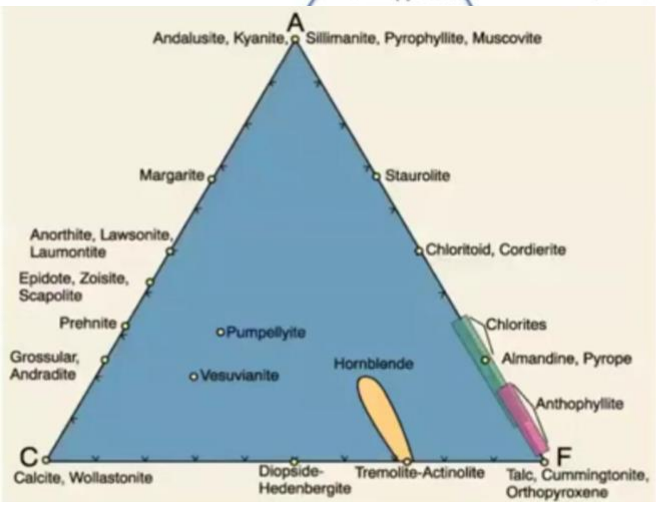
يختلف A-F-C عن A'-F-K بال CaO



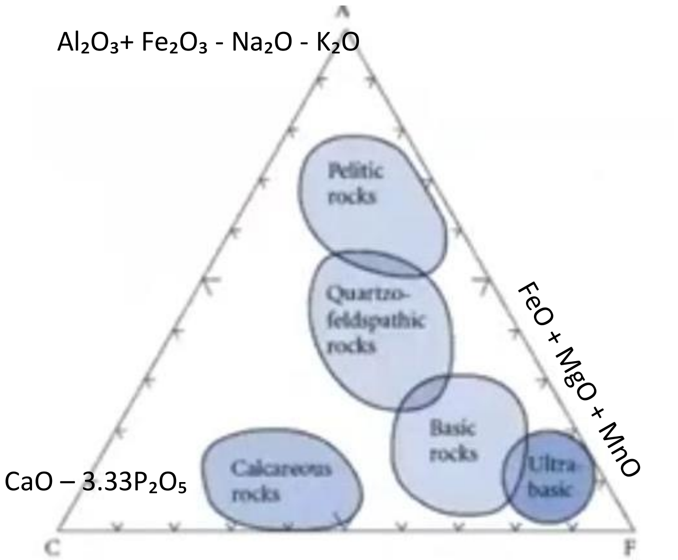
Standard basalt BCR_1 representation



يوضح الجدول تركيب ال standard basalt (BCR_1) وكيف تم اجراء عملية correlation ليتسنى اسقاطه على ال diagram وهو ال diagram الذي يتم استخدامه لإسقاط جميع صخور ال mafic & intermediate ومكافئاتها من ال sedimentary such as greywacke



يستخدم هذا ال diagram (A-C-F) لإسقاط الصخور التي يكون ال protolith لها pelitic or shells



9.5 Metamorphic Reactions

- Most of metamorphic processes is an **isochemical** processes (the chemistry of a rock don't change, compositional & textural changes only)
- If the composition changes during metamorphism (due to contact with other rocks which have different composition or by hydrothermal solution) this process called **Metazomatizem**

- **Dehydration reaction**: loss of water

$KAl_3Si_3O_{10}(OH)_2 + SiO_2 \rightarrow KAlSi_3O_8 + AlSi_2O_5 + H_2O$

Muscovite + Quartz → Feldspar + Sillimanite + water

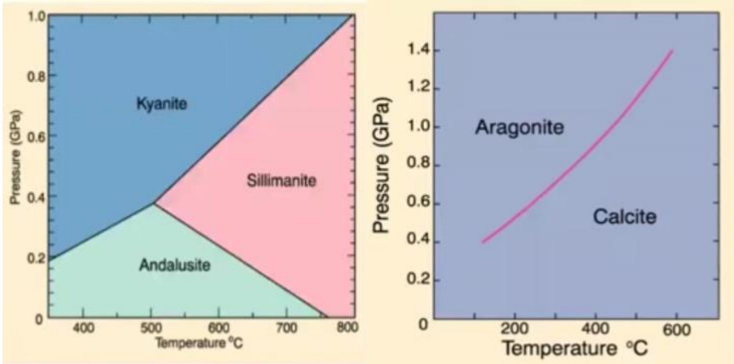
- **Decarbonation**: loss of water carbon dioxide

$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$

Calcite + Quartz → Wollastonite + carbon di-oxide

- **Solid-Solid:** phase transformations, lack of fluids, different structure & same chemical composition, occur at subduction zone
  - As P increase → Grain Size Decrease
  - As T increase → Grain Size Increase

$NaAlSi_3O_8 \rightarrow NaAlSiO_6+SiO_2$ (Albite→Jadeite+Quartz)



Phase transformations of Al_2SiO_5 polymorph 10Kbar = 1GPa	Phase transformations of $CaCO_3$ polymorph 10Kbar = 1GPa

- **Solid-Solid Net-Transfer**: Discontinuous reactions (different structure & different composition)

$NaAlSi_2O_6+SiO_2 \rightarrow NaAlSi_3O_8$ (jadeite+quartz→alpite)

$MgSiO_3 + CaAl_2Si_2O_8 \rightarrow CaMgSi_2O_6 + Al_2SiO_5$

$4FeSiO_3+CaAl_2Si_2O_8 \rightarrow Fe_3Al_2Si_3O_{12}+CaFeSi_2O_6+SiO_2$

- **Exchange Reaction:** differential partitioning of Mg-Fe in mafic phases takes place over a range of P-T
  - Thermometer reaction depending on the T & Parmometer depend on P, & exchange occurs due to P or T, & both depend on composition
  - Garnet-biotite exchange is a most common thermometer reaction (exchange) in a folded rock, & occur at 400°-700°C

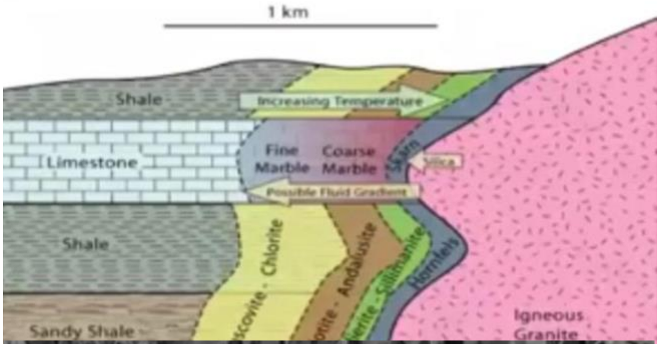
$Fe_3Al_2Si_3O_{12}+KMg_3AlSi_3O_{10}(OH)_2 \rightarrow$

$Mg_3Al_2Si_3O_{12}+KFe_3AlSi_3O_{10}(OH)_2$

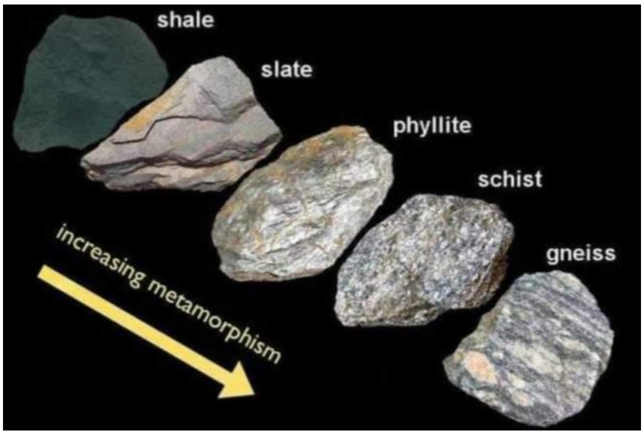
Almandine + phlogopite → Pyrope + Annite

9.6 Type Of Metamorphism

- **Contact** or Thermal metamorphism (T dependent)
  - No foliation, near magmatic body
  - Grain size increase with direction of contact
  - The region of contact metamorphism called **contact metamorphic thereole** (region which is affected by the flux of heat by a magma during contact metamorphism)



- **Regional Metamorphism**: T & P dependent
  - ➢ Tack place at plate boundaries, occur at large scale, & the rock characteristic by folding
  - ➢ not at **cratons** (center region of continents, very stable aria), or **Shields** (Stable, younger than cratons), stable mean no tectonic processes (passive region) except for fault

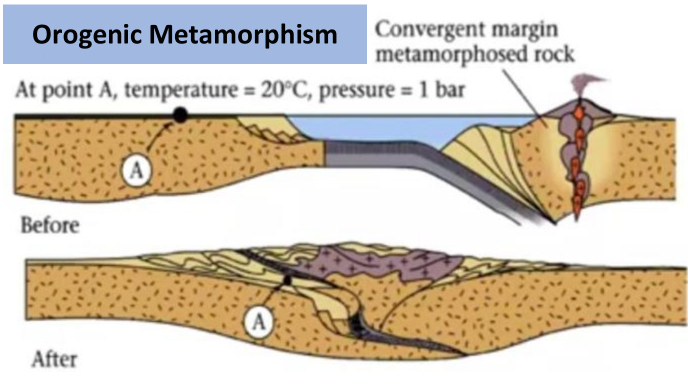


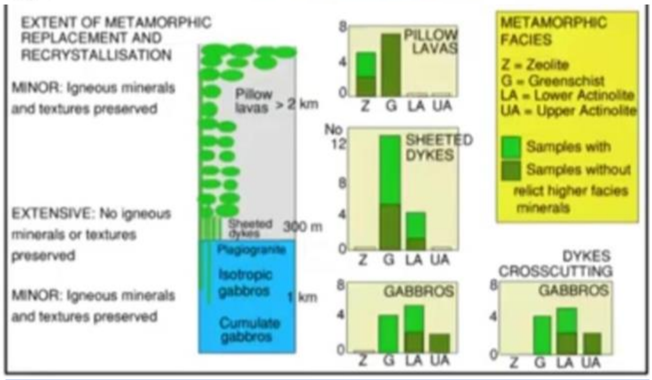
- ➢ There are 3 type of regional metamorphism:

1. **Orogenic Metamorphism:** Occurs in **mobile pellets** region (mountain-building areas) which occur at convergent plate boundaries such as ring of fire, Alps, Andes, Himalayas, & Eeast-African orogeny (Pan-African)
2. **Burial Metamorphism:** Limited in some region, occur due to increase in T as sediments buried & load P, in **Graben** region (2 fault dip in the same directions) such as dead sea
3. **Ocean Floor Metamorphism**: pillow lavas

- **Hydrothermal (Alteration)**: Metazomatism
- **Impact metamorphism**: Shock, occur by meteorite

Orogenic Metamorphism



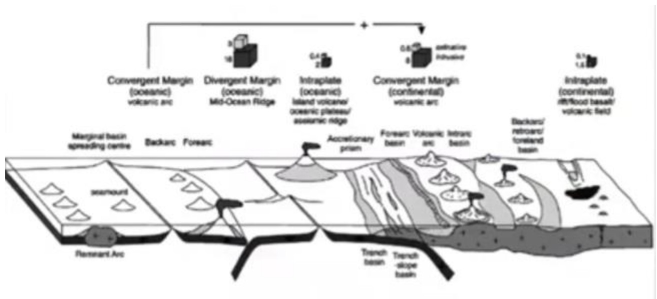


Oceanic Floor Metamorphism

Pillow lava & sheeted dikes metamorphosed into green schist, Zeolite, & Actinolite facies directly after solidified

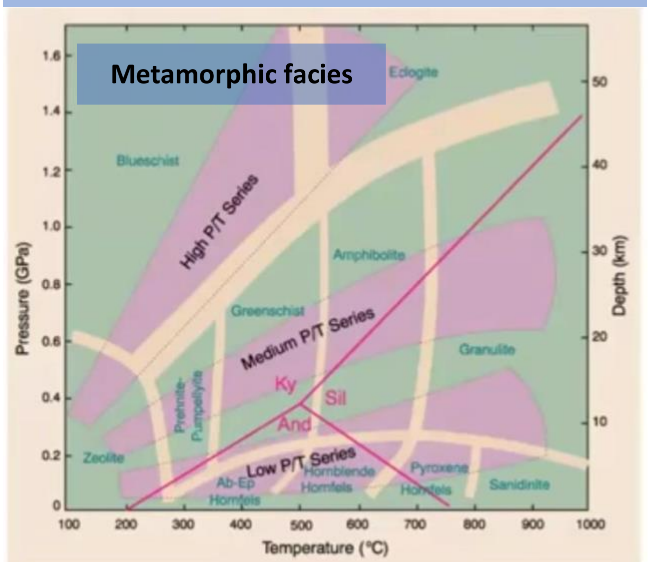
لا يحدث في هذه الصخور foliation لانها thioliitic basalt تفتقر لل K والذي يشكل ال biotite

9.7 Metamorphism of mafic & UM

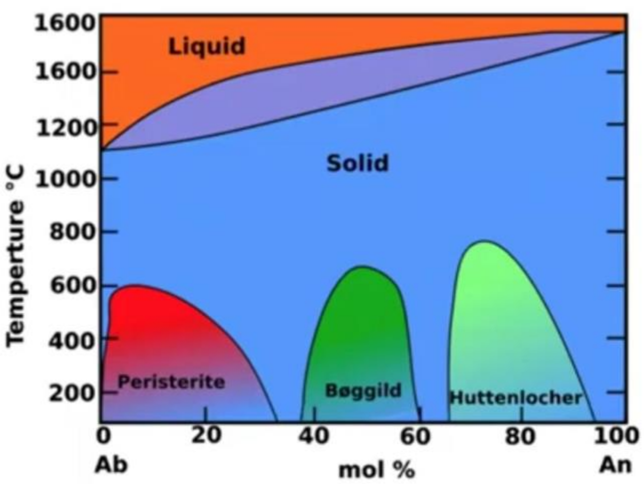


Relative amount of magmas produced at different tectonic setting

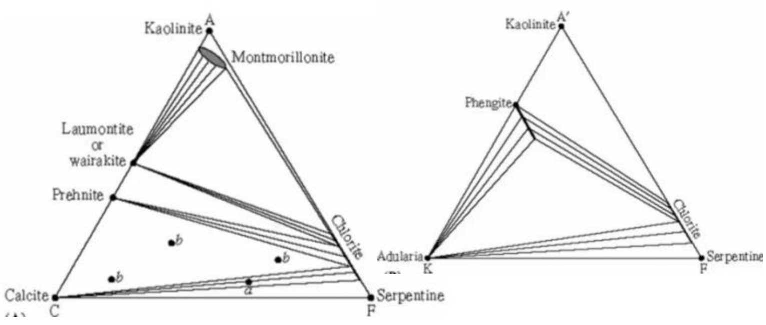
Metamorphic facies



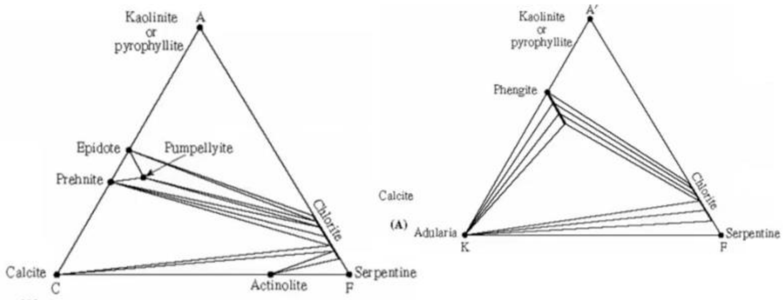
- These rocks include: basalt + gabbro + peridotites + intermediate (Andesites & diorite), which are Metabasites or metamafites, & The ocean crust is built mainly of these rocks which consist of Ca-rich plagioclase & ferromagnesian mineral (olivine + pyroxene + Amphiboles + iron titanium oxides)
- In the region which consist of Zeolite, Prehnite-pumpellyite, & Greenschist facies we can see rock with foliation, soppy texture & light-green color (due to presence of chlorite, epidote, & muscovite)
- **In high-T mafic protolith** Hydrous minerals are not common so hydration is a prerequisite for the development of the metamorphic mineral assemblages that characterize most facies
- mafic igneous rocks will remain largely unaffected in metamorphic terranes, & associated sediments are completely reequilibrated
- **Coarse-grained** intrusive are the least permeable & resist metamorphic changes, **tuffs & greywacke** are the most susceptible to metamorphism
- **Plagioclase:** As T is lowered, Ca-plagioclases become progressively unstable
  - ➢ At low grades only albite (An_{0-3}) is stable
  - ➢ Oligoclase stable in greenschist (An_{1-7} - An_{17-20})
  - ➢ as grade increases – Andesine & more calcic plagioclases are stable in the upper amphibolite & granulite facies
  - ➢ The excess Ca & Al released to calcite, epidote, titanite , or amphibole depending on T-P-X



Typical Mineral Assemblages In Zeolite Facies

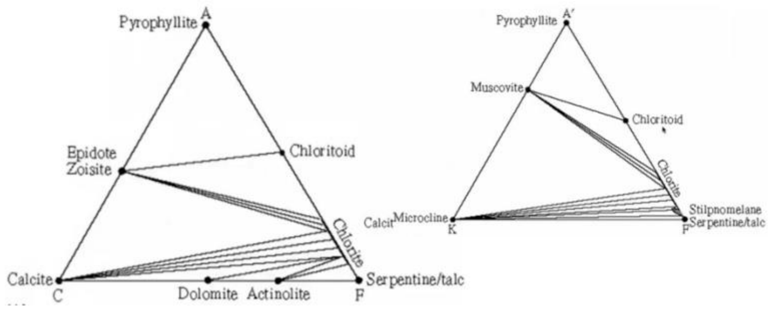


Typical Mineral Assemblages In Perhnite-Pumpellyte



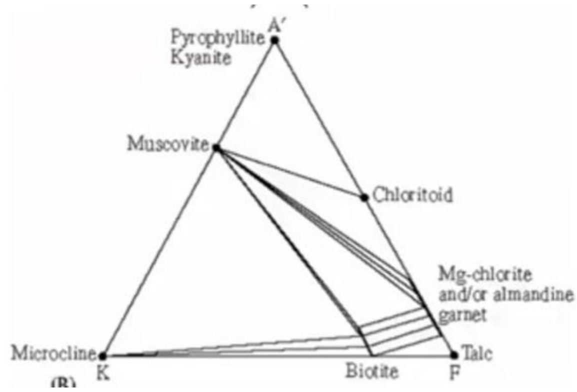
- **Chlorite are sheet silicate contain a lot of water**
- **Mafic Assemblages of the Medium P-T Series**: Greenschist, Amphibolite, & Granulite Facies which constitute the most common facies series of regional metamorphism
  - ➢ Both the classical Barrovian series of pelitic zones, & the lower-P Buchan-Abukuma series are variations on this trend
  - ➢ Typical minerals: chlorite, albite, actinolite, epidote, quartz, & possibly calcite, biotite, or stilpnomelane
  - ➢ **Chlorite**, **actinolite**, **epidote** impart the green color from which the facies get their name

Typical Mineral Greenschist Facies

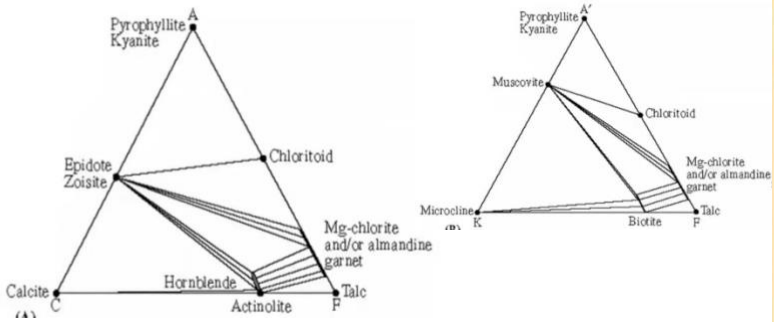


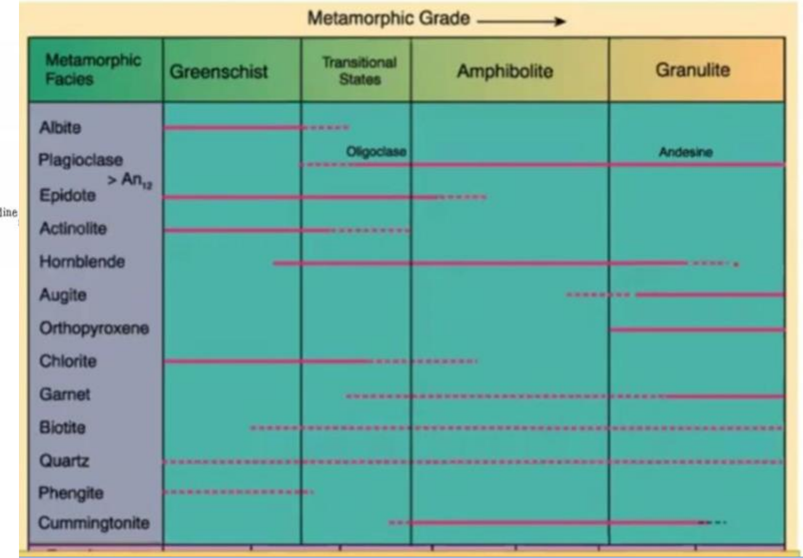
- **Greenschist to amphibolite facies transition involves 2 major mineralogical changes:**
  1. Transition from albite to oligoclase (increased Ca with T across the peristerite gap)
  2. Transition from actinolite to hornblende (amphibole becomes able to accept increasing amounts of Al & alkalis at higher T)
  - ➢ Both occur approximately at the same grade, but have different P-T slopes

Mineral assemblages in upper Greenschist Facies



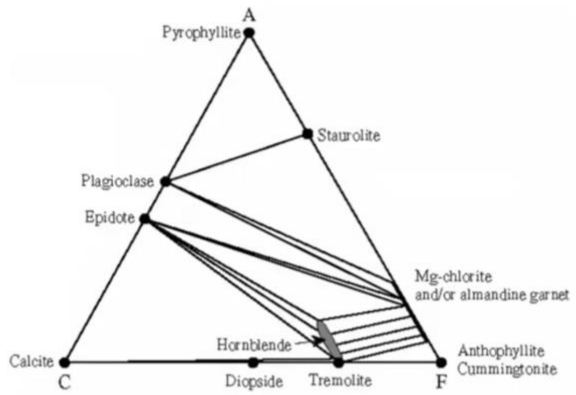
MineralEpidote-Amphibolite Facies





Mineral assemblages in each phase, Mafic protolith

Mineral Assemblages in Amphibolite Facies



كمية ال Ca في هذا ال **facies** تكون اقل لان ال **hornblende** ينشأ

- Transition from amphibolite to granulite facies occurs in the range 650-700°C
  - In the presence of an fluid, pelitic & quartzo-feldspathic rocks (e.g. granitoids) begin to melt in this range at low to medium P, so migmatites may form & the melts become mobilized
  - Not all pelites & quartzo-feldspathic rocks reach the granulite facies
  - Mafic rocks melt at higher T, If water is removed by the earlier melts the remaining mafic rocks may become depleted in water, Hornblende decomposes & orthopyroxene + clinopyroxene appear, & This reaction occurs over a T interval of at least 50°C
  - The granulite facies is characterized by largely anhydrous mineral assemblage
  - In metabasites the critical mineral assemblage is **orthopyroxene**, clinopyroxene, plagioclase ± quartz & minor amounts of Garnet
  - Granulite rocks forms in lower crust with granular texture which formed due to hydrostatic P (equal in all directions)

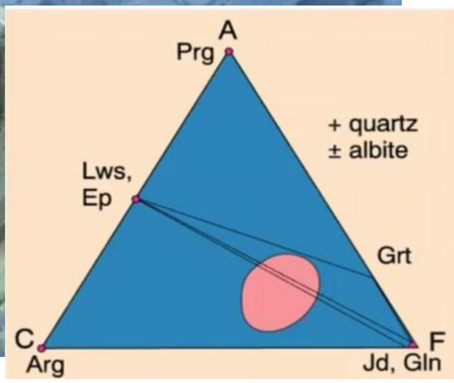
Notes

Metamorphic rocks with **igneous photolith** called **Ortho-** (Orthoamphibolite, Orthogneisses) & with **sedimentary protolith** called **Para-** (Paraamphibolite, paragneisses)

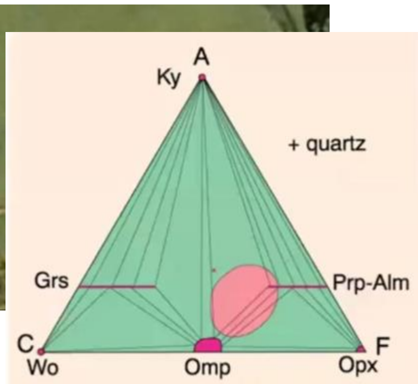
gneiss Vs schist: we can see foliation in a gneiss ether in the hand spacemen or in thin section but in schist in thin section only

- **Blueschist & Eclogite Facies:** Mafic Assemblages of the High P-T Series, High P-T geothermal gradients characterize subduction zones
- **Mafic blueschists facies** recognizable by color, good indicator of ancient subduction zones, metabasites by the presence of a sodic blue amphibole glaucophane (stable at high P), but some solution crossite or riebeckite is possible
  - Glaucophane + Lawsonite associated with Diagnostic, & Crossite is stable to lower P & extend into transitional zones
  - Albite breaks down at high P by reaction to jadeitic pyroxene + quartz: $NaAlSi_3O_8 \rightarrow NaAlSi_2O_6 + SiO_2$

Pillow lavas metamorphosed into blue schist



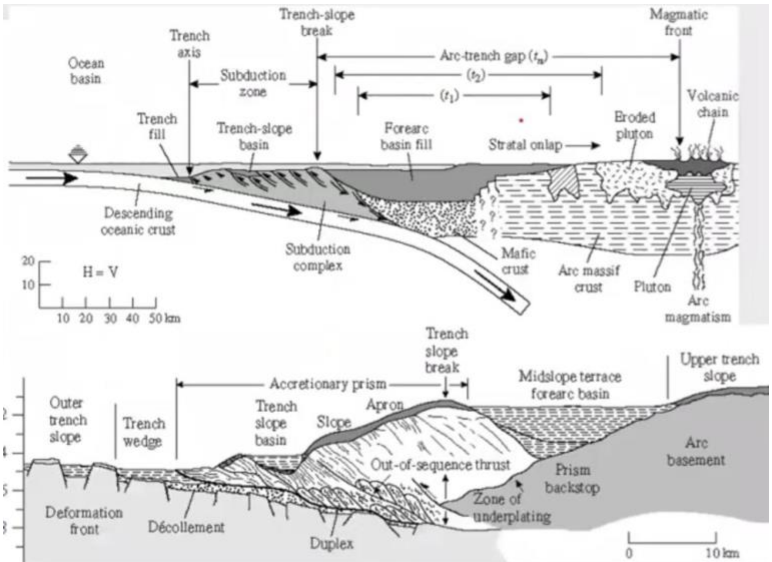
- The great density of **eclogites** suggests that subducted basaltic oceanic crust becomes more dense than the surrounding mantle



- **Very Low-Grade Metamorphism**
  - Clay-sized quartz & albite become coarser
  - Crystallinity of clays increases
  - Chlorite + sericite → phengite & muscovite start to develop
  - Mineral changes under these conditions are best constrained using XRD

9.8 Aluminous clastic (Pelitic)

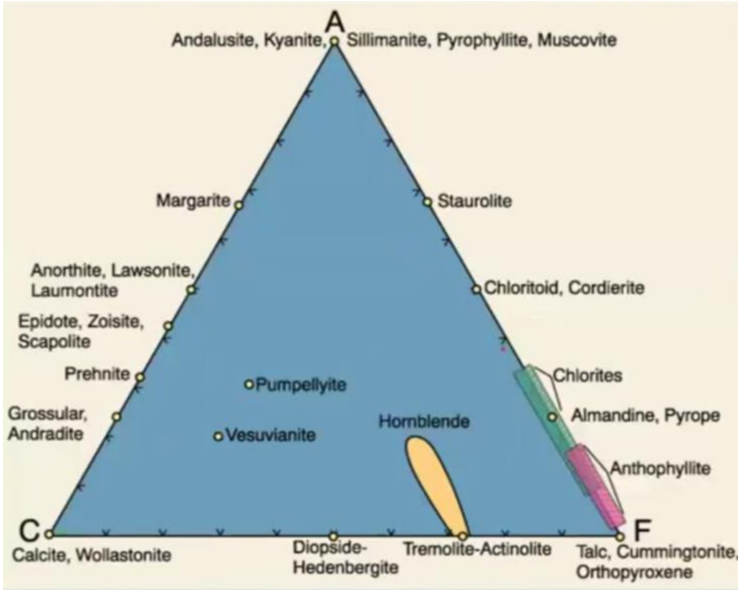
- **Mudstones & shales**: very fine grained mature clastic sediments derived from continental crust, accumulate in distal portions of a wedge of sediment off the continental shelf/slope
- Grade into coarser graywackes & sandy sediments toward the continental source
- **Metapelites**: distinguished family of metamorphic rocks, the clays are very sensitive to variations in T-P, undergoing extensive changes in mineralogy during progressive metamorphism

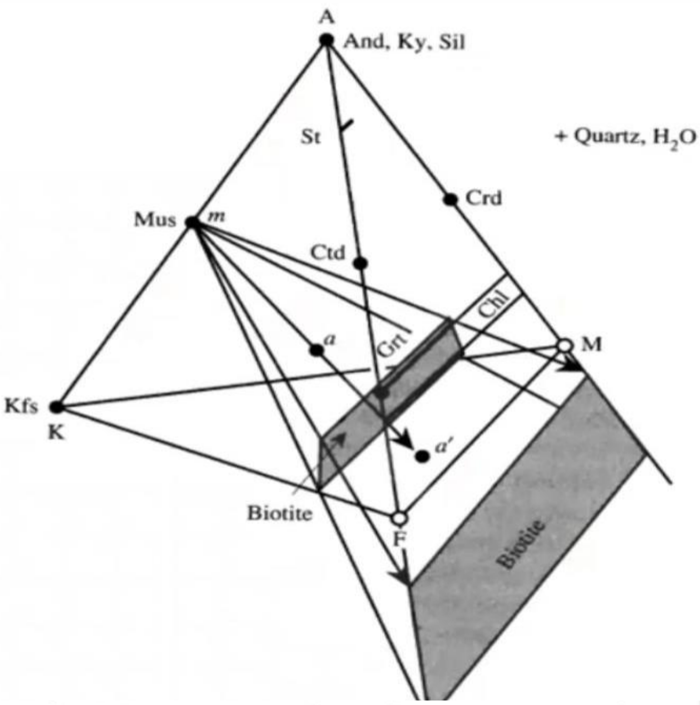


توضح الصورة اماكن تجمع الرسوبيات حيث تسقط في ال Tranche ونتيجة للحرارة والضغط التي تتعرض له تبدأ عملية التحول

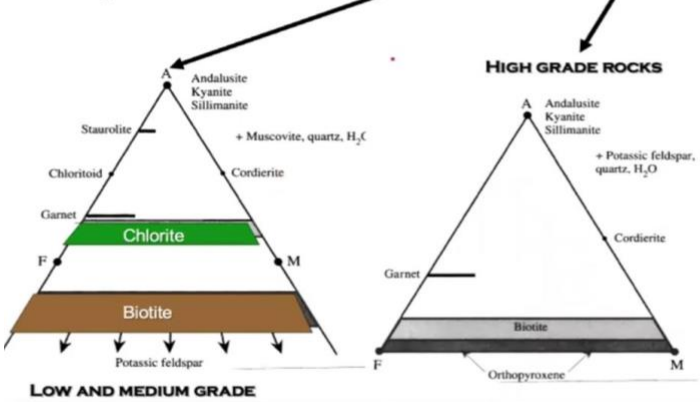
هذا النوع من الرسوبيات (pelitic or shales) حساس جدا للحرارة والضغط لانه يحتوي معادن كثيرة (variable in composition) وايضا مساحة السطح به صغيرة (very fine grain size)

- The mineralogy of pelitic is dominated by:
  - > 50% fine Al-K-rich phyllosilicates such as clays (montmorillonite, kaolinite, smectite)
  - 10-30% quartz
  - white micas (sericite, paragonite, phengite)
  - Chlorite, Albite, K-feldspar, Fe-oxid-hydroxide, zeolites, carbonates, sulfides, & organic matter
- Biotite & Muscovite are typical form metashells
- Distinguishing chemical characteristics:
  - high Al_2O_3 & K_2O, & low CaO
  - High clay & mica content lead to dominance of muscovite & quartz throughout most of the range of metamorphism
  - High proportion of micas & the common development of foliated rocks
- The chemical composition of pelites represented by the system K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O
- If we treat H_2O as mobile the petrogenesis of pelites is represented well in AKF & AKFM diagrams





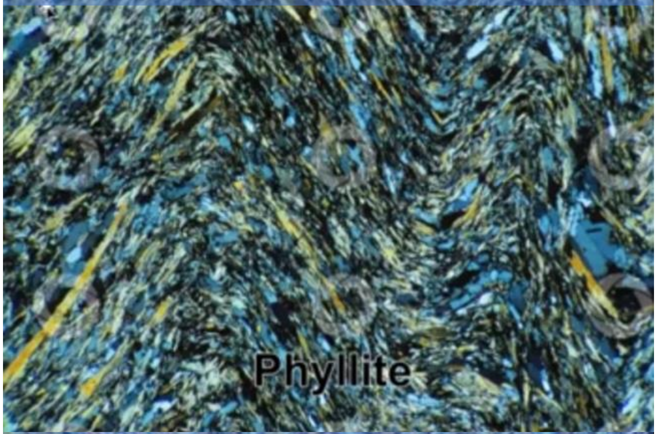
The AFM projection from the muscovite and K feldspar



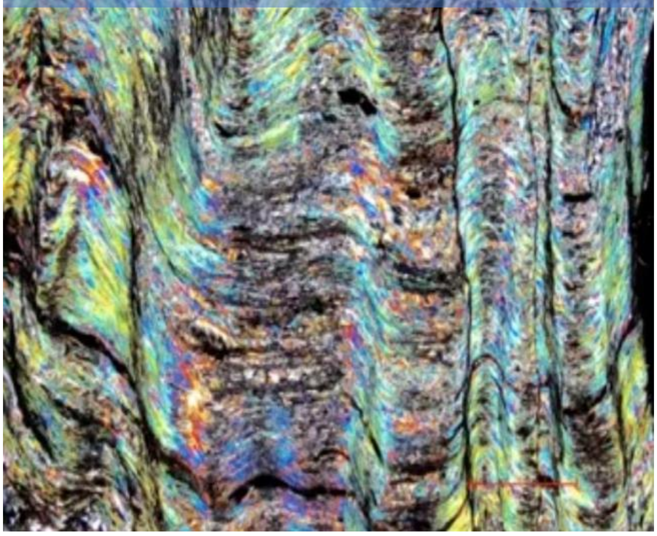
9.8 Metamorphic Zones

- **Shells consist of water (which are released during metamorphism), ferric-Fe^{3+} (Which reduced to ferrous-Fe^{2+}), & other components**

Foliated Chlorite-Muscovite Schist (Phyllite)

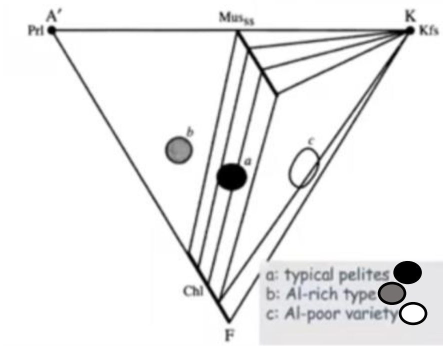


استمرار ال folding بعد تكوين foliation يؤدي ل cleavage



- **Cleavage:** is a different layers between different mineral composition, found in most regional rocks

T	zone	Typical mineral assemblages
200	Chlorite	Qz, chlorite, muscovite, albite
400	Biotite	Qz, chlorite, mica(bi,mu), albite
500	Garnet	Qz, mica, garnet, sodic plagioclase
630	Staurolite	Qz,mica,garnet,plagioclase,staurolite
700	Kyanite	Qz, mica, garnet, plagioclase, staurolite, Kyanite
750	Sillimanite	Qz,mica,garnet,plagioclase,Sillimanite



Chlorite Zone

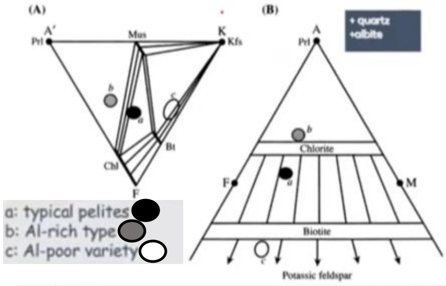
Around 200°-400°C

Mineral Assemblages: Chlorite, K-feldspar, Muscovite, Quartz

Transition between Chlorite to biotite zone involve:

Chlorite → Biotite

Appearances of Chloritoid (Chlorite-like)



Biotit Zone

400°-500°

Biotit formed as porphyroblasts in Metapelites

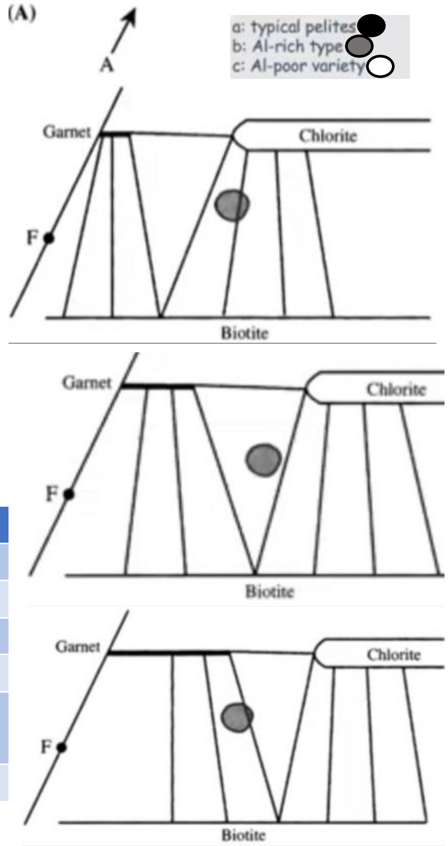
Chloritoid

Transition between Biotite to Garnet zone involve:

Chlorite + Quartz + Muscovite → Garnet + Mg-rich Chlorite + Biotite + Water

Appearance of Almandine rich garnet (Al)

For most Pelitic garnet begin to form at 450°



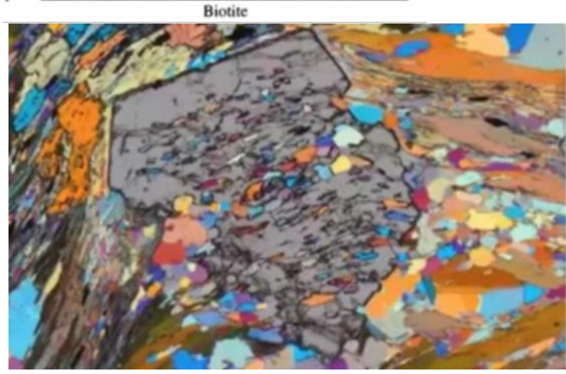
Garnet Zone

500°-630°

Upper Boundary of low grade facies (or series)

The shift in triangle explain the gradual disappearance of Chlorite (garnet increase & chlorite decreases)

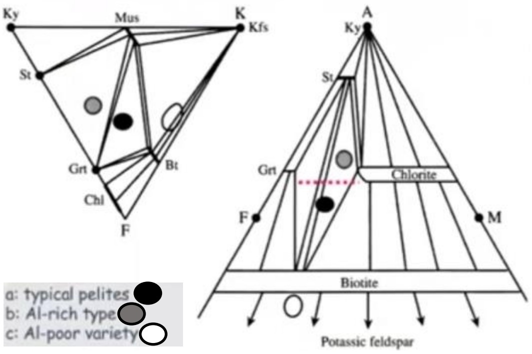
As Garnet-Biotite tie line intersect bulk composition chlorite disappear from assemblages



Garnet porphyroblasts with an inclusion

Transition from Garnet to Staurolite zones:

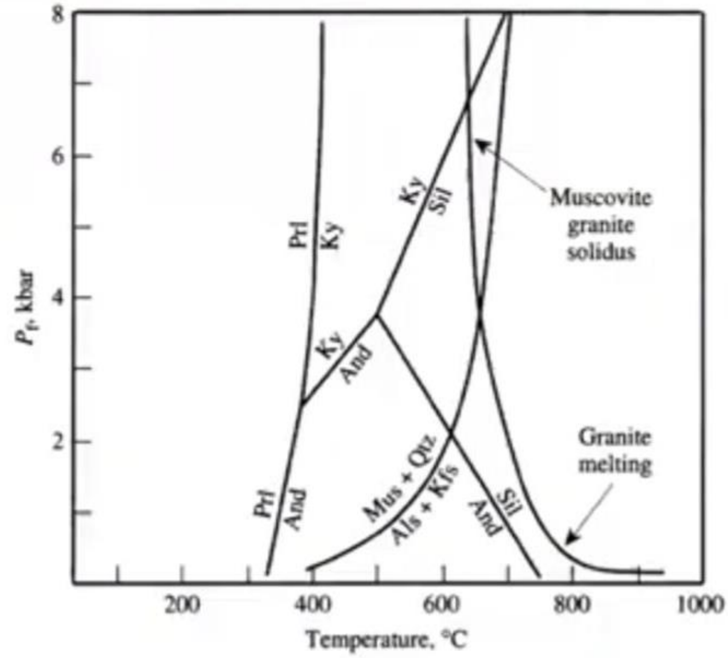
Garnet + Chlorite → Biotite + Staurolite



Staurolite zone

630-700°C

Index mineral for medium grade



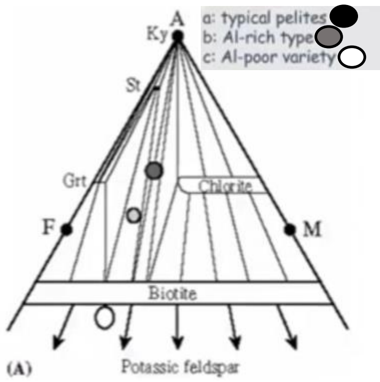
Reactions in medium P-Type with respect to Al_2SiO_5 polymorph & Garnet melting

Transition from Staurolite to Kyanite zones:

Chlorite + Muscovite + Quartz + Staurolite → Biotite + Kyanite + Water

Kyanite begin to form at T = 550° (by thermoparometric reactions)

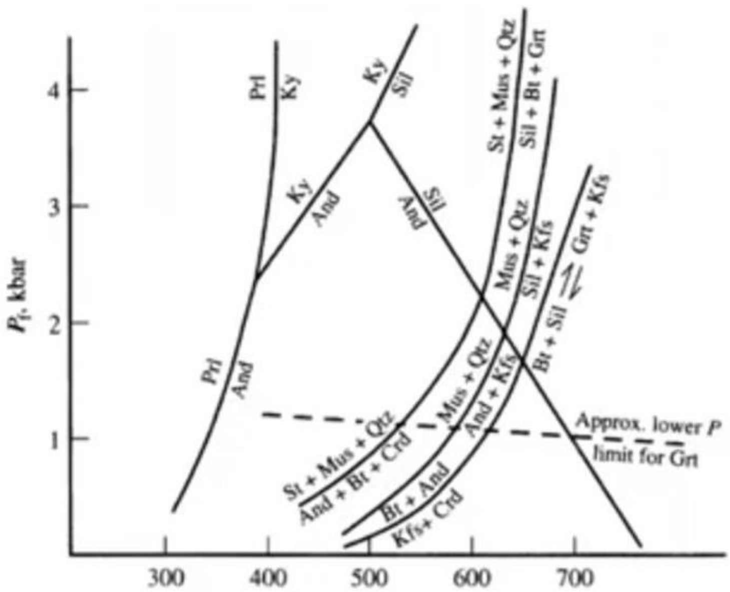
In most Pelitic Kyanite appears will staurolite is still stable



Kyanite zone

630°-700°C

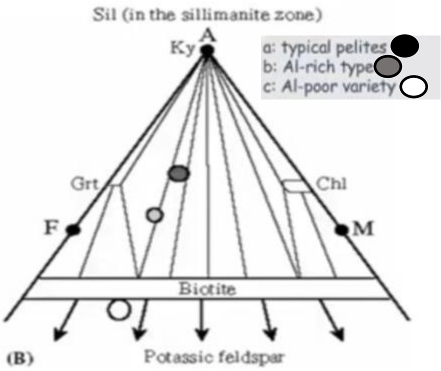
Indicate medium P-type (e.g. Barrovian series) & in low-P type the Andalusite formed rether than Kyanite (Buchan-Abukuma series)



Reactions in low P-Type (Buchan-Abukum)

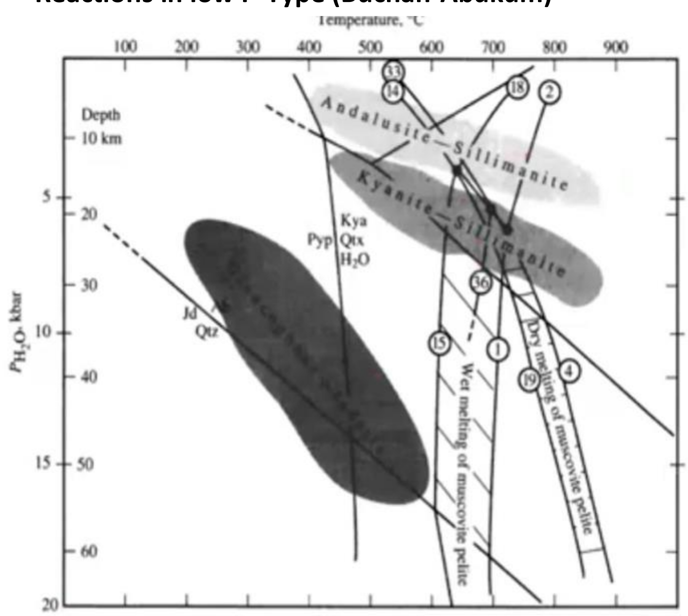
Transition from Kyanite to Sillimanite zones:

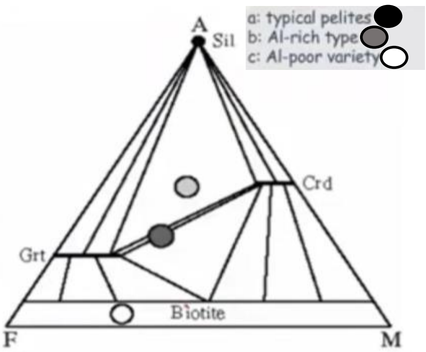
Muscovite + Quartz + Staurolite → Biotite + garnet + Sillimanite + Water



Sillimanite zone

> 700° - 750°



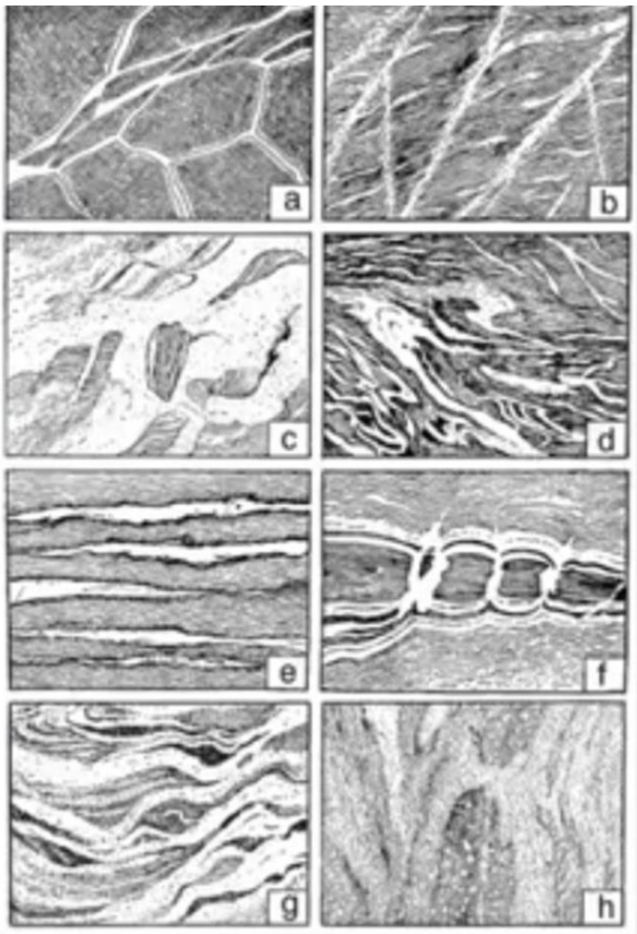


Upper Sillimanite zone (sillimanite-orthoclase)

> 700°C

Microcline + Adularia → Orthoclase

- **Textures of migmatites:**
  - **A. Breccia structure**
  - **B. Net-like structure**
  - **C. Raft-like structure**
  - **D. Vein structure**
  - **E. Stromatic, or layered, structure**
  - **F. Dilation structure in a boudinaged layer**
  - **G. Schleiren structure**
  - **H. Nebulitic structure**



Short Summary

Facies series

andalusite (low T),kyanite (high P),sillimanite (high T)

- Metamorphic facies series:
  1) **Buchan or Abukuma facies series** low P type, & high T (geothermal gradient)
  2) **Barrovian facies series** medium P type
  - ➢ **In low P Kyanite replaced by andalusite**

Metamorphic Reactions

- Most of the reaction in metamorphic rocks are dehydration reactions, isochemical process (no change in composition)
- Muscovite stable at low grade, from medium to a high grade there's no muscovite
- Kyanite replaced by Andalusite in low P types

Meneral Assemblages

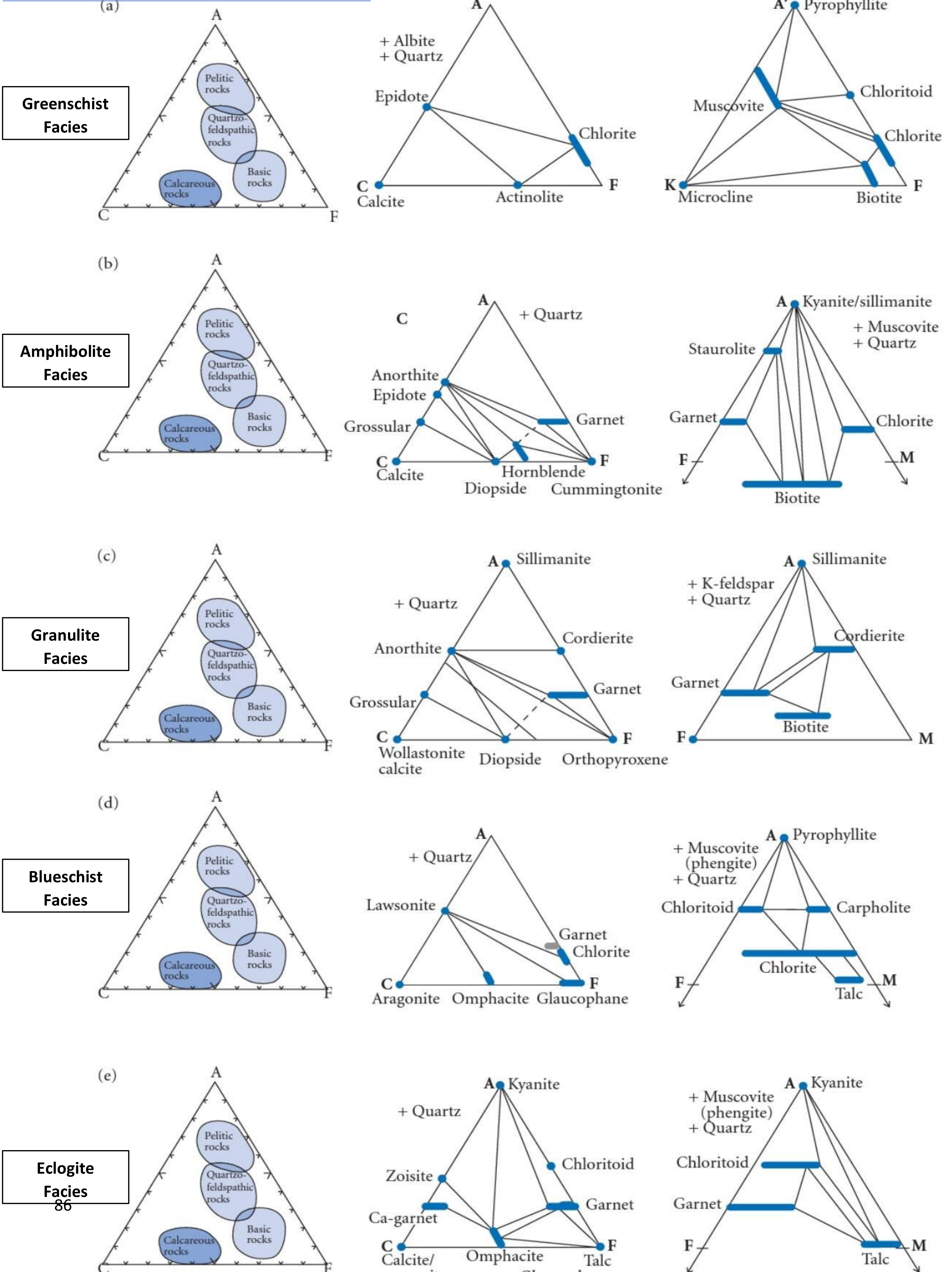
- **Plagioclase:**
  - ➢ As T is lowered, Ca-plagioclases is unstable
  - ➢ At low grades only albite (An_{0-3}) is stable
  - ➢ Oligoclase stable in greenschist (An_{1-7} - An_{17-20})
  - ➢ as grade increases Andesine become stable in the upper amphibolite & granulite facies
- **Mafic Assemblages of the Medium P-T Series**
  - ➢ Greenschist, Amphibolite, & Granulite Facies constitute the most common facies series
  - ➢ chlorite, albite, actinolite, epidote, quartz, & possibly calcite, biotite, or stilpnomelane
  - ➢ **Chlorite, actinolite, epidote** green color
- **Greenschist to amphibolite facies transition:**
  - ➢ Albite → oligoclase (across the peristerite gap)
  - ➢ Actinolite → hornblende (amphibole)
- **in Amphibolite Facies** the Ca become less common because used to form hornblende
- **Transition from amphibolite to granulite facies**
  - ➢ occurs in the range 650-700°C
  - ➢ pelitic & quartzo-feldspathic begin to melt in this range, so migmatites may form & the melts become mobilize but Not all pelites & quartzo-feldspathic rocks reach the granulite facies
  - ➢ Mafic rocks melt at higher T, Hornblende decomposes & pyroxene appear, & This reaction occurs over T interval of at least 750°C
- **The granulite facies** is characterized by largely anhydrous mineral assemblage
  - ➢ In metabasites the critical mineral assemblage is pyroxene, plagioclase ± quartz & Garnet
- **Blueschist & Eclogite Facies:** Mafic Assemblages of the High P-T Series, High P-T geothermal gradients characterize subduction zones
- Mafic blueschists facies recognizable by color, good indicator of ancient subduction zones, metabasites by the presence of a sodic blue amphibole glaucophane (stable at high P), but some solution crossite or riebeckite is possible
  - ➢ Glaucophane + Lawsonite associated with Diagnostic, & Crossite is stable to lower P & extend into transitional zones
  - ➢ Albite breaks down at high P by reaction to jadeitic pyroxene + quartz: $NaAlSi_3O_8$ ⍰ $NaAlSi_2O_6 + SiO_2$
- **Very Low-Grade Metamorphism**
  - ➢ Clay-sized quartz & albite become coarser
  - ➢ Crystallinity of clays increases
  - ➢ Chlorite & sericite → phengite & muscovite
- Thioliitic basalt Lack of K so biotite isn't form from oceanic crust metamorphism

SUMMARY FROM EARTH MATERIALS

Grade	Facies	Characteristics	Common rocks
Contact Metamorphic Rocks, Non-Foliated	Hornfels	• Formed in aureoles or ocean spreading centers	• Fine grained hornfels rocks & coarser rocks with granoblastic textures
	Albite-Epidote hornfels	• T < 450 ° C & P < 2kbar (depth < 6km) • Occur ocean ridges, hotspots & in volcanic arcs • Is a Low P equivalent of the greenschist facies • Index minerals: Albite & epidote	• Mafic, UM, & Pelitic protolith →Hornfels • Quartzo feldspathic → Hornfels, Metaquartzite • calcareous protolith → Marble
	Hornblende hornfels	• 450 – 600°C & < 2.5kbar (<8km) • Low P equivalent of the amphibolite facies • IM: Chlorite, albite, epidote & actinolite	• Mafic, UM, & Pelitic protolith → Hornfels • Quartzo feldspathic → Hornfels,Quartzite • calcareous protolith → Marble
	Pyroxene hornfels	• 600 – 800°C & < 2.5kbar (< 8km) • The low P equivalent of the granulite facies • Hydrous minerals don't occur except for biotite	• Mafic, UM, & Pelitic protolith →Hornfels • Quartzo feldspathic → Hornfels,Quartzite • calcareous protolith → Marble
	Sanidinite hornfels	• high T > 800 °C & low P < 2.5 kbar (< 8km) • in association with basic & ultrabasic intrusions such as xenolith, & is very rare facies	• Mafic, UM, & Pelitic protolith →Hornfels • Quartzo feldspathic → Hornfels,Quartzite • calcareous protolith → Marble
Regional Metamorphic Rocks, Foliated Rocks — Low-Medium (burial metamorphism)	Zeolite	• low grade metamorphic facies produced by T between 150 – 300°C & P< 5kbar (15km depth) • formed by chemical weathering of volcanic ash • Zeolites are a hydrous Na & Ca aluminum tectosilicate • Kaolinite, Serpentine, Calcite, Prehnite, Chlorite, Adularia, Montmorillonite, Laumontite, Wairakite, phengite	• Mafic, & UM → Metabasite, Serpentinite • Pelitic protolith → Metapelite, slate • Quartzo feldspathic → Metaquartzite, metagraywacke • calcareous protolith → Marble
	Prehnite – pumpellyite	• form under low T (250-350), P (<6kbar, 20km) • produced by hydrothermal alteration & burial metamorphism at T-P exceed zeolite facies • Albite, chlorite, muscovite, illite, phengite, smectite, sphene, titanite, epidote, lawsonite, stilpnomelane	• protoliths basalt, graywackes, mudstones • Mafic, & UM → Metabasite, Serpentinite, soapstone, greenstone • Pelitic protolith → Slate, phyllite • Quartzo feldspathic →Metaquartzite
	Greenschist	• Low T (350 – 550) & P (3 – 10kbar, 10 – 30km depth • associated with dynamothermal metamorphism • abundant in orogenic belts (Appalachians, Alps, Otago), fold & thrust belt, & convergent Plate boundaries • epidote, chlorite, & actinolite (green amphibole	• protoliths: igneous rocks, tuff, sandstones, mudrocks, & limestone • Mafic, & UM → Greenschist, Serpentinite, Soapstone, Greenstone • Pelitic protolith → Slate, phyllite, schist
Medium grade	Epidote-Amphibolite		
	Amphibolite	• High T (550-750), moderate-high P (4-12kbar, 12-40km) • Formed in regional orogenic belts at convergent margins • Increase hornblende, garnet, anthophyllite, Kyanite & staurolite (transfer into Sillimanite at higher grade metamorphism) & plagioclase become less sodic (more calcic), & decrease in actinolite chlorite, biotite, talc, &	• protoliths: mafic igneous rocks, tuff, sandstone, mudstone, & limestone • Mafic, & UM → Amphibolite, Schist • Pelitic protolith → Schist, Gneiss • Quartzo feldspathic →Metaquartzite, Gneiss
High & Very High grade	Granulite	• high T (700-900°C), moderate-high P (3-15kbar, 10-50km) • anhydrous mineral (due to dehydration reactions) & Hydrous minerals hornblende & biotite (not muscovite), with Quartz & feldspar, & may be wollastonite, orthopyroxene (hypersthene) & clinopyroxene (diopside)	• Protoliths: granitic to UM rocks, schists, gneisses, pelites, sandstones & limestones • Gneiss, granulite, Charnockites • In orogenic belts, migmatites produced
	Blueschist	• Moderate to high P (4-20kbar, 13-66km), low T (150-500°) • Glaucophane, magnesio-riebeckite, lawsonite, jadeite pyroxene, aegirine, crossite, kyanite • Form in subduction zones where oceanic lithosphere is forced downward to great depths at rapid rates	• Protoliths: mafic rock, sedimentary graywackes, & mudstones • Mafic, Pelitic → Schist • feldspathic → Kyanite Metaquartzite
	Eclogite	• high T (400 – 900°C), very high P (12 – 25kbar, 40 – 82km) • garnet & omphacite, Na-rich jadeitic clinopyroxene, enstatite, jadeite, rutile, zoisite, coesit, phengit, lawsonit, corundum, diamond	• Rocks: Fine to coarse grained, dense, green with reddish brown garnet • Mafic, Pelitic → Eclogite • feldspathic → Kyanite Metaquartzite

هذا الجدول ليس للحفظ، هو مجرد ملخص لاهم الاشياء التي تتعلق في الفيشز من الوحدة الاخيرة من الكتاب، بعضه لم يشرحه الدكتور

A = $(Al_2O_3 + Fe_2O_3) - (Na_2O + K_2O)$, C = $(CaO - 3.33P_2O_5)$, F = $FeO + MgO + MnO$



SUMMARY FROM FOUNDATION OF EARTH SCIENCE

Metamorphic Rock	Texture		Comments	Parent Rock
Slate 	Foliated		**Fine-grained**, tiny chlorite and mica flakes, breaks in flat slabs called slaty cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite 	Foliated		**Fine-grained**, glossy sheen, breaks along wavy surfaces	Shale, mudstone, or siltstone
Schist 	Foliated		**Medium- to coarse-grained**, scaly foliation, micas dominate	Shale, mudstone, or siltstone
Gneiss 	Foliated		**Coarse-grained**, compositional banding due to segregation of light and dark colored minerals	Shale, granite, or volcanic rocks
Marble 	Nonfoliated		**Medium- to coarse-grained**, relatively soft (3 on the Mohs scale), interlocking calcite or dolomite grains	Limestone, dolostone
Quartzite 	Nonfoliated		**Medium- to coarse-grained**, very hard, massive, fused quartz grains	Quartz sandstone