# 3.2 Identifications of rocks and minerals in the field

## 3.2.1 Sedimentary rocks

表3-3 沈積岩及沈積物分類表

| 沈積岩(沈積物) | | | | | | |
|---|---|---|---|---|---|---|
| 碎屑性 | | | | 非碎屑性 | | |
| 冰積物 | 火山碎屑物 | 侵蝕殘餘物 | 混合性沈積物 | 沈澱物：非蒸發鹽 | 沈澱物：蒸發鹽 | 有機殘餘物 |
| 冰積岩<br>(冰積石) | 火山角礫岩<br>(火山碎屑)<br>集塊岩<br>(火山彈)<br>凝灰岩<br>(火山灰) | 角礫岩<br>(角礫石)<br>礫岩<br>(礫石)<br>砂岩(砂)<br>泥岩(泥)<br>頁岩(泥) | 泥灰岩<br>(灰泥)<br>炭質泥岩<br>(炭泥)<br>石灰質砂岩<br>(石灰砂) | 石灰岩<br>白雲岩<br>(碳酸鹽)<br>磷灰岩<br>(磷酸鹽)<br>鐵岩<br>(氧化鐵)<br>燧岩<br>(氧化矽) | 鹽岩<br>(鹵鹽)<br>膏岩<br>(硫酸鹽) | 煤(泥炭)<br>石油<br>天然氣<br>(油母質) |

(修改自 Pettijohn, 1974; Fisher and Schmincke, 1984)

鄧屬予(1997)

表3-2 沈積物粒度及相對的岩石名稱表

| 沈積物(未膠結) | | 直徑(公釐, mm) | 沈積岩(已膠結) | |
|---|---|---|---|---|
| 礫石 (Gravel) | 巨礫 (Boulder) | 大於 256 | 礫岩 (Conglomerate)<br>角礫岩 (Breccia) | |
| | 中礫 (Cobble) | 256-64 | | |
| | 小礫 (Pebble) | 64-4 | | |
| | 細礫 (Granule) | 4-2 | | |
| 砂 (Sand) | 極粗砂 (Very Coarse) | 2-1 | 砂岩 (Sandstone) | |
| | 粗砂 (Coarse) | 1-1/2 | | |
| | 中砂 (Medium) | 1/2-1/4 | | |
| | 細砂 (Fine) | 1/4-1/8 | | |
| | 極細砂 (Very Fine) | 1/8-1/16 | | |
| 泥 (Mud) | 粉砂 (Silt) | 1/16-1/256 | 粉砂岩 (Siltstone) | 泥岩 (Mudstone)<br>頁岩 (Shale) |
| | 黏土 (Clay) | 小於 1/256 | 黏土岩 (Claystone) | |

(修改自Wentworth,1992)

Neoproterozoic Glacial Diamictite, Namibia


This closer view of the diamictite demonstrates the poorly sorted nature of the clasts. Dark clasts are limestone and tan clasts are dolomite. The softer limestone clasts sheared after burial, whereas the stronger dolomite clasts did not.

冰磧石(Tillite, here it is called diamictite)


泥灰岩(marl)

鹽岩(Salt, Yemen)

**CONGLOMERATES AND BRECCIAS**

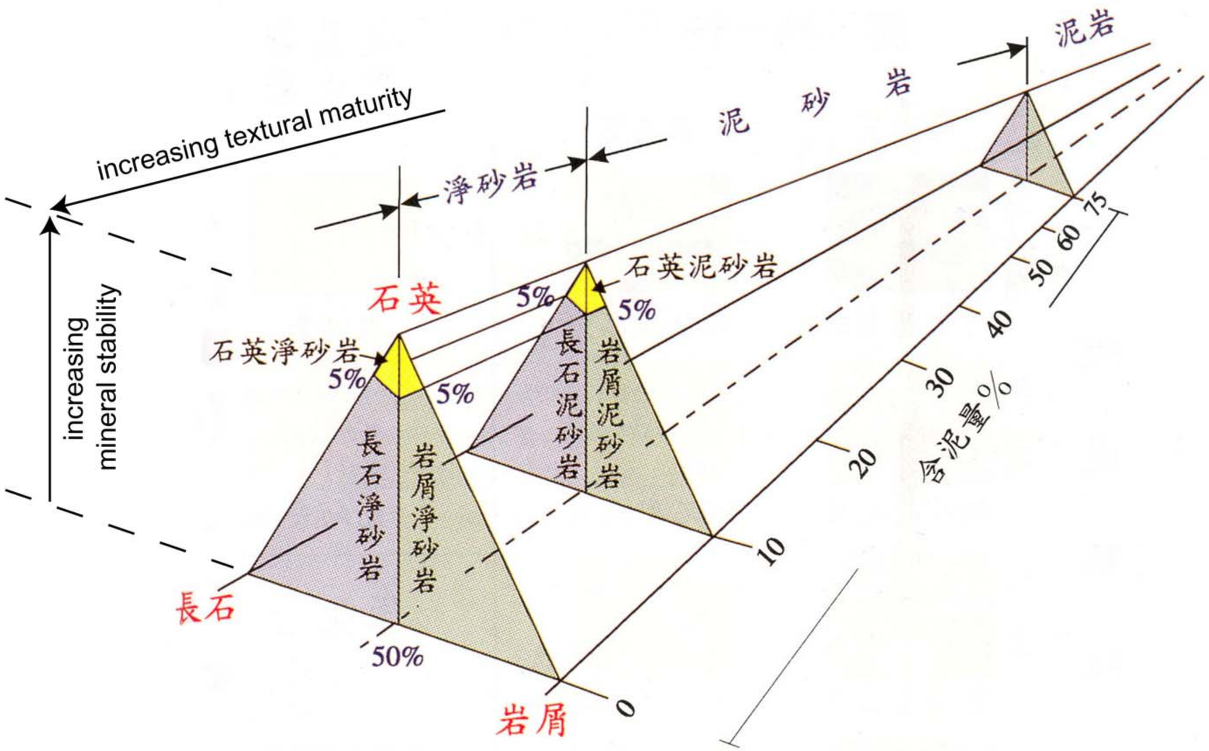
Important features to note in conglomerates (rounded clasts) and breccias (angular clasts) are the types of clast present and grain-size distributions. Clasts may be *intraformational* (almost contemporaneous) or *extraformational* (from pre-existing rocks). There may be a variety of rock types present as clasts (*polymictic*) or just one type (*oligomictic*). Further features to note are whether the rock is clast-supported or matrix-supported and if the clast have any preferred orientation(s).


礫岩(Conglomerate)

角礫岩(Breccia)

# SANDSTONES (ARENACEOUS ROCKS)

There are five components that commonly make up a sandstone: *quartz grains, feldspar grains, rock-fragments* (lithic grains), *matrix,* and *cement*. The matrix, if present, comprises clay and silt-sized particles. Common cements are quartz and calcite; a red coloration is occasionally observed due to the presence of hematite. Sandstones are classified on the basis of percentage quartz (+ chert), feldspar, rock fragments, and matrix (as shown below).




from 鄧屬予(1997) modified from Dott (1964)

Sandstone maturity

● **Compositional maturity**: relative abundance of stable and unstable framework grains (mature: abundant quartz; immature: abundant feldspar or rock fragments)

● **Textural maturity**: relative abundance of matrix and the degree of rounding and sorting of framework grains.

## Sandstone classifications

**淨砂岩:arenite**

石英淨砂岩(quartz arenite);
岩屑淨砂岩(lithic arenite);
長石淨砂岩(feldspathic arenite)

**泥砂岩: wacke**

石英泥砂岩(quartz wacke);
岩屑泥砂岩(lithic wacke);
長石泥砂岩(feldspathic wacke)

**泥岩: mudrock**

Examples

石英淨砂岩

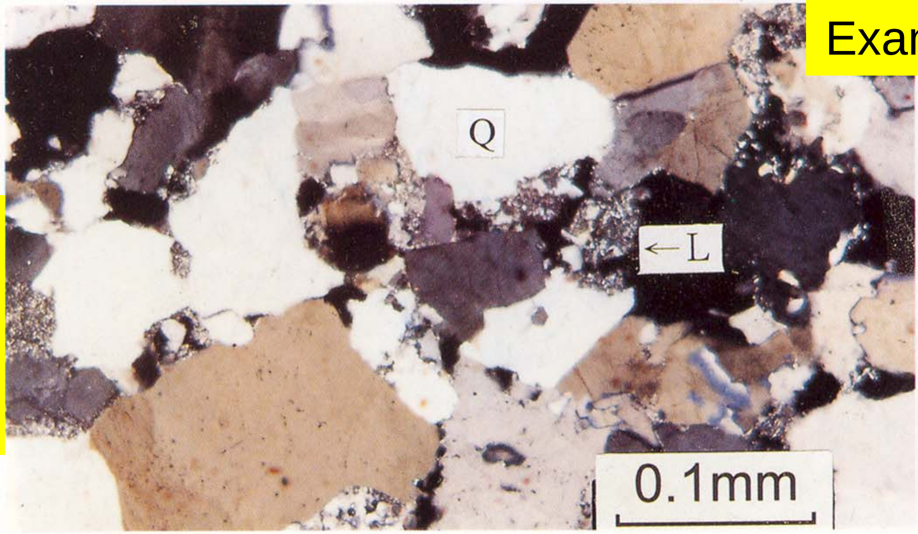
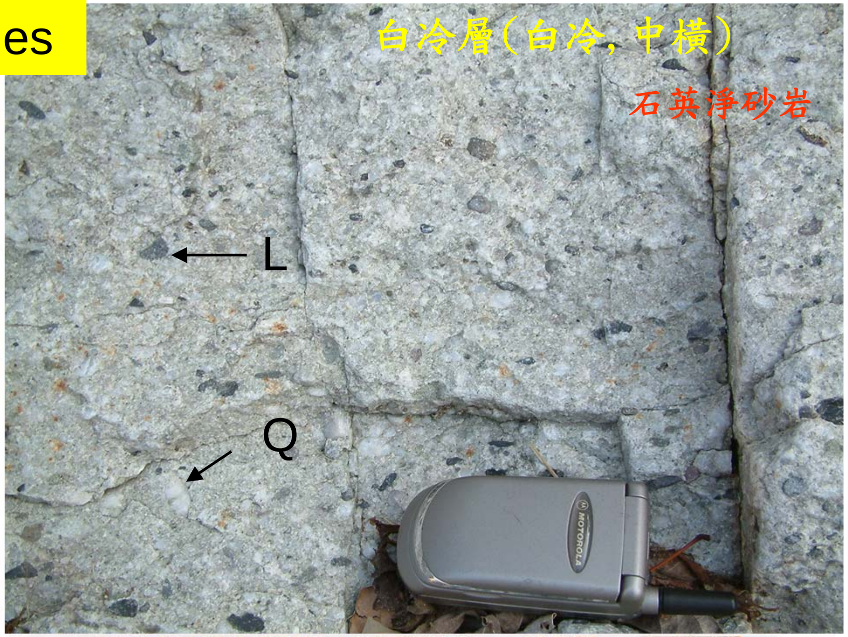



圖3-26 石英砂岩岩象
顯微鏡下的白冷層石英砂岩，由石英(Q)和少許岩屑(L)組成。顆粒多次角形，淘選度佳。由於受過深埋，所以顆粒間有些微的壓溶現象，形成齒狀穿插的邊緣(南投縣水里鄉)。




岩屑淨砂岩

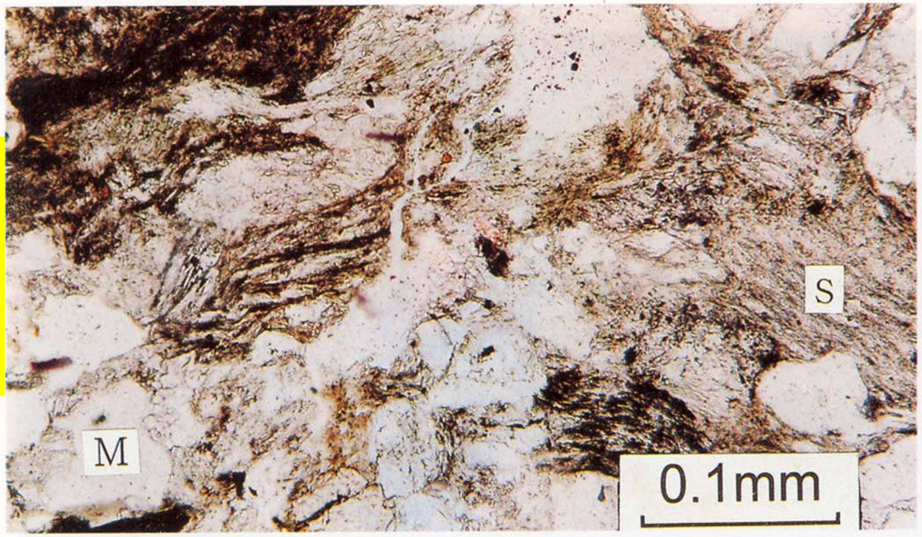
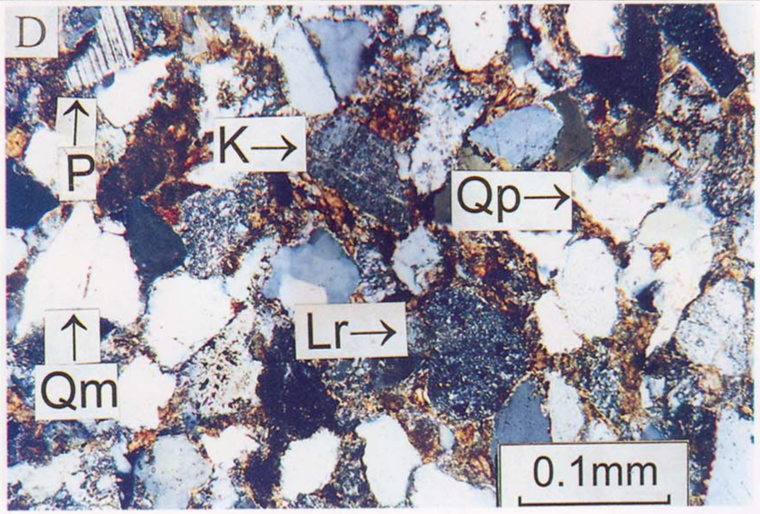



圖3-27 岩屑砂岩岩象
顯微鏡下的八里灣層砂岩，由板岩(S)和變質砂岩(M)的岩屑組成。板岩岩屑的劈理明顯，組成顆粒多次角形，泥基質含量高，淘選度不佳(台東縣東河鄉；Teng, 1979)。




粒呈次角形，孔隙由泥充填。石英有單晶(Qm)和複晶(Qp)兩種，有波狀消光現象；長石含有鉀長石(K)與斜長石(P)；岩屑則有沈積岩(Ls)、酸性火山岩(Lr)與變質岩。

長石淨砂岩

五指山層　鄧屬予 (1997)

**Scheme for nomenclature of fine-grained siliciclastic sedimentary rocks (from Graham, in Tucker, 1988). Common terms in bold.**

| | | *Breaking characteristics* | |
|---|---|---|---|
| *Grain Size* | *General term* | *Non-fissile* | *Fissile* |
| Silt + clay | **Mudrock** | **Mudstone** | **Shale** |
| Silt >> clay | Siltrock | **Siltstone** | Silt shale |
| Clay >> silt | Clayrock | **Claystone** | Clay shale |

Siltstone (Silt shale, 茅埔頁岩,後堀溪)

Claystone (clay shale, 鹽水坑頁岩,鹽水坑溪)

# LIMESTONES

A. Classification based on dominant constituent (Folk)

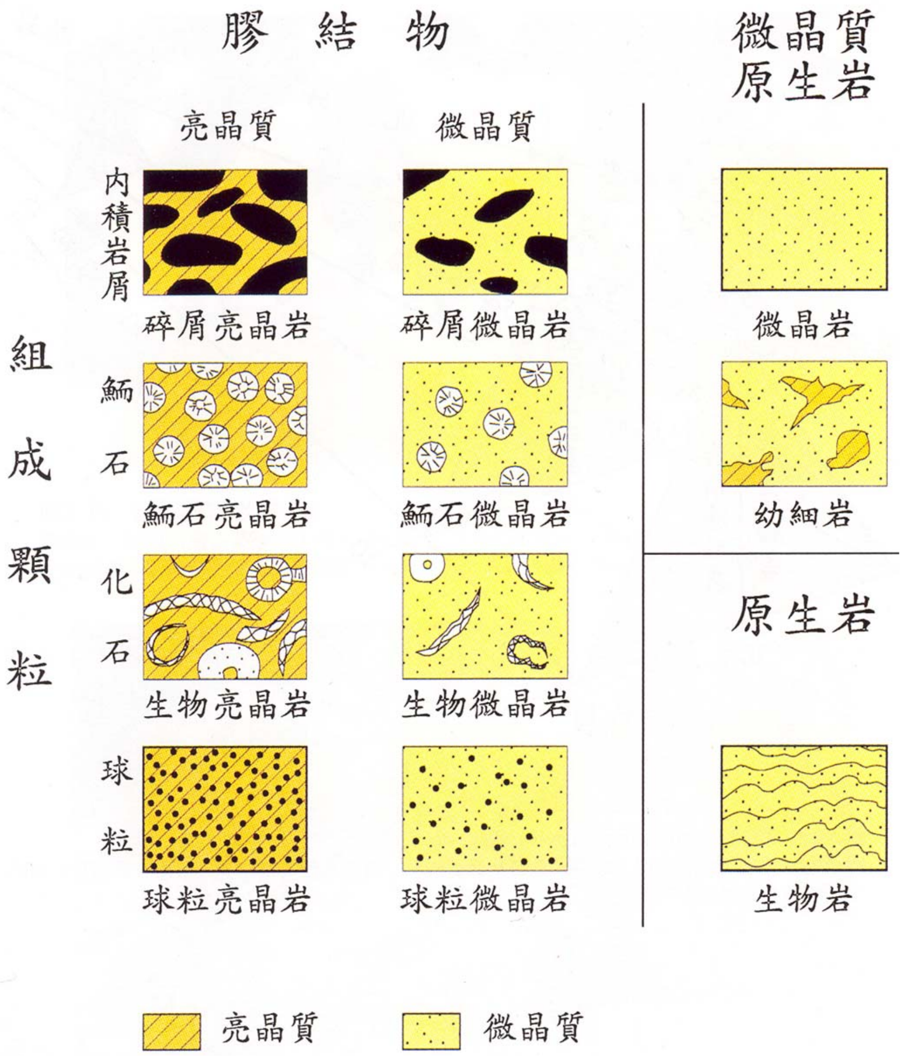



**圖3-29** 石灰岩分類圖(修改自Folk, 1962)

石灰岩以組成顆粒與膠結物的性質來分類(左半部)，倘若沒有粗粒的碎屑物，或僅有原生的生物體，則以右半部的原生岩命名。

Three components make up the majority of limestones: *carbonate grains* (allochems); *micrite* (microcrystalline calcite,微晶質) and *sparite* (very finely to very coarsely crystalline calcite cement,亮晶質).

The main allochems are *oöids (鮞石), peloids(球粒), bioclasts* (skeletal grains化石) and *intraclasts(內積岩屑)*.

Allochems > 10%

| | |
|---|---|
| 碎屑亮晶岩(Intrasparite) | 碎屑微晶岩(Intramicrite) |
| 鮞石亮晶岩(Oösparite) | 鮞石微晶岩(Oömicrite) |
| 生物亮晶岩(Biosparite) | 生物微晶岩(Biomicrite) |
| 球粒亮晶岩(Pelsparite) | 球粒微晶岩(Pelmicrite) |

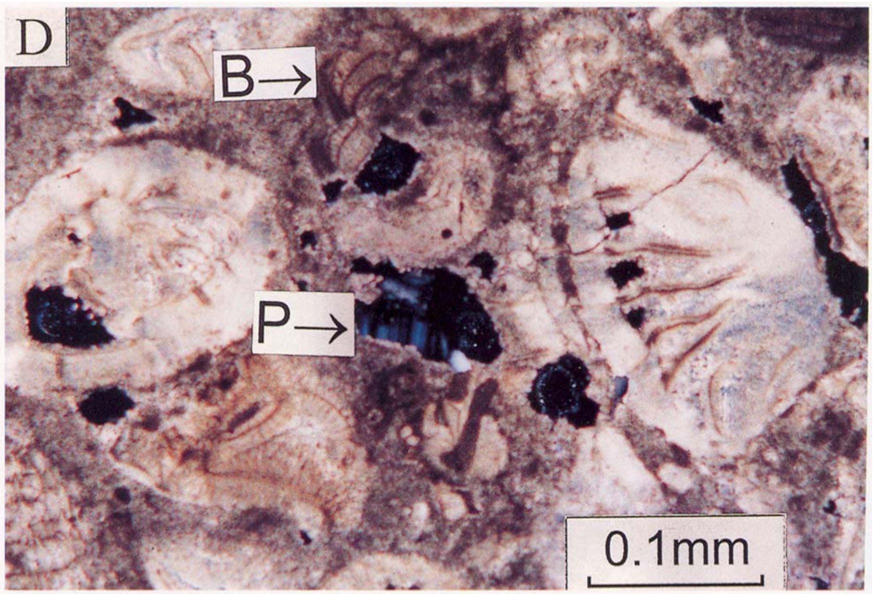
Allochems < 10%

微晶岩(micritic limestone)
幼細岩(dismicrite, micrite with cavities (usually spar-filled)

生物岩(biolithite, e.g, reef-rock or stromatolite)


圖版四十一 【東河石灰岩二】

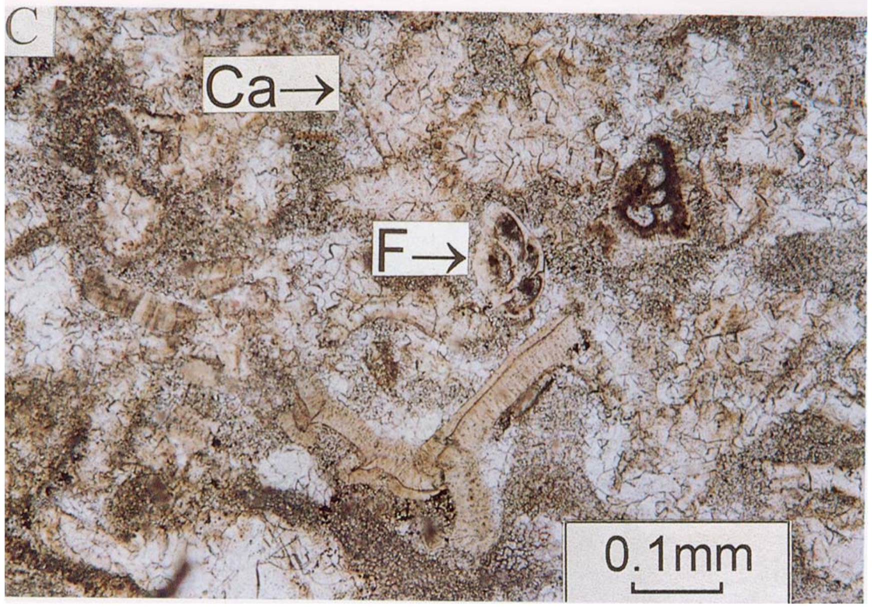
採自臺東縣東河鄉都巒山層頂部的上新統石灰岩，爲白色生物微晶岩(圖版A、B)，組成以有孔蟲(F)爲主，並有藻類(B)與少量的斜長石(P)。質地緻密，但孔隙仍多，生物組織明顯。顆粒間由微晶質方解石膠結，具有輕微的再結晶現象(圖版C、D)。





圖版十四 【半屏山石灰岩】

採自高雄市半屏山的更新統礁灰岩體，爲白色略帶粉紅色的生物亮晶岩(圖版A、B)，質地堅硬，有許多孔隙。組成以珊瑚(Co)爲主，另有貝類、藻類、有孔蟲(F)和少量的石英，顆粒間由亮晶質方解石(Ca)膠結(圖版C、D)。



## B. Classification based on grain size

| *Most grains:* > 2 mm | 2mm – 62µm | < 62µm |
|---|---|---|
| Calcirudite | Calcarenite | calcilutite |

## C. Classification based on texture (Dunham)

| *Textural features* | | *Rock types* |
|---|---|---|
| Carbonate mud absent | Grain-Supported | Grainstone |
| Carbonate mud present | | Packstone |
| | Mud-supported (>10% grains) | Wackestone |
| | Mud-supported (<10% grains) | (lime) mudstone |
| Components organically bound | | Boundstone |

## Common sedimentary structures. (Modified from Graham, in Tucker, 1988)

*Observed primarily as internal structures of beds in section:*

- Cross-stratification
- Lamination
- Grading
- Soft sediment deformation
- Bioturbation (general burrowing) and trace fossils
- Stromatolites
- Pedogenic horizons, hardgrounds
- Cavities (mainly in limestones)
- Concretions (whole specimen may be a concretion)
- Styolites (dissolution)

*Observed primarily on bedding surfaces*

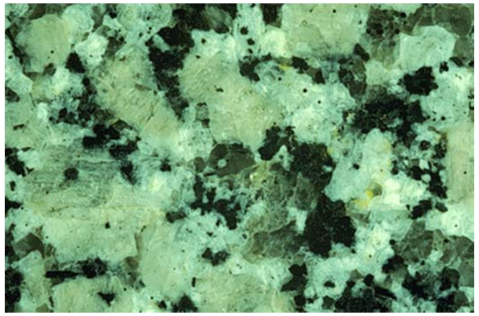
(i) Best seen on bottom surfaces (sole marks)
- Flute marks
- Tool marks
- Load casts
- Topographic infill above bedforms

(ii) Best seen on top surfaces
- Bed forms (e.g. ripple, dunes, hummocks)
- Shrinkage cracks
- Sand volcanoes
- Raindrop impressions

(iii) Seen on both top and bottom surfaces
- Trace fossils
- Primary current lineation

## 3.2.2 Igneous rocks

Coarse-grained texture of granite



**DESCRIPTION OF IGNEOUS ROCK HAND SPECIMENS.**
Make an examination taking account of the following features:

### (a) Grain size

This description should also include any detail about variations e.g. porphyritic (斑狀) textures etc.


Phaneritic (顯晶質, Coarse) : crystals visible to the naked eye
1. coarse grain – grains essentially > 5mm
2. medium grain – grains 1-5mm
3. fine grain – grains < 1mm

Aphanitic (隱晶質, Fine): hand lens needed
1. Microcrystalline (微晶質) –grains visible under the microscope
2. Cryptocrystalline (潛晶質,隱晶質) – not distinguishable microscopically but crystallinity indicated by such methods as X-ray
3. Glassy (玻璃質) – essentially amorphous – no crystalline structure distinguishable

### (b) Average color

Color can also be defined according to a color index, which is the volume percentage M of the mafic minerals present: M100-90: ultramafic (超基性,超鎂質); M90-65: Melanocratic (暗色, 鐵鎂質); M65-35: Mesocratic (中色的): and M35-0: Leucocratic (淡色的)

**(c) Crystallinity**

Wholly, partly, or non-crystalline (may be glassy). This should also include a description of crystal shape and size, including variations, as well as the proportion of glass, if any, present.

1. Holocrystalline (全晶質) – composed entirely of crystalline grains

   Hypocrystalline (半晶質) – composed partly of crystalline grains and partly of glass (essentially a porphyritic glass)

2. Holohyaline (全玻質) – composed of glass

**(d) Density**

Low, medium or high. This is usually only a rough estimate from hefting the specimen in your hands.

**(e) Fabric**

Does the rock have any obvious arrangement or pattern of its constituent minerals? The rock may be streaky, layered, banded, laminated, lineated or contain inclusions.

Characteristic textures of volcanic rocks are vesicular (多孔狀), amygdaloidal (杏仁狀), porphyritic, streaky (條帶狀), and graded (as in pyroclastics, 火山碎屑物). Characteristic textures of intrusive rocks are equigranular (等粒狀), porphyritic, drusy (晶簇狀), granophyric (花斑狀,文像斑狀), pegmatitic (偉晶狀), ophitic (輝綠狀), layered, laminated, veined (脈狀的), xenolithic (捕獲的).

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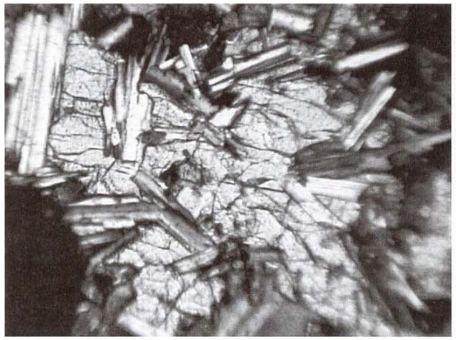

Ophitic texture: The envelopment of plagioclase laths by larger clinopyroxenes, and is commonly interpreted to indicate that the clinopyroxene formed later.

**Figure 3–8** Ophitic texture. A single pyroxene envelops several well-developed plagioclase laths. Width 1 mm.

Winter, J. D. (2001) An Introduction to Igneous and Metamorphic Petroloey. Prentice Hall, 697pp.

**(f) Mineralogy**

List all the minerals you can identify from cleavage (解理), habit (結晶性), color, luster, twinning, hardness etc., and estimate their relative amounts. Note: cleavage (劈理 in structural geology)

1. Primary Minerals – those crystallizing directly from magma.

a. Essential Minerals – minerals which determine the 'root name of the rock'.
b. Characterizing Accessory Minerals – minerals whose presence modifies the root name.
c. Minor Accessory Minerals – minerals whose presence do not affect the name of the rock.
d. Color – depends on both grain size and mineral content. The terms leucocratic, mesocratic and melanocratic are used for light, medium and dark colored rocks.
e. Texture – mineral textures can often give the petrologist useful information:
  (1) zoning (環帶) – indicates change in fluid composition during mineral growth
  (2) exsolution (凝析作用) – indicates subsolidus exsolution of mineral phases during slow cooling
  (3) embayments – indicates phenocryst (斑晶) not in equilibrium with fluid, common during volcanic eruptions
  (4) order of crystallization – worked out by studying which mineral encloses which.

2. Secondary Minerals – minerals formed by the alteration of primary minerals, or deposited after solidification of the igneous body.

Common types of secondary processes:

a. Kaolinization (高嶺石化) – alteration of alkali feldspars to clay minerals

b. Saussuritization (鈉黝簾石化) – alteration of calcic plagioclase to saussurite (鈉黝簾石), a mixture of albite (鈉長石 ) and epidote (綠簾石) minerals. It is characterized by a greasy luster, green color, and absence of cleavage and twinning

c. Chloritization (綠泥石化) – alteration of Fe, Mg minerals to chlorite

d. Serpentinization (蛇紋石化) – alteration of Fe, Mg minerals to serpentine

e. Uralitization (次閃化) – alteration of replacement of pyroxene to amphiboles (uralite假像纖維角閃石or 次纖閃石)

f. Silicification (矽化) – replacement of part of the rock by secondary silica

g. Propylitization (青盤岩化) – the formation is 'propylite' (青盤岩 ), common to andesites, by the:
 (1) alteration of plagioclase to albite + epidote
 (2) alteration of Fe, Mg minerals to chlorite, calcite,

Using your assessment of the points above classify the rock(s) according to your preferred scheme.

Plutonic melts

Volcanic melts

## Crystallization sequences of silicate melts

Gabbro

Plagioclase-rich gabbro

Pyroxene diorite

Quartz diorite

Granodiorite

Alkaline granite

Calcalkaline granite

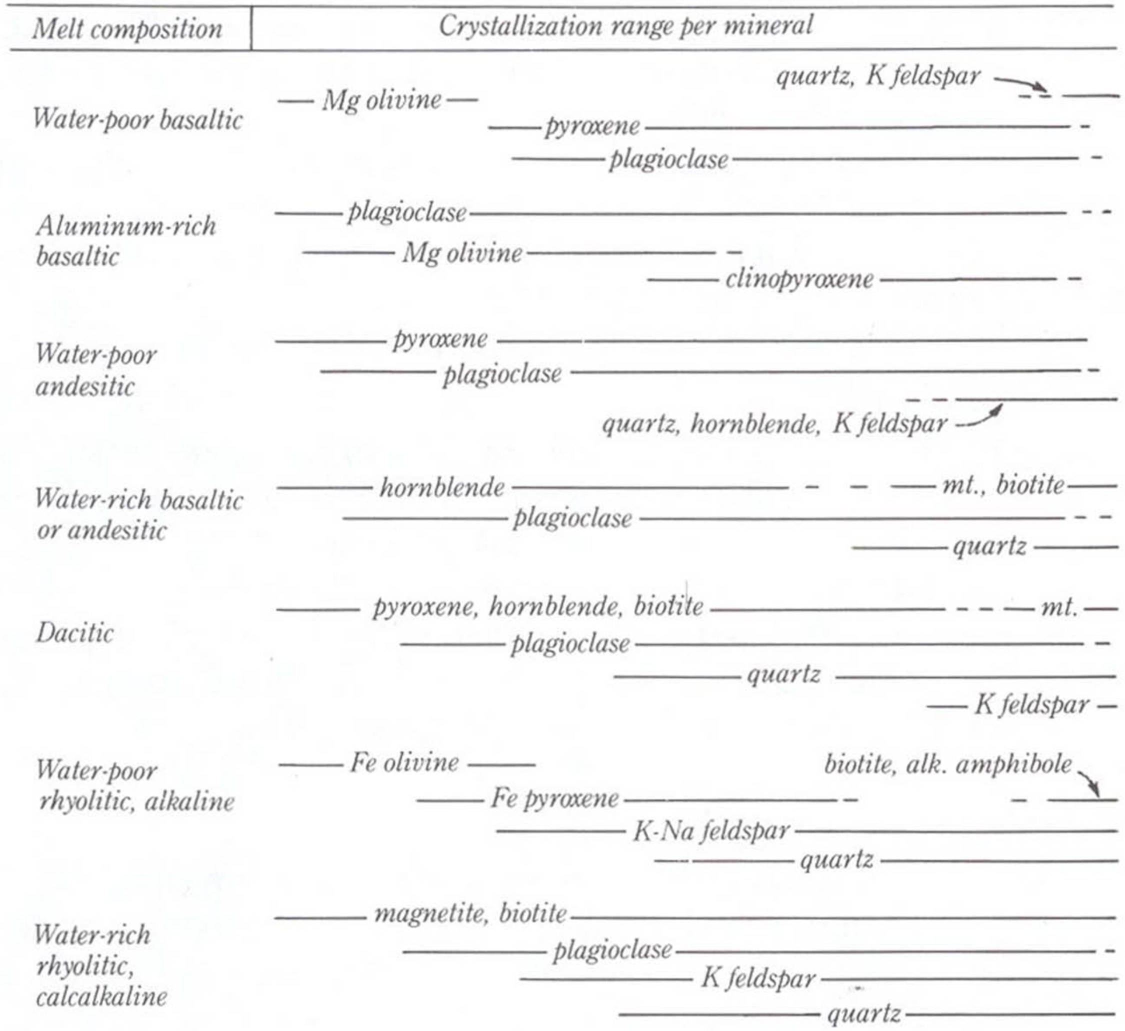


**Fig. 4-12.** Typical crystallization sequences of common silicate melts in the upper crust. Solid lines represent dominant range of crystallization and dashed lines possible additional ranges. Magnetite *(mt)* typically forms early in water-rich melts and may continue to form at later stages. The plutonic equivalents of the seven volcanic melt names are gabbro, plagioclase-rich gabbro, pyroxene diorite, quartz diorite (or quartz gabbro, or mafic tonalite), granodiorite, alkaline granite, and calcalkaline granite.

**Mineral Identification In the Field- Survival Guide!**

Recognition of minerals in hand specimen is a skill which develops in parallel with increasing field experience. The following gives properties of common minerals encountered in the field and hopefully should assist you towards an identification:

**General Rock-Forming Minerals**

***Quartz:*** White to pale grey; will not scratch knife blade i.e. hardness of quartz=7; it usually has a glassy appearance not opaque except in veins where it can be milky.

***Calcite:*** White and cleaved ; hardness of ~3 and easily scratched this helps differentiate from quartz; fizzes with dilute HCl.

***Dolomite:*** yellowish brown, hardness ~3.5. fizzes with dilute HCl only when powdered.

***Feldspars:*** Hardness Usually plagioclase is white and potassium feldspar (orthoclase) is pink. Easy to distinguish from quartz as they are usually opaque not glassy like quartz. They maybe replaced by epidote (especially plagioclase) which imparts an apple green color.

***Pyroxene:*** Hardness of 5-6; Typically dark green-black in color. forms prismatic crystals. Two cleavages at 90 degrees if you can see them.

***Amphiboles :*** Hardness 5-6 easy to confuse with pyroxene but have two cleavages at 120 degrees. Hornblende the most commonly encountered may be green or black often forms long prisms or needles.

***Epidote:*** Hardness 6; green color usually in veins or replacing feldspar.

***Serpentine:*** Hardness 4-6. It has a waxy luster and occurs in structureless masses i.e. it is massive in hand specimen. Formed in the marble from hydration of olivine variant forsterite (鎂橄欖石).

***Chlorite:*** Hardness ~2; Pale to dark green; found on fault planes and as an alteration of mafic silicates.

***Micas:*** Hardness 2.5 easily scratched - Biotite (dark brown) and Muscovite (silvery grey) are most commonly encountered. Two of the easiest to identify in the field.

**Metamorphic Minerals**

***Garnet*** (石榴子石 ): Hardness 6-7.5; Reddish to dark brown, usually forms equant grains.
***Andalusite*** (紅柱石 ): Hardness 7. Pink or white in color. Elongate prisms with square looking basal sections.
***Sillimanite*** (矽線石): Hardness 7. White with pearly luster. Sometimes occurs as bundles of fibers (fibrolite, 細矽線石) several mm across.
***Cordierite*** (董青石): Hardness 7. Porphyroblasts (斑狀變晶) up to 2 cm across can be sometimes observed cordierite is commonly pinitised (塊雲母化).
***Staurolite*** (十字石 ): Hardness 7. Golden brown prisms in pelites.

This list is not comprehensive but should help for the most common minerals.

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## Igneous rock classification (see the following figures):

To use the diagrams:
(1) Select the triangle with the appropriate minerals at its corners;
(2) Use the percentages of any two of these minerals to form a ratio (for example, if mineral A is 5% and mineral B is 20%, the ratio is 1:4);
(3) Use the ratio to locate a point on the appropriate side of the triangle (at a ratio of 1:4 it would be 1/5th of the distance from corner B to corner A;
(4) Do similarly for either of the other two mineral pairs;
(5) Draw of visualize lines passing from the two points to the opposite corners;
(6) Use the intersection of the lines to plot or visualize a point, which will serve to name the rock.

Example: use the diagram of plutonic rock classification (phaneritic texture). A rock is of the mineral composition: Q:5%, A:20%, P:60%. What is name of this rock?

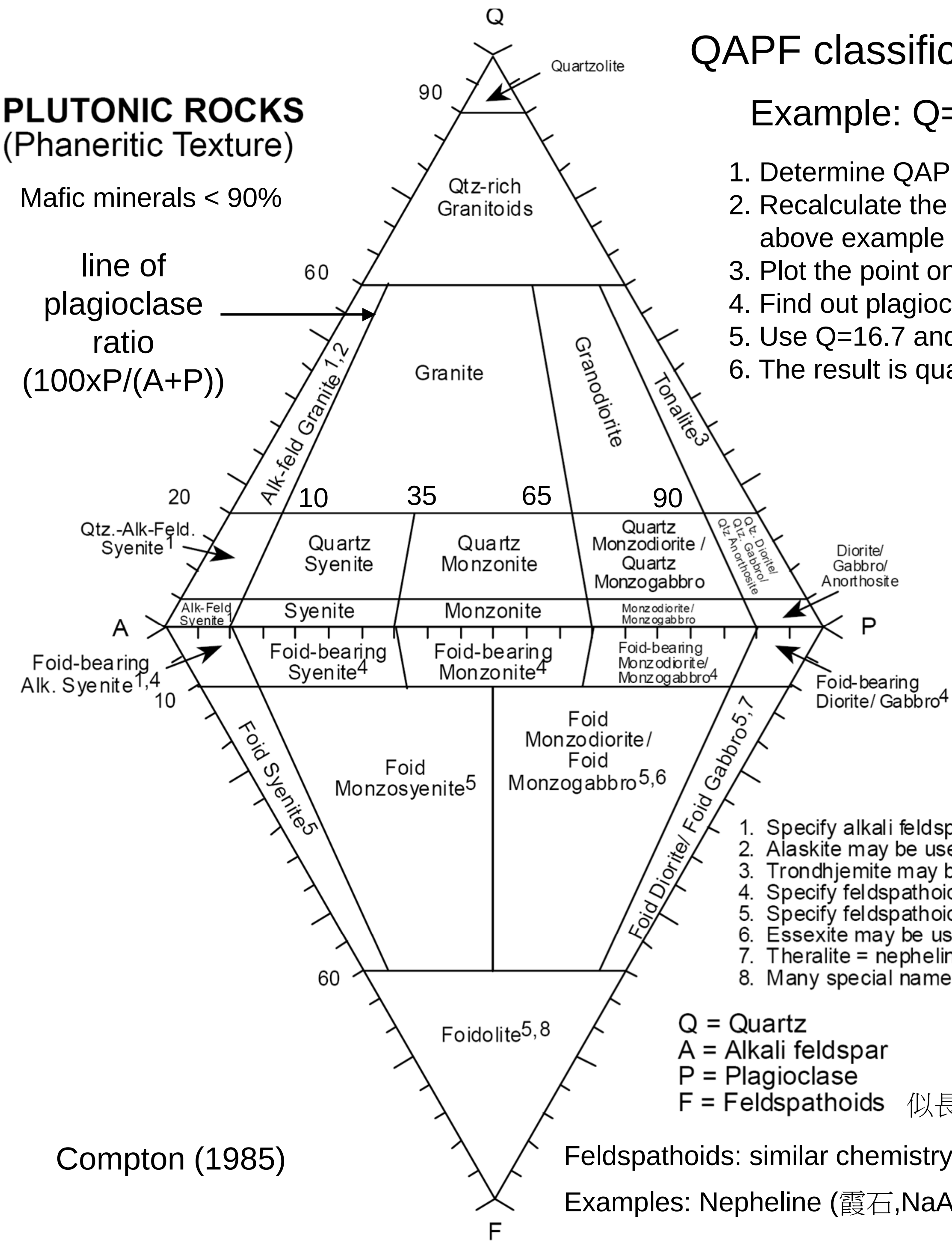
# QAPF classification recommended by IUGS

## Example: Q=10%, A=30%, P=20%, M=40%

1. Determine QAPF percentage. (Q & F are mutually exclusive).
2. Recalculate the QAPF percentage so that their sum is 100%. The above example yields Q=100x10/(10+30+20)=16.7; A=50.0; P=33.3
3. Plot the point on the diagram. Or
4. Find out plagioclase ratio=100xP/(A+P)=100x20/(30+20)=40
5. Use Q=16.7 and Plagioclase ratio=40 to plot a point on the diagram.
6. The result is quartz monzonite.

**PLUTONIC ROCKS**
(Phaneritic Texture)

Mafic minerals < 90%




Compton (1985)

Granitoid: 花崗質岩
Granite: 花崗岩
Granodiorite: 花崗閃長岩
Syenite: 正長岩
Monzonite: 二長岩
Diorite: 閃長岩
Gabbro: 輝長岩
Anorthosite: 鈣長岩
Tonalite:英雲閃長岩

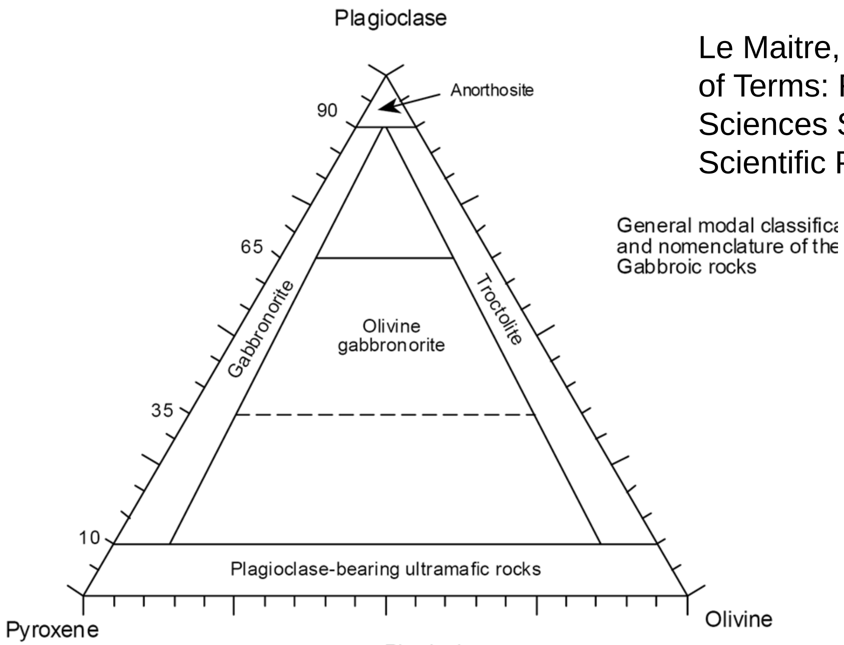
1. Specify alkali feldspar in each case (e.g. orthoclase granite)
2. Alaskite may be used for light coloured alkali-feldspar granite
3. Trondhjemite may be used for light-coloured tonalite that contains oligoclase or andesine
4. Specify feldspathoid(s) present in each case (e.g. nepheline-bearing syenite)
5. Specify feldspathoid(s) present in each case (e.g. nepheline syenite)
6. Essexite may be used for nepheline monzodiorite/ monzogabbro
7. Theralite = nepheline gabbro / Teschenite = analcite gabbro
8. Many special names exist (e.g. nepheline-rich foidolites include urtite & ijolite)

Q = Quartz
A = Alkali feldspar
P = Plagioclase
F = Feldspathoids 似長石(霞石類)

Feldspathoids: similar chemistry and structure to feldspars but with less $SiO_2$

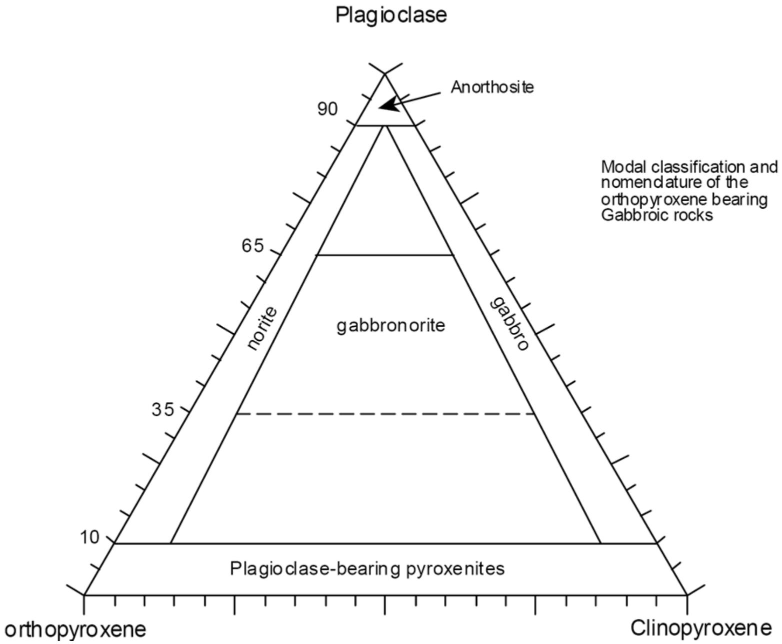
Examples: Nepheline (霞石,$NaAlSiO_4$); Leucite (白榴子石 ，$KAlSi_2O_6$)

# Classification of Gabbroic rocks




Le Maitre, R. W. ed. (1989) A Classification of Igneous Rocks and Glossary of Terms: Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks. Blackwell Scientific Publications, 193pp.

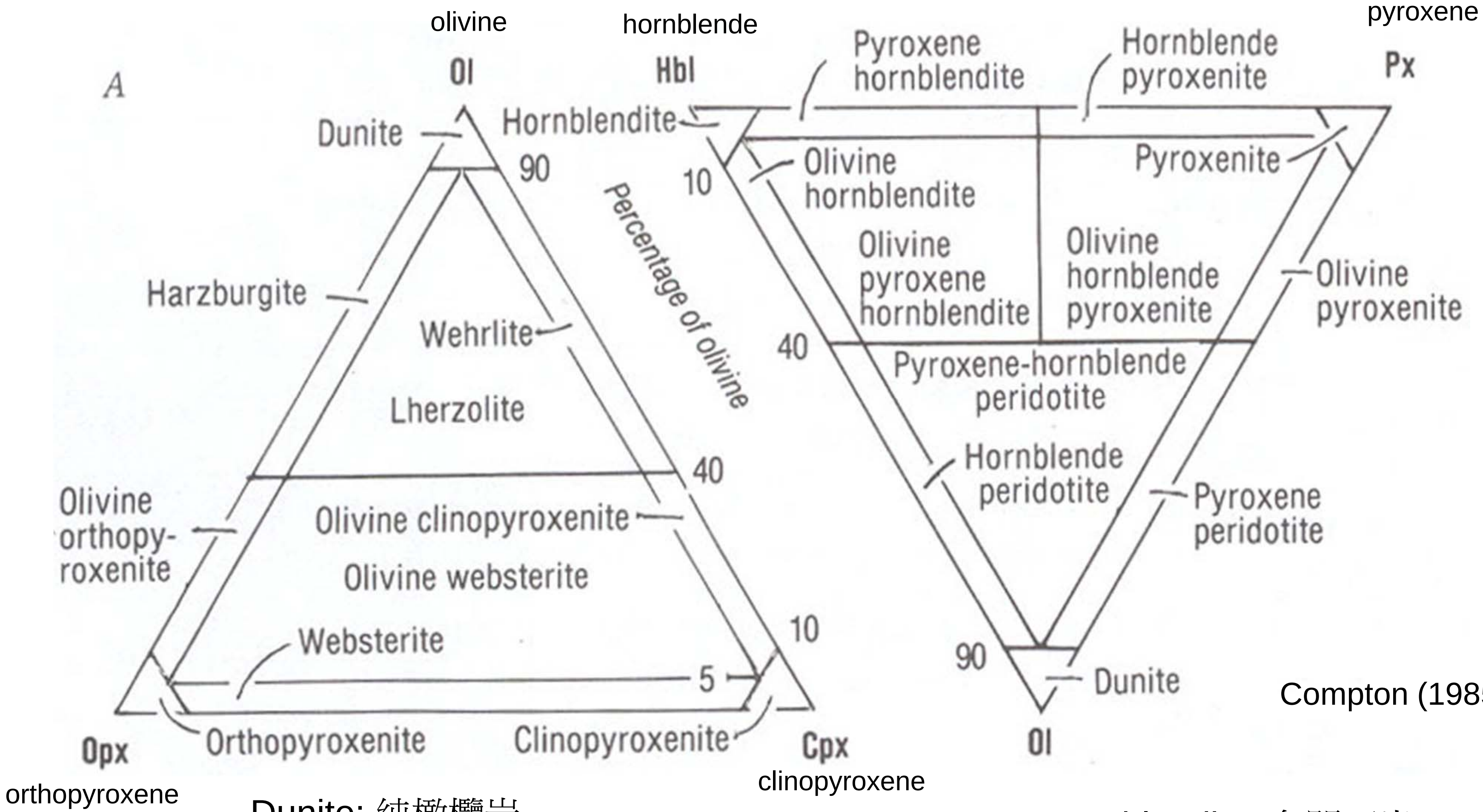
Norite: 蘇長岩
Troctolite: 橄長岩




## Classification of orthopyroxene-bearing Gabbroic rocks

Pyroxenite: 輝石岩

Classification of ultramafic rocks (>90% mafic minerals)




Compton (1985)

Dunite: 純橄欖岩
Harzburgite:斜輝橄欖岩
Orthopyroxenite: 直輝岩
Clinopyroxenite: 斜輝岩
Lherzolite:兩輝橄欖岩
Websterite: 二輝岩

Hornblendite: 角閃石岩
Pyroxenite:輝石岩
Peridotite:橄欖岩

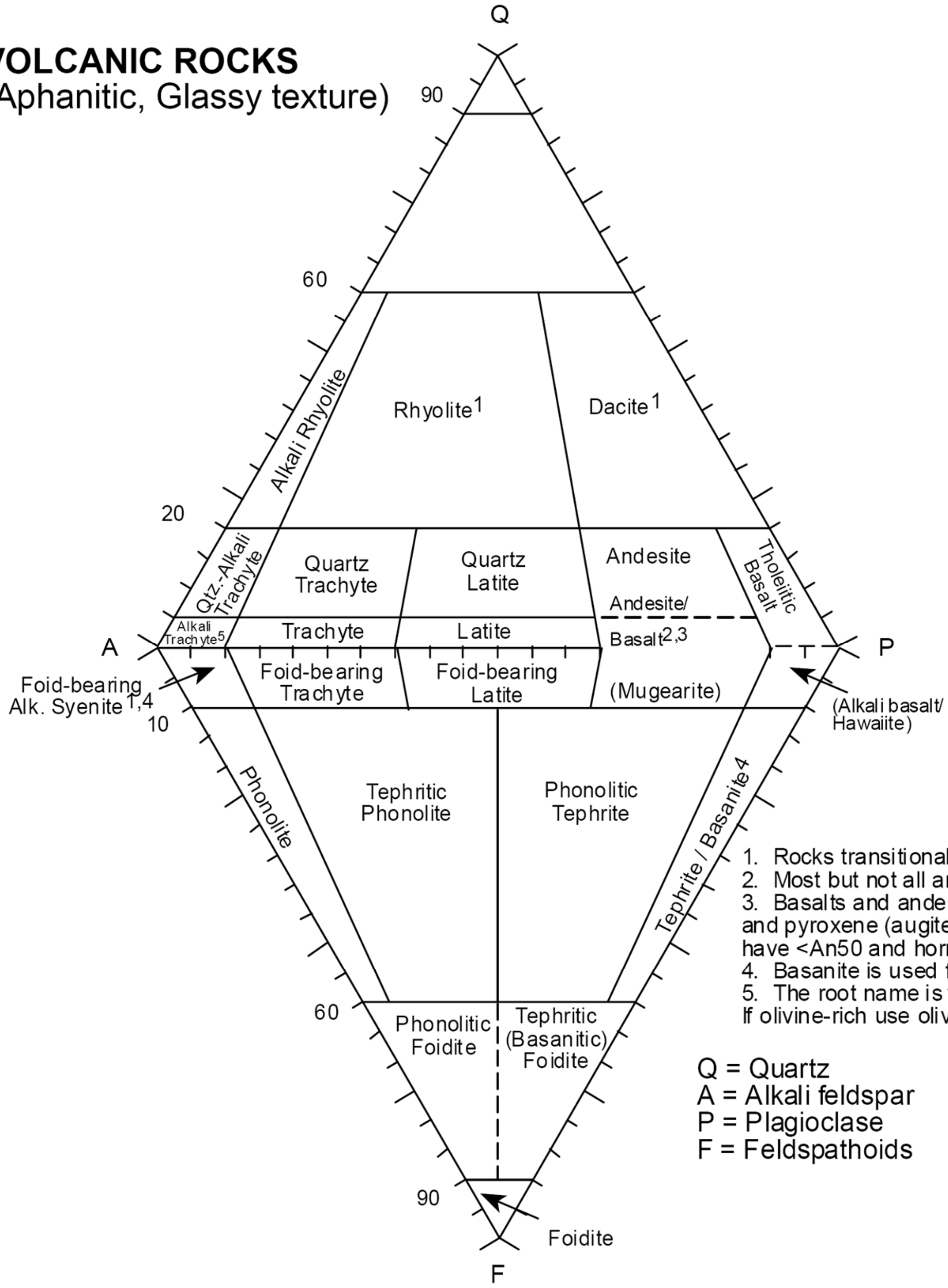
**Table 4-2.** Naming Volcanic Rocks on the Basis of Phenocrysts.

| | | | |
|---|---|---|---|
| Rocks with quartz | Alkali feldspar : plagioclase ratio typically > 1:2; biotite or pyroxene generally < 5% | RHYOLITE | 流紋岩 |
| | Alkali feldspar : plagioclase ratio < 1:2 and alkali feldspar commonly absent; quartz may be scarce; hornblende, pyroxene, and biotite all likely | DACITE | 石英安山岩 |
| Rocks without quartz, feldspathoids, melilite, or analcite | Alkali feldspar : plagioclase ratio > 4:1; biotite or pyroxene ± scarce olivine | TRACHYTE | 粗面岩 |
| | Alkali feldspar : plagioclase ratio < 4:1; hornblende, biotite, or pyroxene ± scarce olivine | LATITE | 二長安山岩 |
| | Alkali feldspar absent; plagioclase abundant; pyroxene and (or) hornblende ± scarce olivine | ANDESITE | 安山岩 |
| | Olivine and plagioclase abundant (high-alumina basalt), or pyroxene abundant and plagioclase and olivine abundant to scarce | BASALT | 玄武岩 |
| Rocks with feldspathoids, melilite, or analcite | Alkali feldspar abundant and > plagioclase; pyroxene, biotite, and amphiboles all possible | PHONOLITE | 響岩 |
| | Plagioclase abundant and > alkali feldspar; clinopyroxene abundant; no olivine | TEPHRITE | 鹼玄岩 |
| | Plagioclase abundant and > alkali feldspar; clinopyroxene abundant; with olivine | BASANITE | 碧玄岩 |
| | Feldspathoids abundant; little or no feldspar; clinopyroxene abundant ± olivine | NEPHELINITE, etc. | 霞石岩 |

Melilite: 方柱石
Analcite:方沸石

Compton (1985)

## VOLCANIC ROCKS
(Aphanitic, Glassy texture)




1. Rocks transitional between rhyolite and dacite are termed rhyodacites
2. Most but not all andesites fall in the field indicated
3. Basalts and andesites distinguished by basalts containing plagioclase compositions >An50 and pyroxene (augite or hypersthene) or olivine as the main mafic phases, whereas andesites have <An50 and hornblende or hypersthene as the main mafic phases
4. Basanite is used for rocks with >5% olivine
5. The root name is foidite but the feldspathoid(s) present must be specified (e.g. nephelinite). If olivine-rich use olivine nephelinite etc.

Q = Quartz
A = Alkali feldspar
P = Plagioclase
F = Feldspathoids

# Pyroclastic materials/rocks

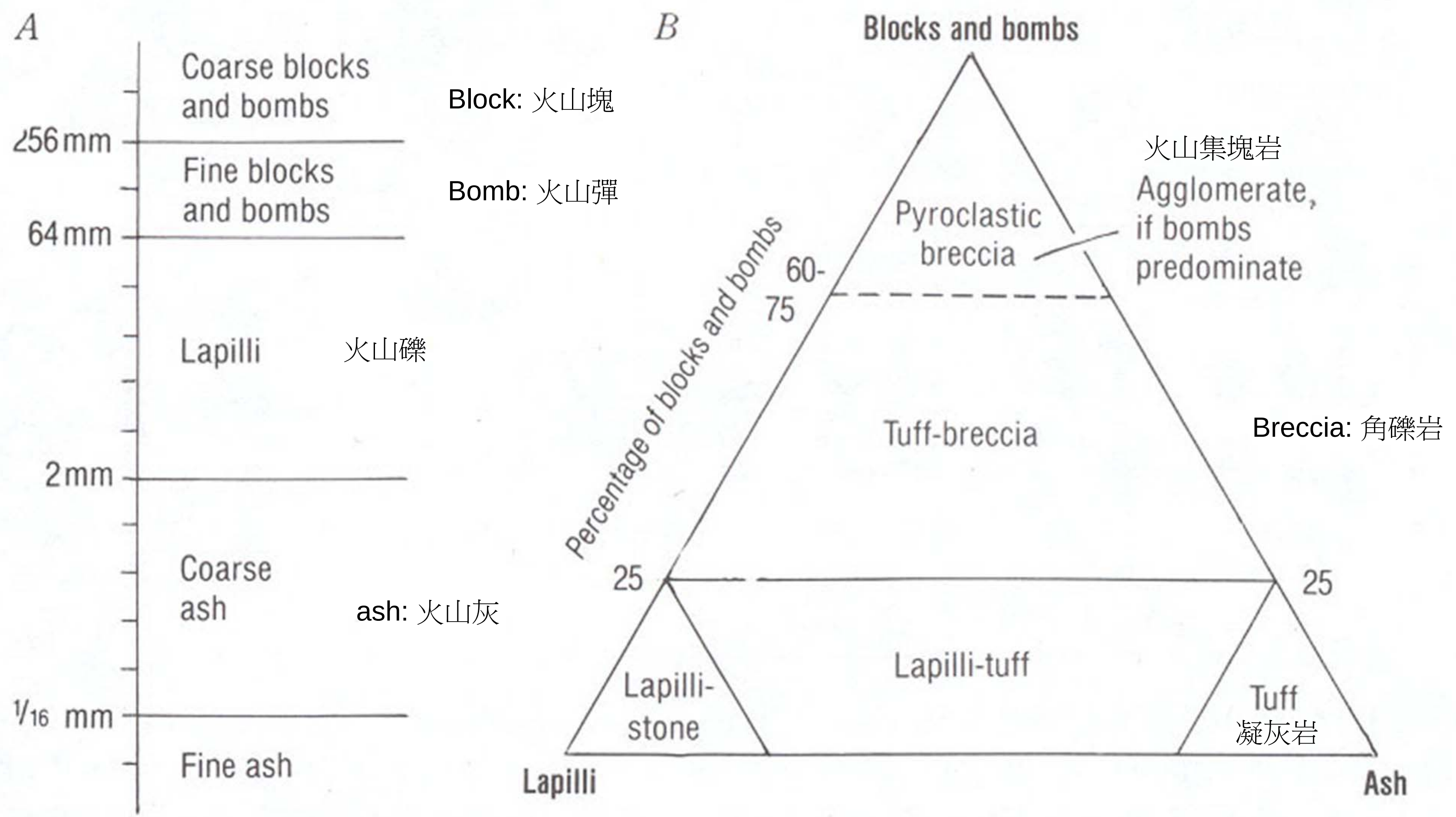



**Fig. 4-16.** Names for size categories of pyroclastic materials *(A)* and for pyroclastic rocks *(B)*. The dashed boundary in *B* is somewhat arbitrary (see Fisher and Schmincke, 1984, p. 92). *A* is after Fisher (1961) and *B* after Fisher (1966), with permission.

Compton (1985)

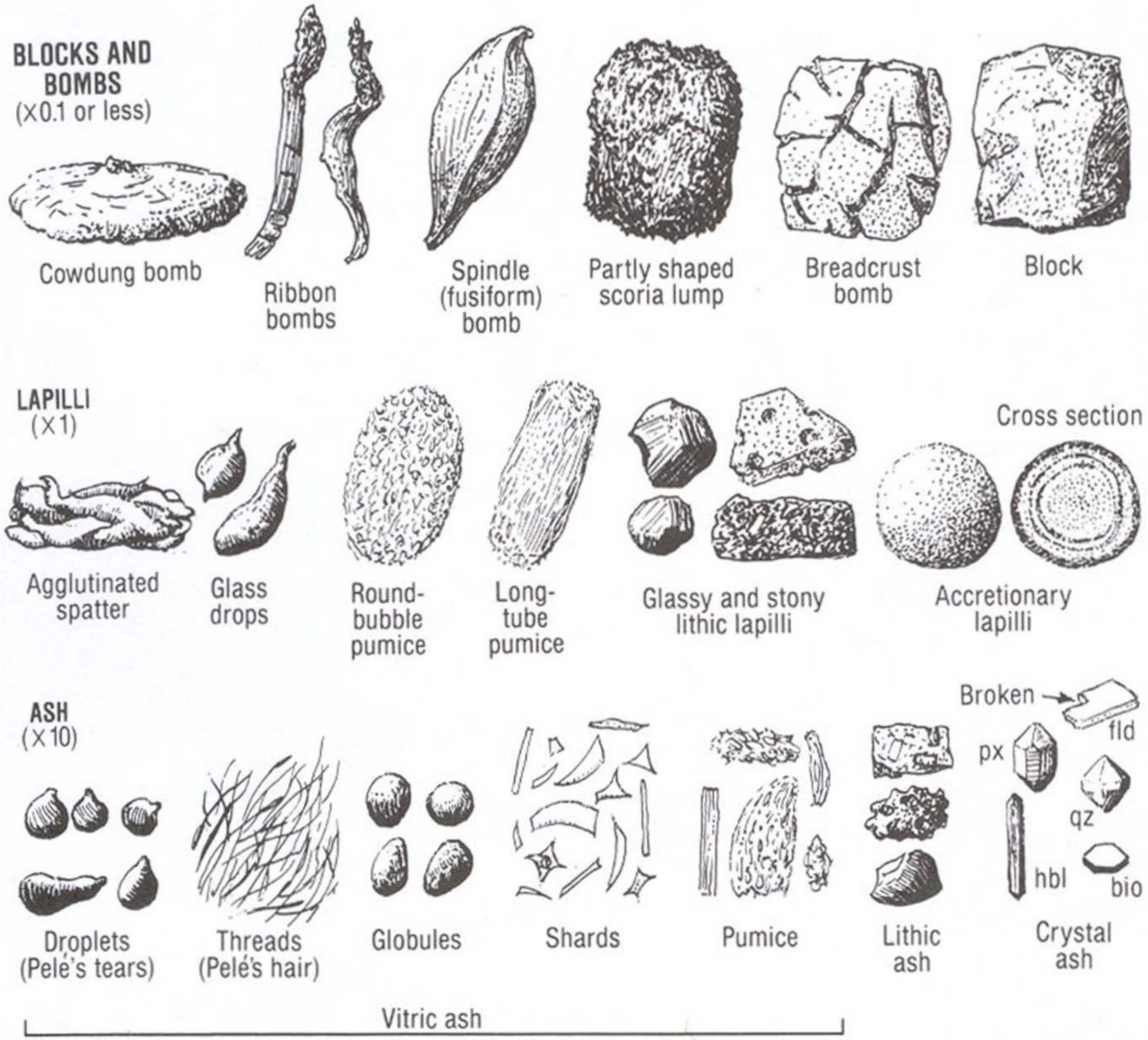


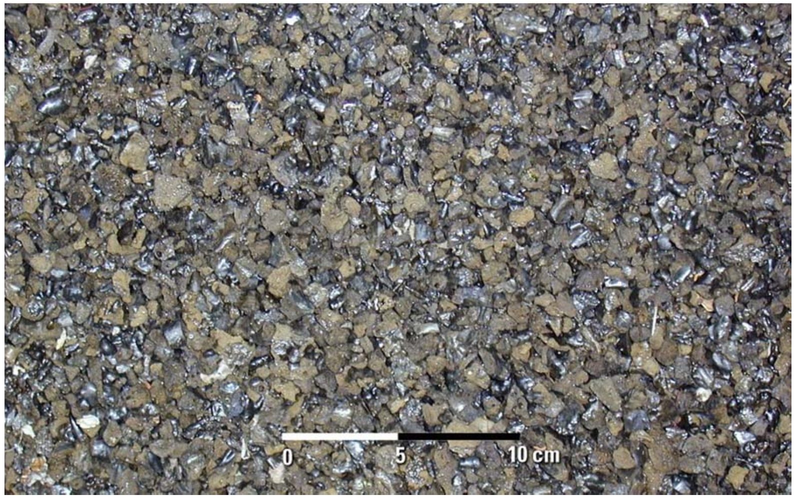

**Fig. 4-17.** Kinds of tephra (pyroclasts). In each row, viscosity increases from left to right. The cracked surface of breadcrust bombs is due to expansion of their interiors. Pumice and most shards result from vesiculation and disintegration of melt, and accretionary lapilli form by adhesion of fine ash in wet eruption clouds (Moore and Peck, 1962). The block and other lithic fragments are solid rocks derived from vent walls or beneath the volcano; some may be xenoliths brought up from great depths. Crystal ash may be of euhedra, as shown, but is more commonly of mineral fragments.

## Kinds of pyroclasts

Pyroclastic debris consists of pumice(浮石) , scoria(火山渣), glass shards, crystals, and accessory lithic fragments. All of this material is explosively ejectively ejected from vents and then falls or flows in air or water under the influence of gravity.

Compton (1985)

These basaltic lava bombs were erupted by Mauna Kea Volcano, Hawai`i.




This lapilli was erupted by Pu`u Pua`i (gushing hill) from the summit of Kilauea Volcano in 1959 and fell to the ground about 800 m downwind.

http://volcanoes.usgs.gov

Layer of tephra consisting of accretionary lapilli surrounded by wind-deposited ash in the Ka`u Desert, Kilauea Volcano. This layer is one of several found at this location, about 10 km from Kilauea's summit caldera.

A car-sized volcanic block.石梯坪, Coastal Range

# Pyroclastic Deposits produced by explosions

Three genetic kinds of pyroclastic deposits, from bottom to top:

1. Base surge deposits: accumulated from clouds that are initiated by strong explosions and sweep outward along the ground at hurricane velocities.
2. Pyroclastic flow: formed from hot debris streams and the turbulent clouds that rise above them.
3. Airfall (or fallout) deposits: material falling from high eruption clouds.

Pyroclastic flow

Compton (1985)

Impact structure

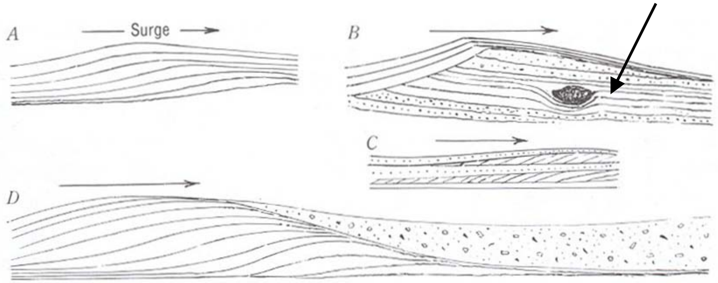



Fig. 13-9. Depositional structures formed by a base surge current near a vent. *A.* Simple antidune. *B.* Antidune cast onto eroded strata with a bomb sag (impact structure made by a falling block or bomb). *C.* Cross-bedding dipping toward the volcano. *D.* Antidune with unsorted coarse accumulation to its lee.

Base surge deposits

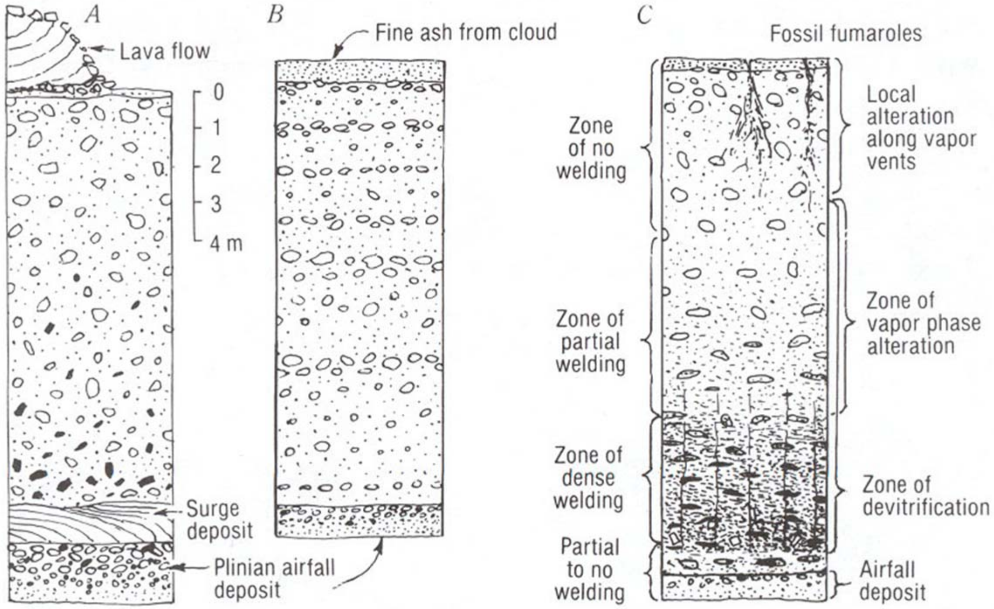
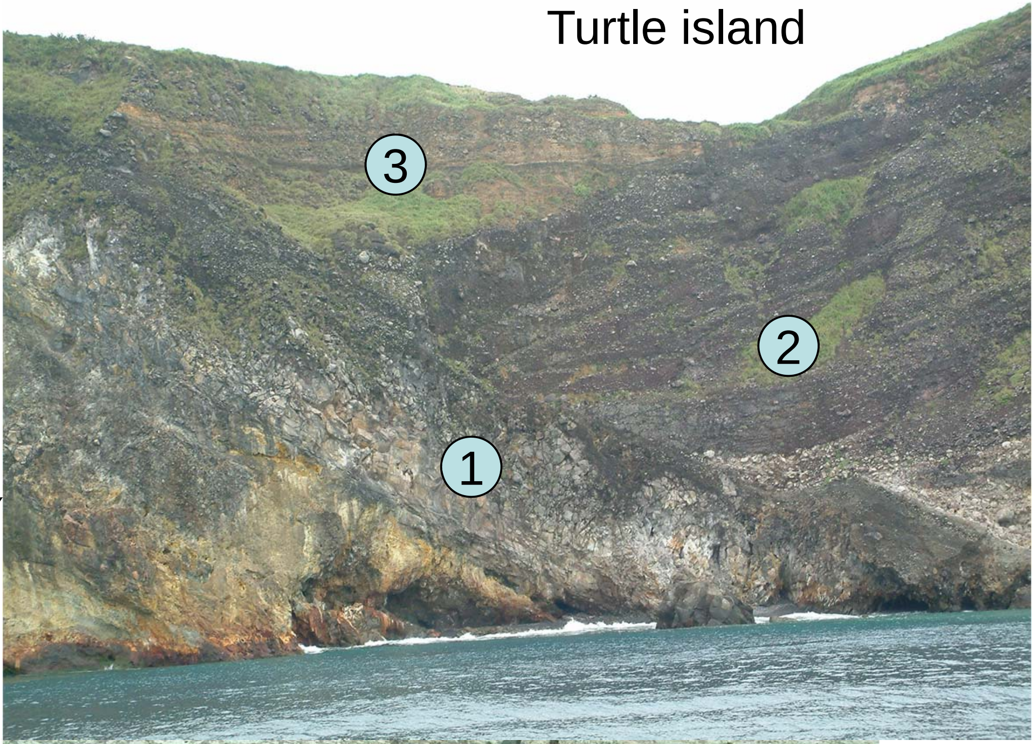
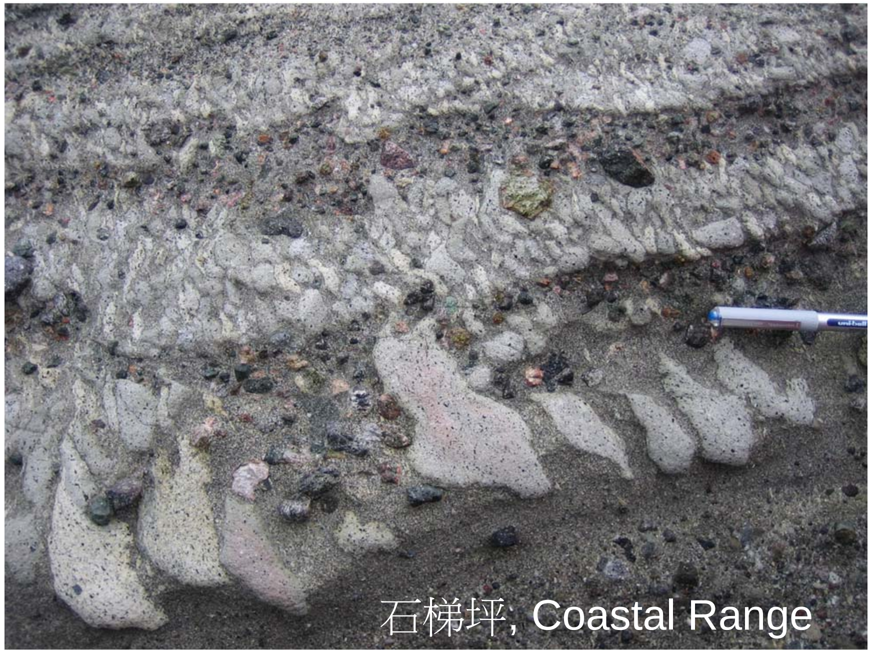



Fig. 13-10. Vertical sections through thick pyroclastic flows near volcano *(A)* and distant from volcano *(B)*, showing idealized textural variations and depositional subunits. Pumice lumps are unpatterned and lithic fragments are black. The layering in *B* may represent separate flows or differentiated flow units within one flow (Sparks, 1976; Sheridan, 1979). *C.* Zones due to welding are labeled on the left and zones due to crystallization and vapor effects on the right. Flattening of pumice lapilli indicates degree of compaction. Smith (1960, plate 20) has illustrated additional vertical arrangements as well as typical lateral variations.

Characteristics of pyroclasitc flow deposits:

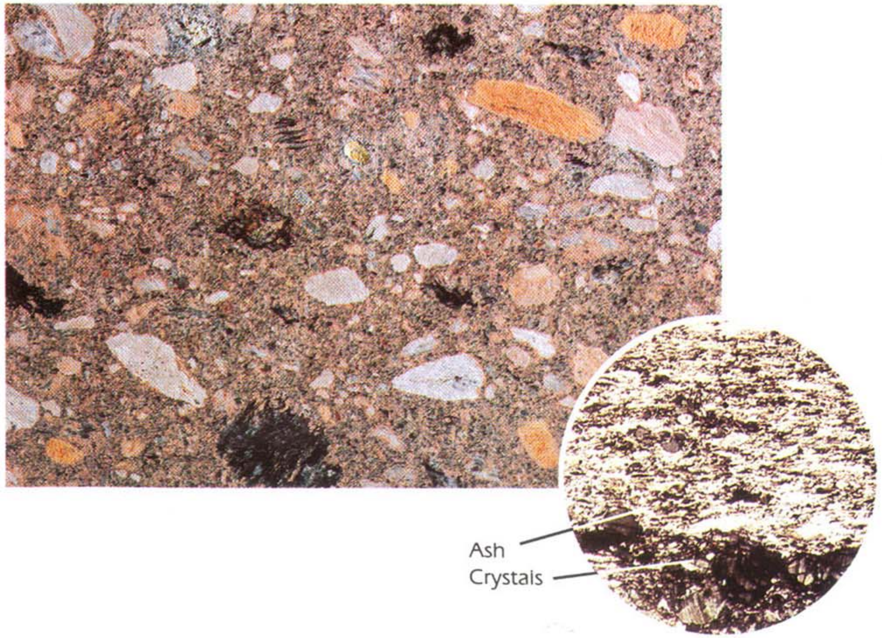
1. Very poor to moderate sorting;
2. Lack of bedding within a single flow unit;
3. Thicknesses of meters to tens of meters;
4. Presence of accessory or accidental lithic fragments;
5. Level or smoothly sloping upper surfaces and uneven (topographic) lower surfaces.





**B. Tuff** is composed of fragments of volcanic material and has a fragmental texture more characteristic of sedimentary rock. It forms from fragmental material and droplets of lava that erupt from volcanic vents and are transported through the air before settling back to the surface. This hot, fragmental material is referred to as pyroclastic. Rocks formed from the consolidation of such material are classified by grain size as follows: (1) *tuff* (fine ash and dust less than .25 inch in diameter), (2) *volcanic breccia* (coarse ash and angular blocks .25–2 inches in diameter), and (3) *agglomerates* (volcanic bombs and blocks greater than 2 inches in diameter). This specimen is composed of coarse fragments of pumice and fine-grained ash.

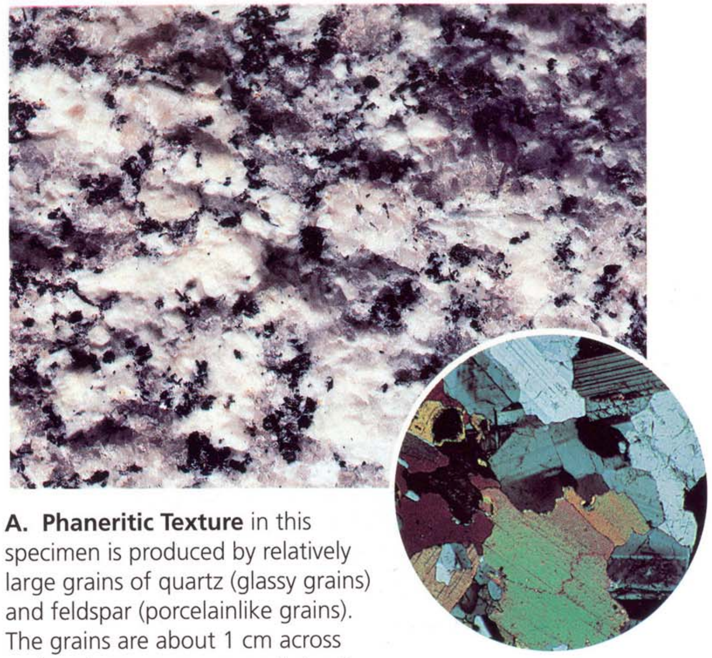



**C. Ash-Flow Tuff** is composed of volcanic ash (fragments of volcanic glass, broken crystals, droplets of lava, and fragments of country rock fused into a tight, coherent mass). It differs from ash-fall tuff (B) in that the fragments were very hot when extruded. As a result, the fragments were fused, flattened, or bent out of shape. This unique texture forms from a cloud of hot, incandescent ash that moves very rapidly, like a flow. The specimen in Figure 3.7B is also an ash-flow tuff.

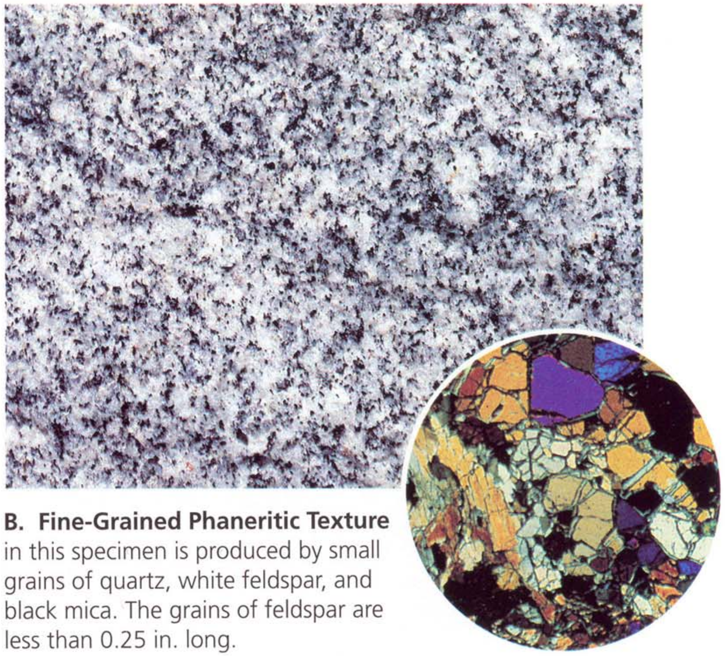
FIGURE 3.13
Other Igneous Rocks

Hamblin & Howard (2002)

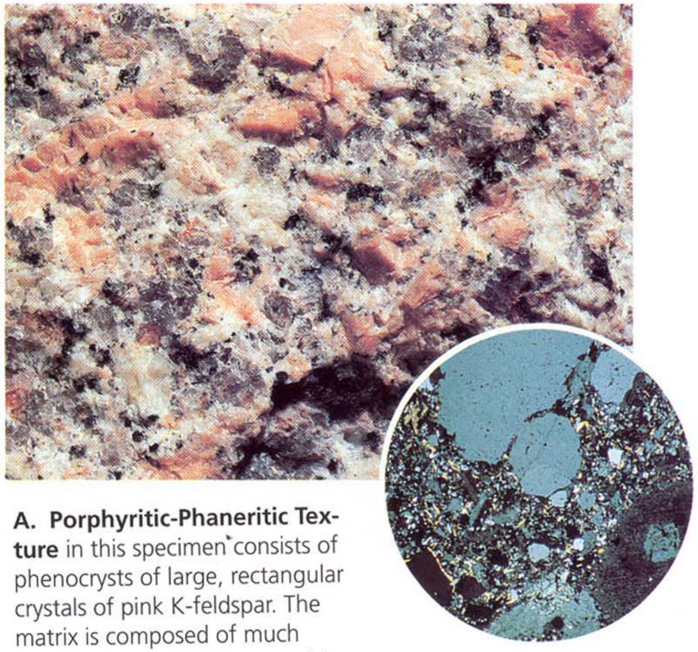
# Textures for igneous rocks



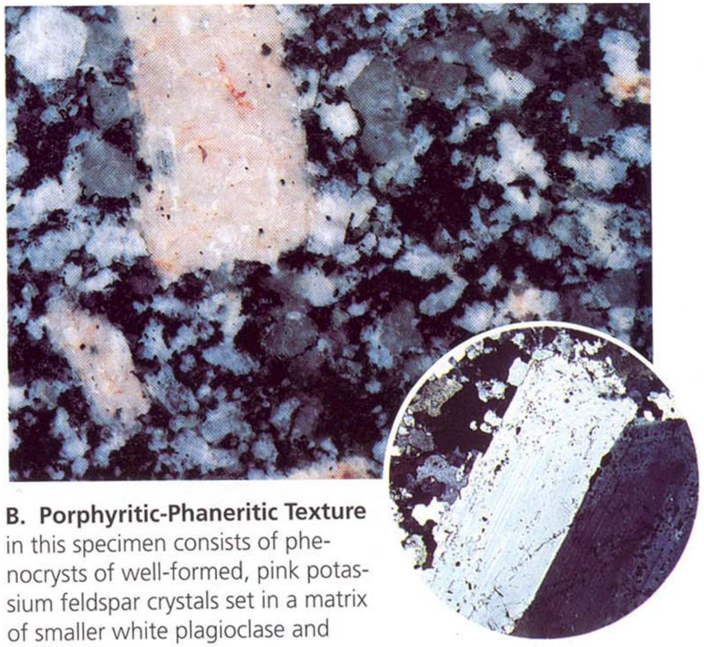
**A. Phaneritic Texture** in this specimen is produced by relatively large grains of quartz (glassy grains) and feldspar (porcelainlike grains). The grains are about 1 cm across and are intergrown, so well-developed crystal faces have not formed. The black grains are biotite.



**B. Fine-Grained Phaneritic Texture** in this specimen is produced by small grains of quartz, white feldspar, and black mica. The grains of feldspar are less than 0.25 in. long.



**A. Porphyritic-Phaneritic Texture** in this specimen consists of phenocrysts of large, rectangular crystals of pink K-feldspar. The matrix is composed of much smaller grains of white porcelainlike plagioclase, smoky quartz, and black ferromagnesian minerals.

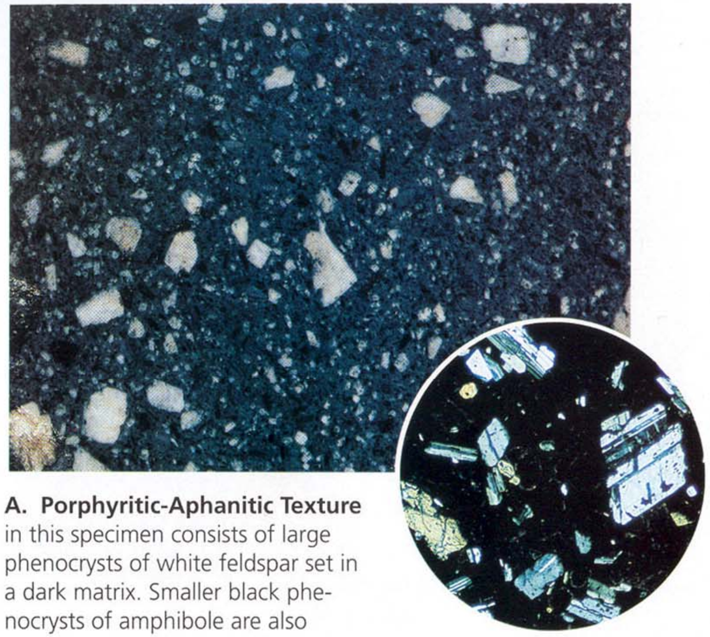


**B. Porphyritic-Phaneritic Texture** in this specimen consists of phenocrysts of well-formed, pink potassium feldspar crystals set in a matrix of smaller white plagioclase and darker minerals.

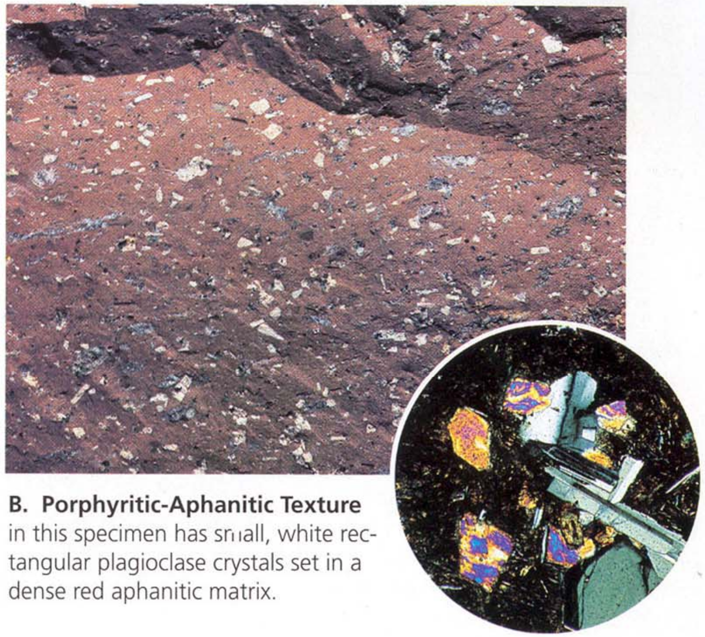
Hamblin & Howard (2002)

**A. Aphanitic Texture** may appear dense and structureless in hand specimens, such as this, but under the microscope individual mineral crystals can be distinguished (See also Figure 3.11A). Note that some secondary crystals have grown in cavities, so a few crystal specks can be seen without a microscope.

**B. Aphanitic Texture** may contain vesicles (holes formed by gas bubbles trapped in the lava as it cooled). This rock is composed of microscopic crystals and is typical of aphanitic texture.

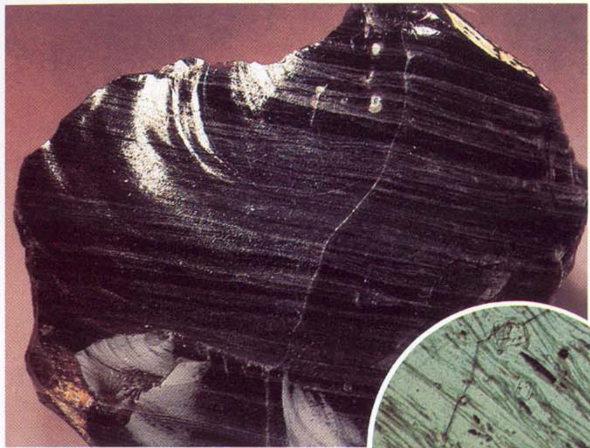
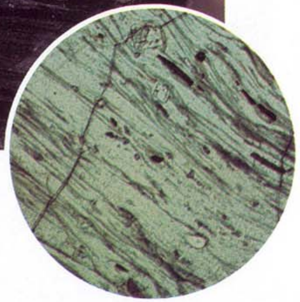


**A. Porphyritic-Aphanitic Texture** in this specimen consists of large phenocrysts of white feldspar set in a dark matrix. Smaller black phenocrysts of amphibole are also apparent. Close study of the dark material indicates aphanitic texture. (See also Figures 3.10B and 3.11B.)

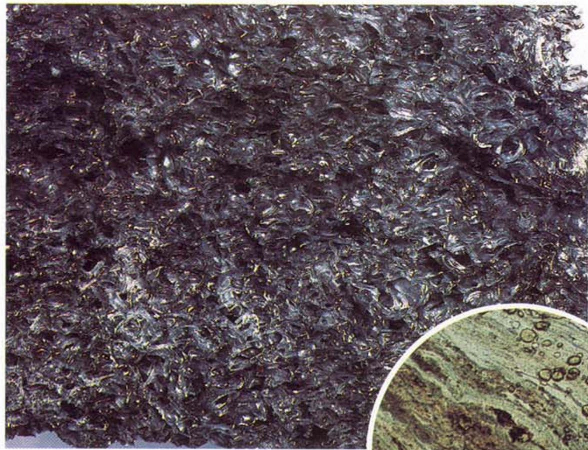


**B. Porphyritic-Aphanitic Texture** in this specimen has small, white rectangular plagioclase crystals set in a dense red aphanitic matrix.

Hamblin & Howard (2002)

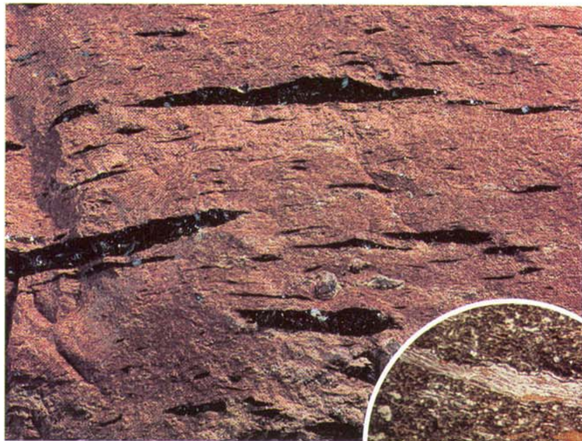
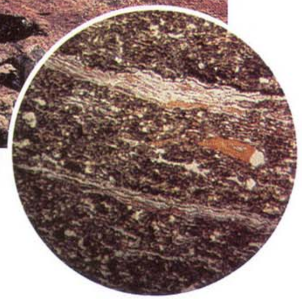



**A. Glassy Texture** in igneous rocks is similar to common glass. It can be dense and massive, as in this specimen, or made of interwoven thread-like filaments, as shown in (B). Note the conchoidal fracture and knife-sharp edges.




**B. Glassy Texture** in this specimen occurs as tangled, thread-like filaments. Pore spaces are produced by gases that escaped as the lava cooled.

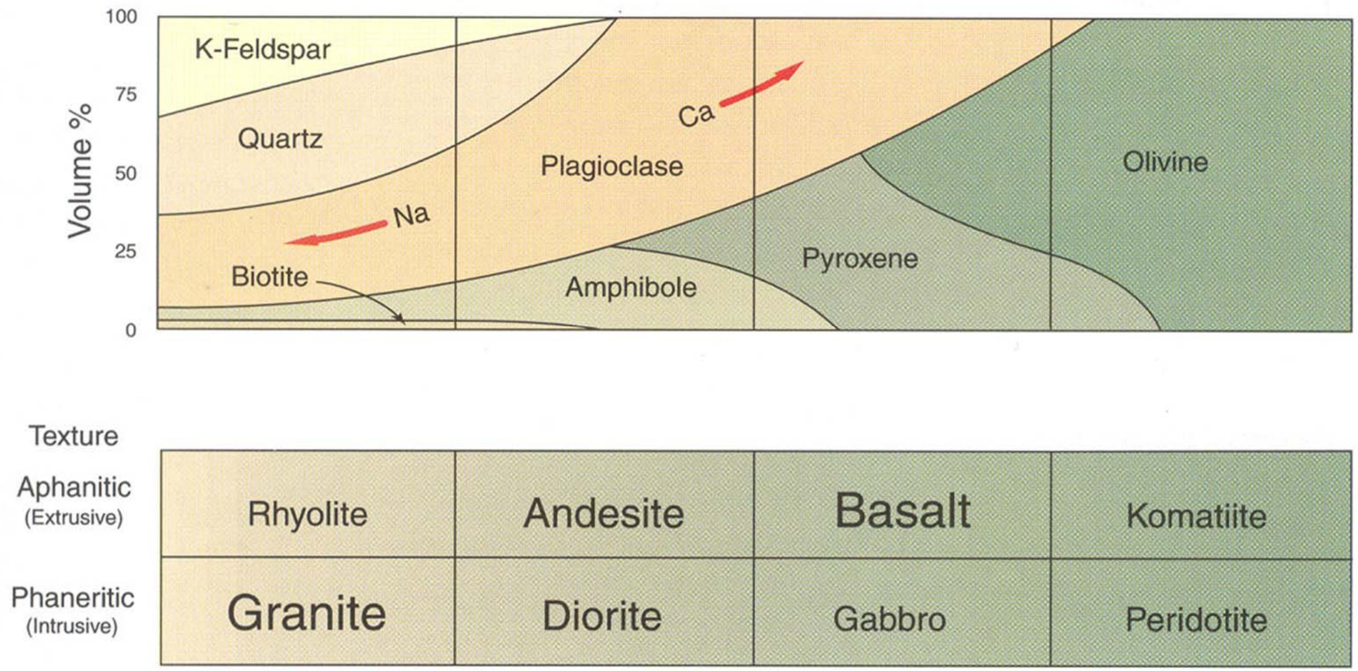

**A. Pyroclastic Texture** in this specimen consists of white, fine-grained volcanic ash with larger fragments of brown pumice and some angular rock fragments. An ash fall produced this texture.

**B. Pyroclastic Texture** produced by an ash flow is commonly dense and massive. Fragmental material in this specimen was very hot when extruded and flowed en masse close to the ground. As the material cooled, the hot particles fused. Black lenses were originally frothy pumice fragments like those in (A) but were so hot that the cellular structure collapsed and the mass became welded into a dense black lens.

Hamblin & Howard (2002)

## Simplified igneous rock classification: (based on composition and texture)



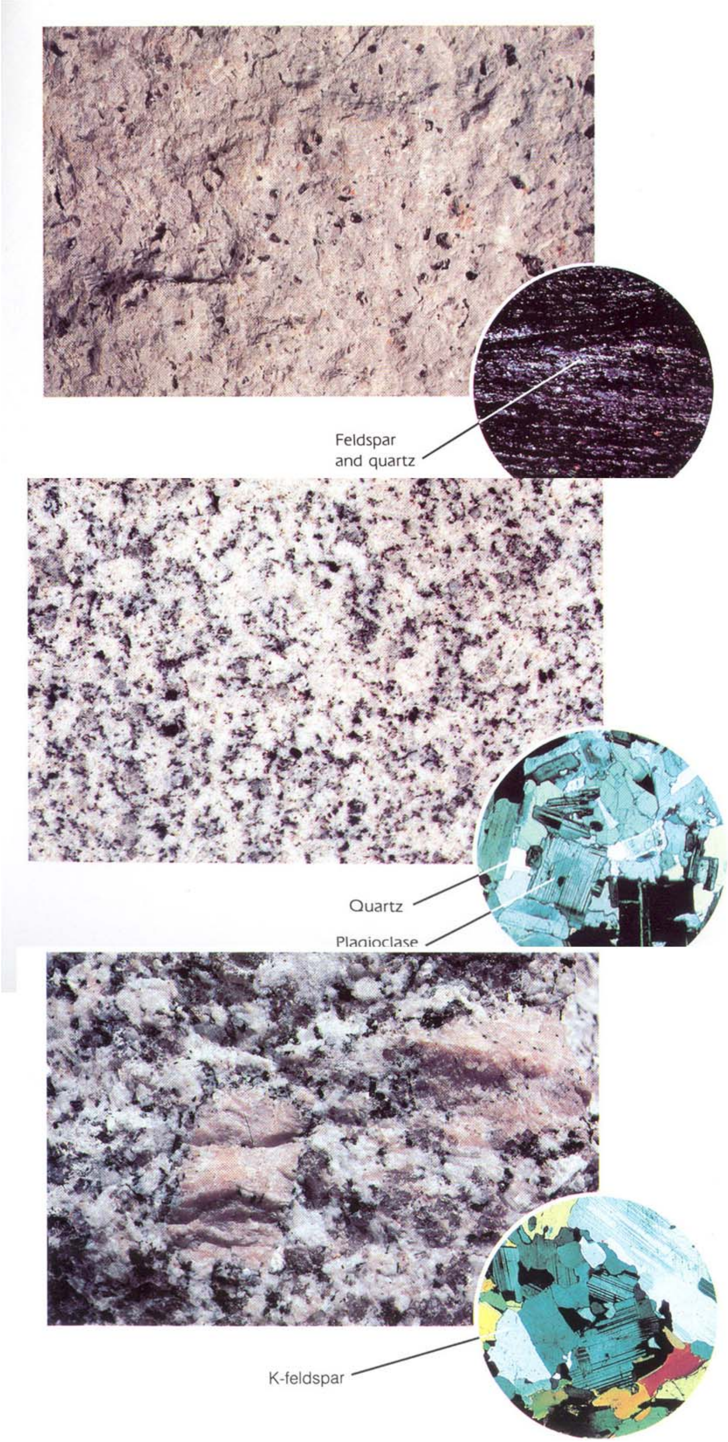

| Granite-rhyolite family: | |
|---|---|
| Quartz | 10-40% |
| Potassium feldspar | 15-30% |
| Plagioclase (high Na) | 0-33% |
| Biotite and amphibole | 8-15% |

| Gabbro-basalt family: | |
|---|---|
| Plagioclase (high Ca) | 25-70% |
| Ferromagnesian minerals (olivine, pyroxene, and amphibole) | 25-75% |

| Diorite-andesite family: | |
|---|---|
| Plagioclase | 55-70% |
| Amphibole and biotite | 15-40% |

| Peridotite family: | |
|---|---|
| Olivine | 65-100% |
| Pyroxene | 0-25% |
| Ca-plagioclase | 0-5% |
| Ore minerals (magnetite, ilmenite, chromite) | 0-10% |

Hamblin & Howard (2002)

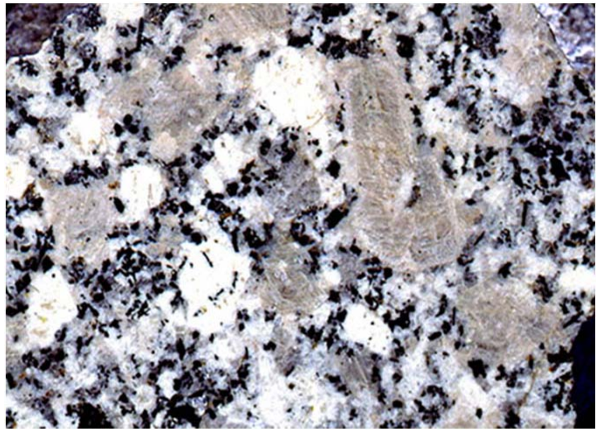



**A. Rhyolite** is an aphanitic rock with the same composition as granite. It is commonly white, gray, or pink in color and almost always contains a few phenocrysts of feldspar or quartz (2–10%). If phenocrysts constitute more than 10% of the volume, the rock is properly termed porphyritic rhyolite. Because the texture is aphanitic, the only minerals that can be identified in a rhyolite hand specimen are those occurring as phenocrysts. This specimen is from a typical porphyritic rhyolite deposit in the western United States. The dark phenocrysts are smoky quartz, but most of the rock has a characteristic aphanitic texture. In thin section, flow structures are commonly apparent, and a considerable amount of glass is present between the fine-grained crystals. The specimen in Figure 3.4A is also a rhyolite.

**B. Granite** is a phaneritic igneous rock composed predominantly of feldspar and quartz. Biotite, amphibole, and plagioclase (early-formed crystals) are generally euhedral (having well-developed crystal faces). In this specimen, white crystals are sodium-rich plagioclase, light-gray glassy grains are smoky quartz, and dark crystals are biotite. Many granites are gray, but if K-feldspar dominates, coloration may be pink or red. Specimens in Figures 3.2A and B are also granites. From one granitic body to another, there may be a wide range in the average crystal size, but the crystals are large enough to be seen without the aid of a microscope.

**C. Porphyritic Granite** usually indicates two stages of cooling: an initial stage in which large crystals formed, followed by a stage in which more rapid cooling developed smaller grains. In this specimen, the phenocrysts are large crystals of pink K-feldspar. The porcelain-white mineral is plagioclase, and the glassy grains are quartz. Small biotite grains are also apparent. Although grain size, color, and general specimen appearance are quite different from the specimen in (B), the composition of the two rocks is essentially the same. Both are composed mostly of quartz, K-feldspar, and calcium plagioclase. The only significant difference is in texture. The specimen in Figure 3.3A is also porphyritic granite.

FIGURE 3.9
Granite-Rhyolite Family



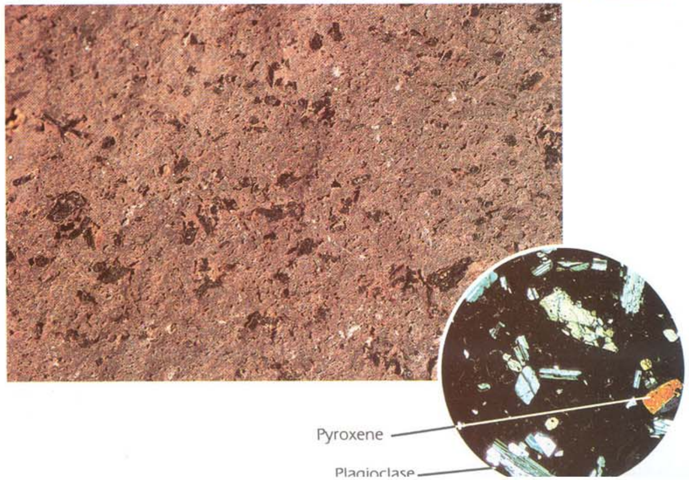
Catalina Granite

This polished surface of a hand specimen is approximately 8 cm across. The Catalina granite is about 28 million years old and outcrops in the Santa Catalina Mountains near Tucson, Arizona. This coarse-grained, porphyritic granite is composed of 35% orthoclase, 30% quartz, 25% plagioclase, 10% biotite, and 510% hornblende. The large phenocryst of orthoclase in the upper right is mantled with sodium plagioclase.

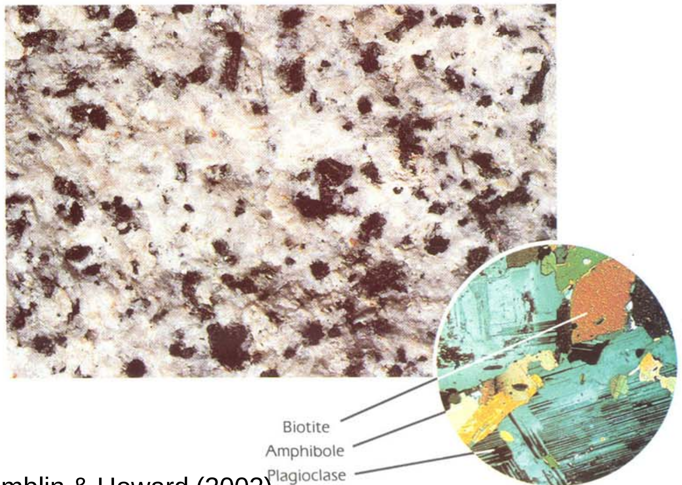
Press & Siever (2000) supplemental CD

Hamblin & Howard (2002) Exercise in Physical Geology, 11th ed. Prentice Hall, 256pp.

**A. Andesite** is an aphanitic rock composed of Na-plagioclase, amphibole, and pyroxene, with little or no quartz. Specimens are generally dark gray, green, brown, or red. The name *andesite* comes from the Andes Mountains in South America, where volcanic eruptions have produced this rock type in great abundance. Andesitic magmas originate in subduction zones by partial melting of the oceanic crust. After basalt, andesite is the most abundant volcanic rock. Completely aphanitic andesite is relatively rare because most flows contain some phenocrysts.



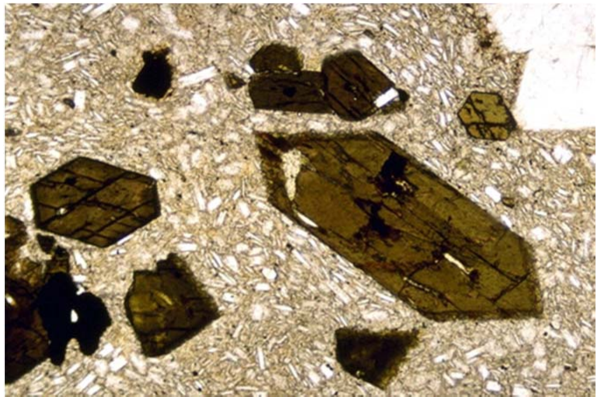

**B. Porphyritic Andesite** is the most common variety of intermediate extrusive rock. Phenocrysts are composed mainly of plagioclase, amphibole, or biotite set in an aphanitic matrix of plagioclase and some glass. In this specimen, black phenocrysts are amphibole. Porphyritic andesite and basalt comprise 95% of all volcanic material. The specimen in Figure 3.5B is also porphyritic andesite.




**C. Diorite** has a texture essentially the same as granite. (Compare this specimen with that in Figure 3.2.) The two differ in composition only. Essential minerals in a granite are K-feldspar, quartz, and Na-plagioclase, whereas diorite is composed predominantly of Na-Ca-plagioclase and ferromagnesian minerals. In this specimen, ferromagnesian minerals (amphibole) are abundant and give it a speckled appearance. In thin section, it is clear that quartz and K-feldspar are absent; plagioclase and amphibole predominate. Quartz accounts for less than 5% of the total volume. Diorite occurs in large intrusives such as stocks or batholiths. It is found also in dikes, sills, and laccoliths.

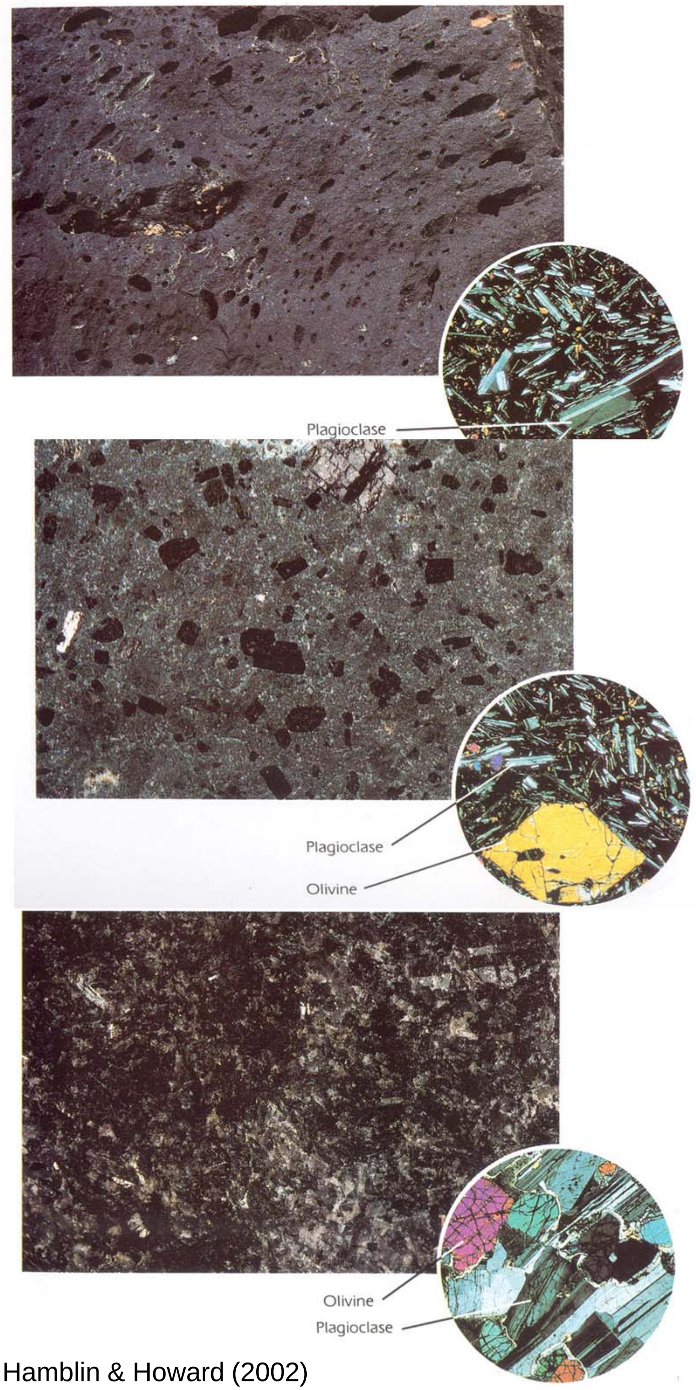
FIGURE 3.10
Diorite-Andesite Family

Hamblin & Howard (2002)



Photomicrograph of porphyritic andesite with phenocrysts of hornblende and plagioclase
Photograph by Peter L. Kresan

Press & Siever (2000) supplemental CD



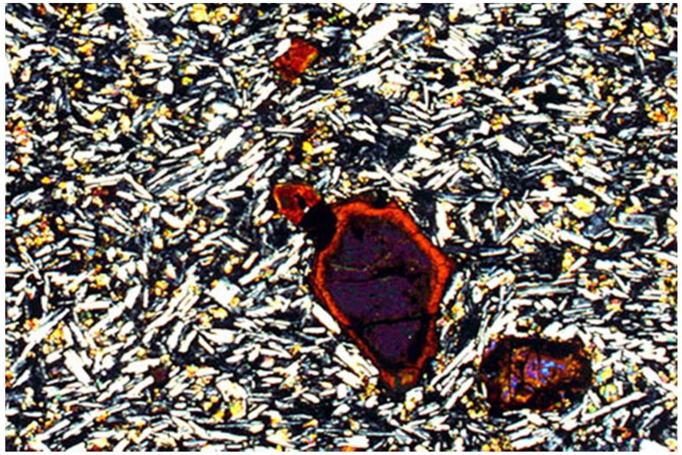

**A. Basalt** is an aphanitic rock composed predominantly of calcium-rich plagioclase and pyroxene, with small amounts of olivine and amphibole. It is characteristically black, dense, and massive. Although individual crystals cannot be seen without magnification, basalt is generally easy to recognize. Many specimens are clinker-like in appearance, with half of the total volume consisting of small holes, or vesicles. Vesicular texture develops as gas bubbles rise toward the top of a flow and are trapped by the overlying cooling crust. Under the microscope, crystals of individual minerals can be seen and studied. Plagioclase crystals commonly occur as a mesh of lath-like crystals surrounding crystals of pyroxene, olivine, or amphibole.

**B. Porphyritic Basalt** is common because many basaltic lavas have some early-formed crystals of olivine, pyroxene, amphibole, or Ca-plagioclase. In this specimen, phenocrysts are amphiboles. Figure 3.5A is also a porphyritic basalt, but phenocrysts are plagioclase. Basalt is the most abundant extrusive rock. It is the bedrock for the oceanic crust and is found also in great floods produced at rift systems on some continents. Basaltic magma forms from partial melting of the upper mantle and is extruded mostly along fissures in rift zones.

**C. Gabbro** has a phaneritic texture similar to granite but is composed almost entirely of pyroxene and Ca-plagioclase, with minor amounts of olivine. Its composition is thus the same as basalt. Calcium-rich plagioclase is the dominant feldspar and usually occurs as dark, elongated crystals, like those in this specimen. Coloration is characteristically dark green, dark gray, or almost black because of the predominance of Ca-plagioclase and ferromagnesian minerals. Gabbro is not common in the continental crust, but large exposures occur north of Duluth, Minnesota, in Labrador, and in Finland. Most gabbro is produced at divergent plate margins and forms the bottom layer of the oceanic crust.

FIGURE 3.11
Gabbro-Basalt Family

Hamblin & Howard (2002)



Photomicrograph of Basalt, 2.53, Under Polarized Light

Compare the grain size in basalt with that of diabase and gabbro. The smaller grains of plagioclase and pyroxene in this photomicrograph are indicative of quickly cooled volcanic rocks. This is a porphyritic basalt. The larger crystal is a phenocryst of olivine with an alternation rim, probably of serpentine. Olivine tends to be unstable in basalt at lower temperatures and pressures and is the first mineral to crystallize from a mafic magma. This crystal grew relatively slowly in the magma while it was still underground and erupted onto the Earth's surface as a crystalline solid in the molten lava. The ring of alteration of the olivine may have protected the interior of the crystal from being completely altered.

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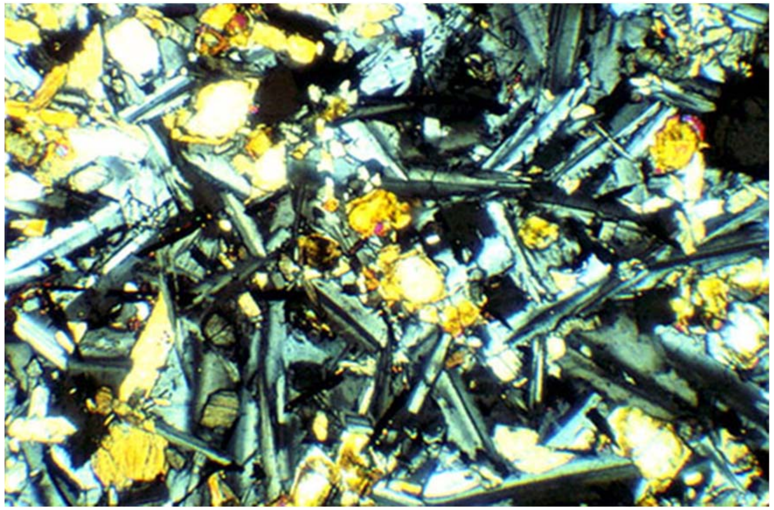
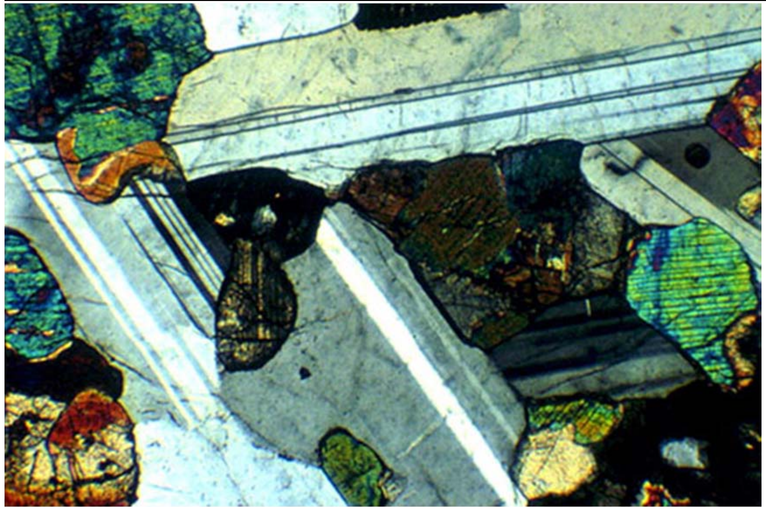
Diabase輝綠岩 (dolerite粗粒玄武岩 ):
A rock intermediate in grain-size between basalt and gabbro and composed essentially of plagioclase, pryoxene and opaque minerals; often with ophitic texture.



Photomicrograph of Diabase, Under Polarized Light
Diabase contains the same minerals as gabbro, but its crystals are smaller because the magma cooled faster. Diabase is a mafic, shallow intrusive rock that typically forms dikes and sills (see the right figure).

Mafic Dike
A mafic dike cuts the Hakatai shale at Hance Rapids, Grand Canyon, Arizona. The red Hakatai shale is even redder along the contact with the dike due to low-grade contact metamorphism of the shale. With a mafic composition and an intermediate rate of crystallization, dikes, like this one, and sills commonly display a texture similar to the left figure.



Photomicrograph of Gabbro, Under Polarized Light

Coarse grains of calcium plagioclase and pyroxene are the most common minerals in this rock. Gabbros may also contain olivine, chromite, and magnetite grains. Gabbro is a mafic plutonic rock and is relatively uncommon on the surface of the Earth.

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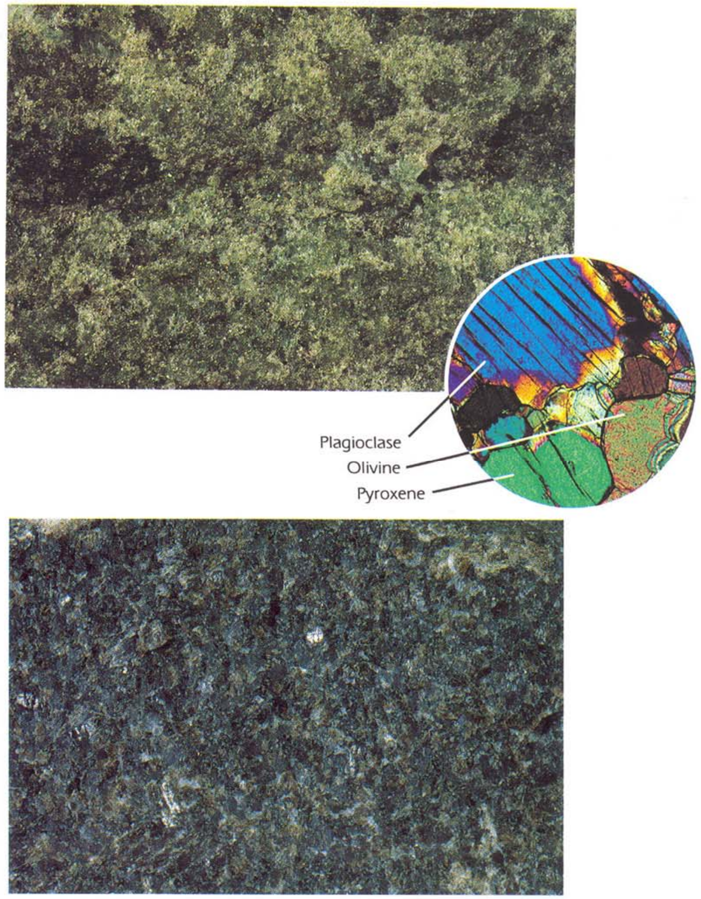



**A. Peridotite** is relatively easy to identify because it is composed almost entirely of olivine; however, significant amounts of pyroxene and lesser amounts of Ca-plagioclase may occur. This specimen is composed mostly of olivine. Olivine crystals are characteristically light green and have a distinctive glassy luster. They are typically equidimensional and are medium to coarse grained, so the rock may resemble a green, glassy sandstone. Rocks of the peridotite family have phaneritic texture and originate far below the surface. No extrusive rocks have an equivalent composition.

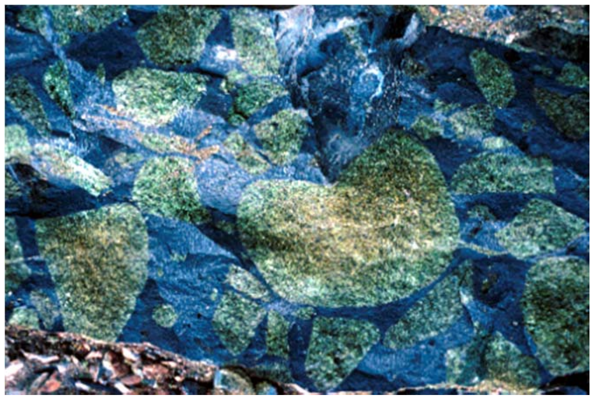
**C. Peridotite** is not an abundant rock type in Earth's crust, but it is important in studying Earth's dynamics because it is believed that the entire upper mantle is composed almost exclusively of this type of rock. Indeed, it is probable that the melting and movement of peridotite in the asthenosphere is intimately involved in the tectonic system.

Hamblin & Howard (2002)

FIGURE 3.12
Ultramafic Rocks

Peridot Mesa, San Carlos, Arizona
Photograph by Peter L. Kresan

Concentrated in the lower half of the flow, the nodules of olivine (the yellow-green patches) are
abundantly displayed in the basalt cliff next to the geologist. San Carlos Apache Indians mine the nodules for gem quality olivine, called peridot. The lava flow is by far the world's best source of gem quality peridot. These nodules may represent the residual solids that are carried up with the material that did melt - the basalt - from the upper mantle. Given more time and heat, these nodules may have melted too (Lynch, 1989).



Nodules of mostly olivine (Lherzolite), varying in size from a few inches to over a foot long, appear in an outcrop of the Peridot Mesa basaltic lava flow. Usually, the olivine occurs as small yellow-green to brown grains about one to a few millimeters in diameter.
The nodules are composed mostly of olivine (forsterite and fayalite) with varying amounts of pyroxene (augite, enstatite, pigeonite and jadeite) and small grains ofspinel. The blue-black matrix is fine-grained basalt.



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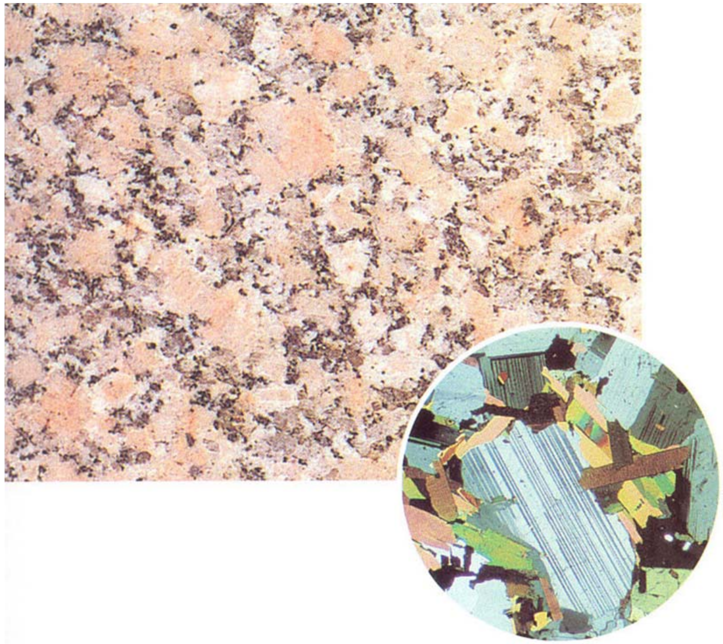
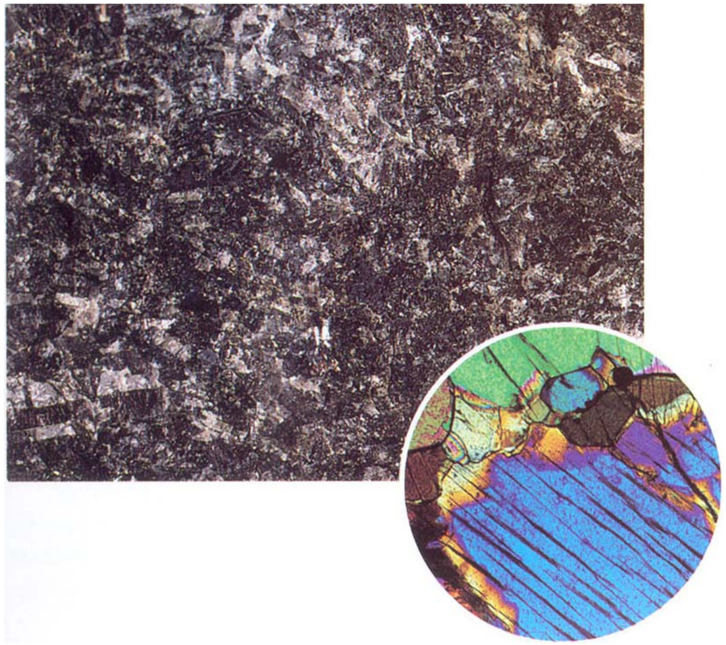


**Composition**

| | |
|---|---|
| K-feldspar | 40% |
| Na-Plagioclase | 30% |
| Quartz | 20% |
| Biotite | 10% |

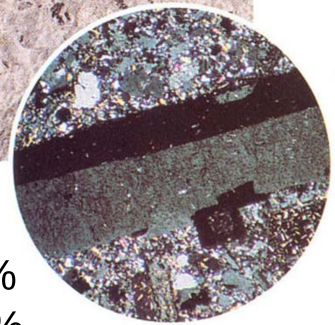
Rock name:
Origin:



**Composition**

| | |
|---|---|
| Ca-Plagioclase | 50% |
| Pyroxene | 45% |
| Olivine | 5% |

Rock name:
Origin:

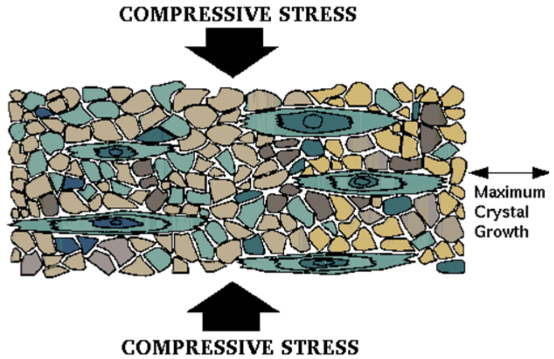


**Composition**

| | |
|---|---|
| K-feldspar | 30% |
| Na-Plagioclase | 25% |
| Quartz | 35% |
| Biotite | 5% |
| Amphibole | 5% |

Rock name:
Origin:

## 3.2.3 Metamorphic rocks




Metamorphic rocks are generated by **recrystallization** of either igneous or sedimentary rocks by the action of any or all of the following: **Pressure, Temperature and Pore Fluids.**

The **lower limit** of metamorphic temperatures is 150 degrees Celsius. The **upper limit** is the melting temperature when magma forms.

The type of metamorphic rock is determined by the **parent rock** and the **P/T conditions**. In general, metamophism causes: (1) *Growth of new minerals; (2) Deformation and rotation of mineral grains*; (3) *Recrystallization of minerals as larger grains; (4) Production of strong brittle rocks or anisotropic rocks.*

Metamorphic rocks need to be described in several ways:

- As metamorphic rocks, with a view to determining the conditions of metamorphism.
- In terms of the original, pre-metamorphic rock type.
- In terms of the deformation processes that in many cases accompany metamorphism.

**DESCRIPTION OF METAMORPHIC ROCK HAND SPECIMENS.**

Make an examination taking account of the following features:

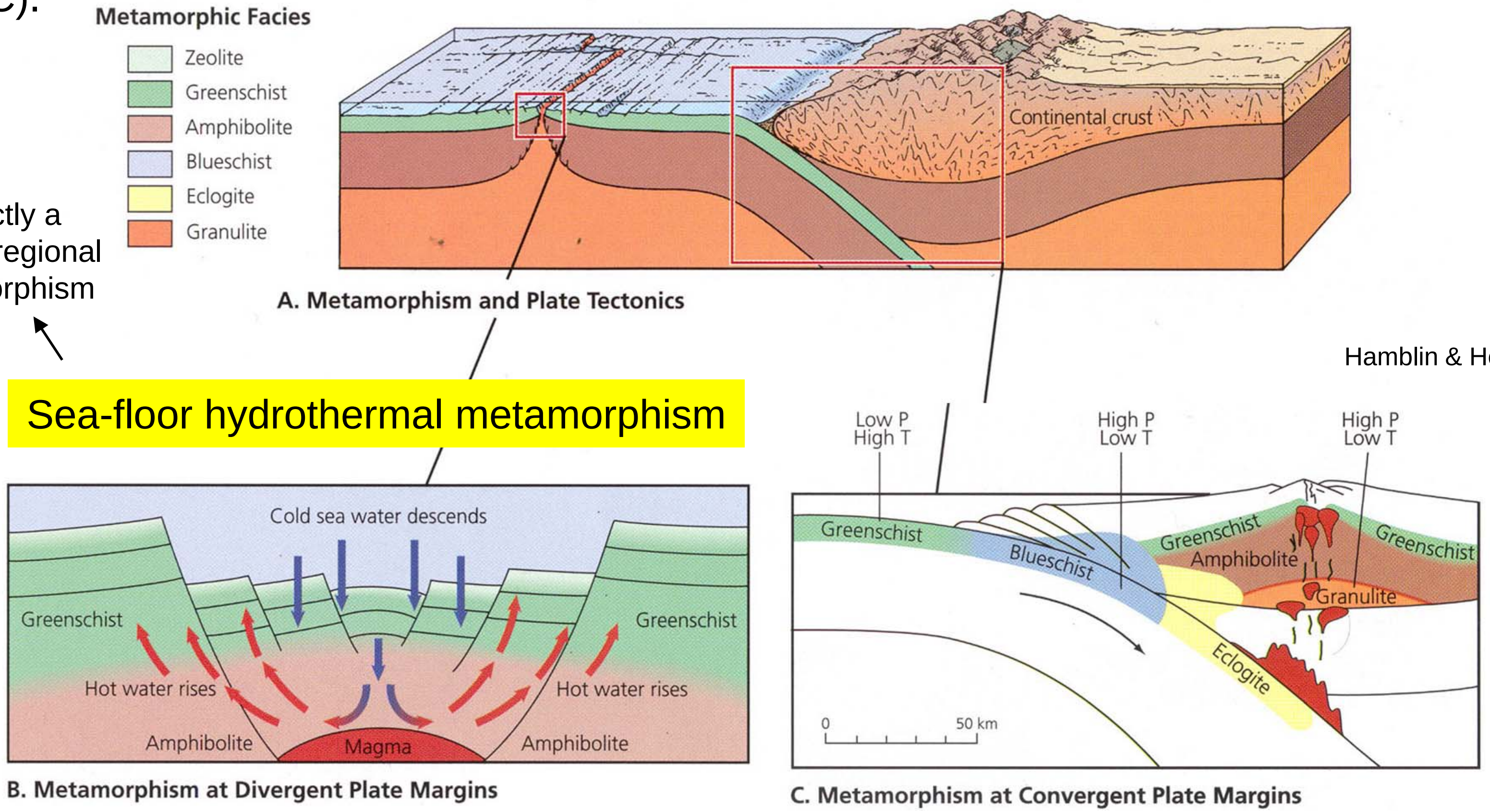
- Composition: by identifying minerals and estimating their relative proportions.
- Structure and microstructure on the outcrop to microscopic (hand lens) scale: compositional layering, relict sedimentary or igneous textures, porphyroblasts, folding/microfolding, preferred orientations, penetrative or spaced cleavages.

Doing this well requires skill and experience, but a good start is made by developing good technique with a hand lens and getting plenty of practice (e.g. on laboratory practical materials).

# METAMORPHIC SETTINGS:

## *1. Regional Metamorphism*

Metamorphic rocks which do not have the relatively localized distribution characteristic of contact or dynamic metamorphism, but which occur on a regional scale, are the products of regional metamorphism. The mineralogy and texture of regional metamorphic rocks generally reflect the influence of both pressure and temperature (regional dynamothermal metamorphism) and tend to be related to orogenesis. Another form of regional metamorphism bears little or no genetic relationship to orogenesis and is produced dominantly by load pressure with temperature playing a subordinate role (regional burial metamorphism, < circa 250°C).




A. Metamorphism and Plate Tectonics

B. Metamorphism at Divergent Plate Margins

C. Metamorphism at Convergent Plate Margins

Not strictly a type of regional metamorphism

Sea-floor hydrothermal metamorphism

Hamblin & Howard (2002)

The following rock names are frequently applied to regional metamorphic rocks:

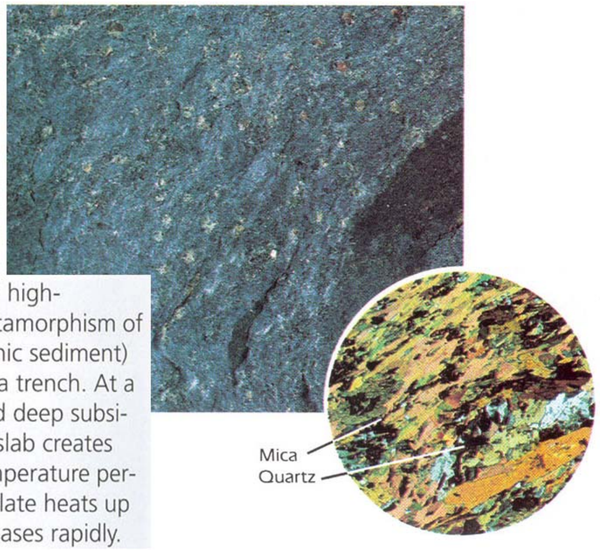
Greenschist (綠片岩) – a schistose rock rich in green minerals such as chlorite, tremolite(透閃石) and epidote (綠簾石) and hence the product of low grade regional metamorphism of pelitic or basic/ultrabasic rocks.

Greenstone (綠岩) – a massive rock rich in green minerals as above. Commonly derived from igneous rocks.

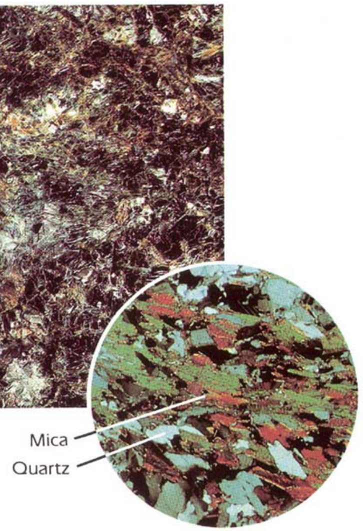
Blueschist (藍片岩) – a schistose rock rich in glaucophane. Formed from pelitic, semi-pelitic and basic rocks in high grade regional metamorphism.

Charnockite (紫蘇花崗岩) - a rock of generally acid composition consisting of quartz, feldspar, hypersthene, garnet and ore. Formed in very high grade regional metamorphism.

Eclogite (榴輝岩) – a basic or ultrabasic rock characterized by the association garnet-clinopyroxene (soda-rich omphacite綠輝石) and in which feldspar, though present in the norm, is not stable.




**C. Blueschist** results from the high-pressure, low-temperature metamorphism of oceanic crust (basalt and oceanic sediment) in the subduction zone below a trench. At a subduction zone, the rapid and deep subsidence of the cool lithospheric slab creates the high pressure. The low temperature persists because the descending plate heats up slowly, while the pressure increases rapidly.




**D. Greenschist** results from the high-pressure, high-temperature metamorphism of a variety of rock types. It forms in the roots of mountain belts, where high pressure is created at depths similar to those at which blueschist is formed. In the mountain roots, however, high temperature also occurs as a result of the ascending magma generated by melting at convergent plate margins. Under some high-temperature conditions, blueschist is metamorphosed into greenschist.

***2. Contact Metamorphism***

Contact or thermal metamorphism occurs adjacent to igneous rocks. The dominant effect is that of temperature and the pressure effect is always subordinate if not negligible. The steep temperature gradient, decreasing away from the hot igneous contact towards the unaltered country rock, characteristically gives rise to zones of metamorphic rocks which differ in their mineralogy and fabric. The zone of rocks affected by contact metamorphism is known as the contact aureole.

The following rock names are frequently applied to contact metamorphic rocks:-

Spotted slate or schist – partially recrystallised rocks from the outer zones of contact aureoles. The spots are porphyroblasts of minerals such as andalusite (紅柱石) or cordierite (菫青石) or segregations of carbonaceous matter which appear to represent the incipient crystallisation of these minerals.

Pencatite (水滑大理岩) – a rock consisting of calcite and periclase (方鎂石) (and/or brucite水鎂石 ) in approximately equal proportions. Formed by the metamorphism of dolomite.

Predazzite (水滑結晶石灰岩) – a rock consisting of calcite together with smaller amounts of periclase and/or brucite. Formed by the metamorphism of dolomitic limestone.

Ophicalcite (蛇紋大理岩) – a contact metamorphosed calcite-serpentine rock with a delicately mottled appearance due to the colour contrast between these minerals.

Calc-flinta (鈣質燧石) – a very fine grained flinty calc-silicate rock produced by contact metamorphism. Often has a finely banded structure, or more rarely the minerals recrystallise in concentric fashion.

Porcellanite (矽頁岩) – a hard, very fine grained rock with a porcelain-like fracture and fabric. Porcellanites are formed by the baking of clays or shales at an igneous contact.

Fritted or vitrified sandstone – a hard massive rock in which quartz grains are set in a silica glass and/or tridymite (鱗石英) matrix formed by melting.

Buchite (波化岩) – a partially fused hornfelsic rock, generally of sedimentary origin, found as xenoliths in igneous rocks. It is often characterised by alumina-rich minerals such as corundum (剛玉 ), mullite (富鋁紅柱石), spinel (尖晶石), sillimanite (矽線石) and cordierite which, together with feldspars, pyroxenes and silica minerals, are set in a glassy matrix.

Sanidinite (透長石岩) – a buchite-like rock containing sanidine (透長石) in addition to the minerals listed.

### *3. Dynamic Metamorphism*

Dynamic (or cataclastic) metamorphism is the product of rock deformation, principally folding, faulting and thrusting. Mechanical crushing and/or shearing cause changes in the rock fabric, sometimes without significant recrystallisation.
Other types of cataclastic rock include:

Augen schist and augen gneiss – porphyroclasts or ‘eyes’ (augen眼球) of original rock or original minerals set in a schistose or gneissose matrix. The term flaser rock has a similar meaning.

Phyllonite (千枚糜嶺岩) or phyllite mylonite – a rock of phyllitic appearance produced by the mylonitic breakdown of a coarser-grained rock as a result of differential movement on structural surfaces. The superimposition of shearing on older ‘S’ surfaces gives a characteristic lenticular structure to the rock.

8.5 Augen Mylonitic Gneiss

This 4 cm by 6 cm polished surface of a mylonitic gneiss dramatically illustrates metamorphism resulting from the combined effects of pervasive brittle and ductile deformation. The specimen is cut perpendicular to the planes of shear. Partially broken down and rotated orthoclase phenocrysts form the augens or porphyroblasts. The brittle deformation of the feldspars contrasts strongly with the ductile deformation of the quartz, which is smeared out in the thin darker layers. The tails on the porphyroblasts suggest a clockwise rotation. A shear plane cuts diagonally down to the right immediately below the largest porphyroblast in the lower center. This sample is from a mylonite zone associated with a Tertiary age metamorphic core complex in southeastern Arizona.

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8.12 Close-up of Augen Gneiss Near Nyalam, Southern Tibet
Photograph by Peter L. Kresan

This outcrop of a classic augen gneiss (porphyroblasts 2 - 8 centimeter in diameter) is in the heart of the High Himalayas. It is a metamorphic rock derived from preexisting rock that was intensely sheared (smeared) and recrystallized.

This gneiss is part of the High Himalayan crystalline rocks, also known as the Greater Himalayan Sequence, intruded by dikes and sills of leucogranites. Some geologists consider the High Himalayan leucogranites to be the only migmatitic products of the Himalayan orogeny (Le Fort, 1996). Their composition suggests an origin from the partial melting of gneisses.

### *4. Metasomatism (換質作用)*

Metamorphism is normally regarded as being an iso-chemical process, i.e. on a gross scale the bulk composition of the rock undergoes no change in chemical composition other than dehydration (or decarbonation in the case of carbonates). When ions are added to or removed from the rock in sufficient quantity to create a significant change in bulk composition, the process is known as metasomatism.

The following rock names are frequently applied to metasomatic rocks:-

Skarn (矽卡岩) - a Swedish mining term for the silicate matrix of ores found within limestones. The term is now used to describe rocks found at limestone-igneous rock contacts, where the skarn often shows a complex zonation and has a composition or compositions which contrast strongly with the compositions of the rocks on either side.

Luxullianite (電氣花岡岩) – a partially tourmalinised granite consisting of pheno-crysts of pink feldspar set in a ground mass consisting of tourmaline and quartz.

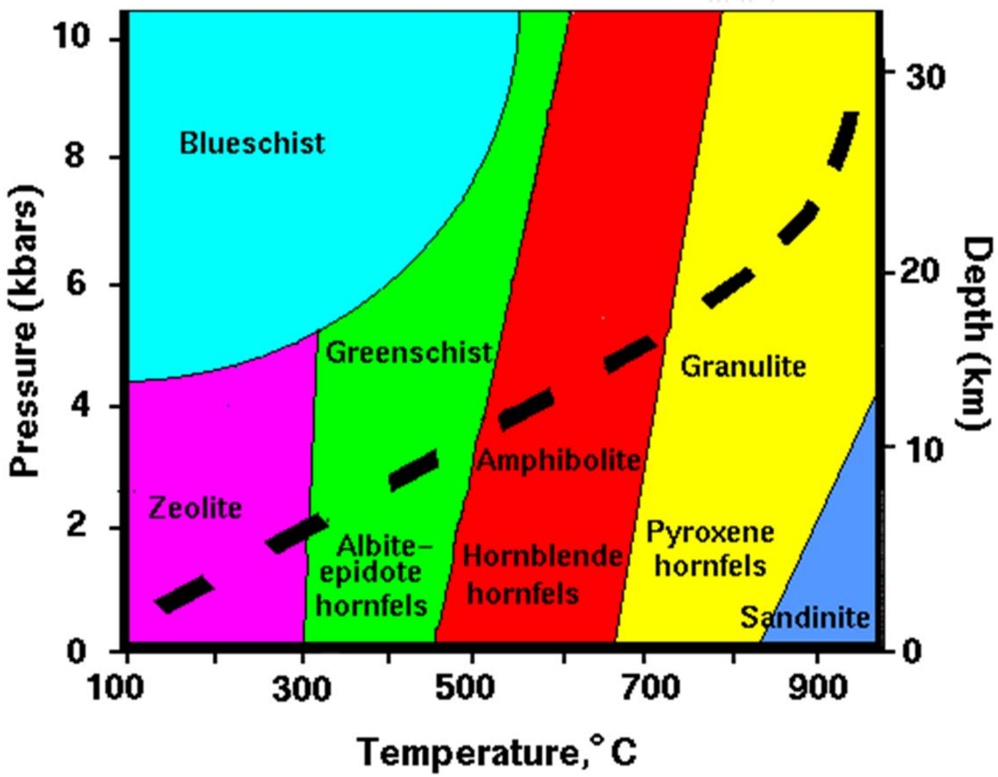
Schorl (黑電氣石) – a completely tourmalinised granite consisting of tourmaline and quartz.

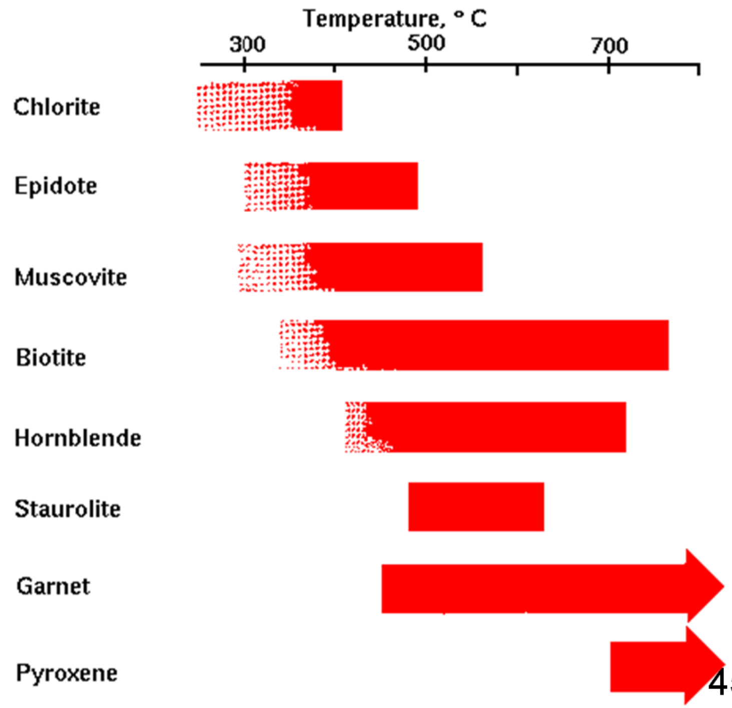
Adinole (鈉長英板岩) – an albite-rich rock formed by contact metasomatism generally at shale/dolerite contacts.

Greisen (雲英岩) – a quartz-mica (muscovite or lepidolite鱗雲母 ) rock occurring near the contacts of granite masses. Forms layers and veins which are gradational into unaltered granite. Contains topaz (黃晶) and a large range of accessory and ore minerals.

**METAMORPHIC FACIES**

Certain minerals and assemblages of minerals are known to occur only under restricted conditions of temperature and pressure. A group of metamorphic mineral assemblages which is repeatedly associated in space and time, such that there is a constant relation between mineralogy and bulk chemical composition of the rock, defines a metamorphic facies. By investigating the limiting conditions under which diagnostic minerals and assemblages occur, using experimental mineralogy and petrology, it has proved possible to place approximate temperature and pressure limits on each metamorphic facies. Taken in conjunction with structural geology studies, this permits the geological history of metamorphic areas to be unravelled.



# Metamorphic Rock names

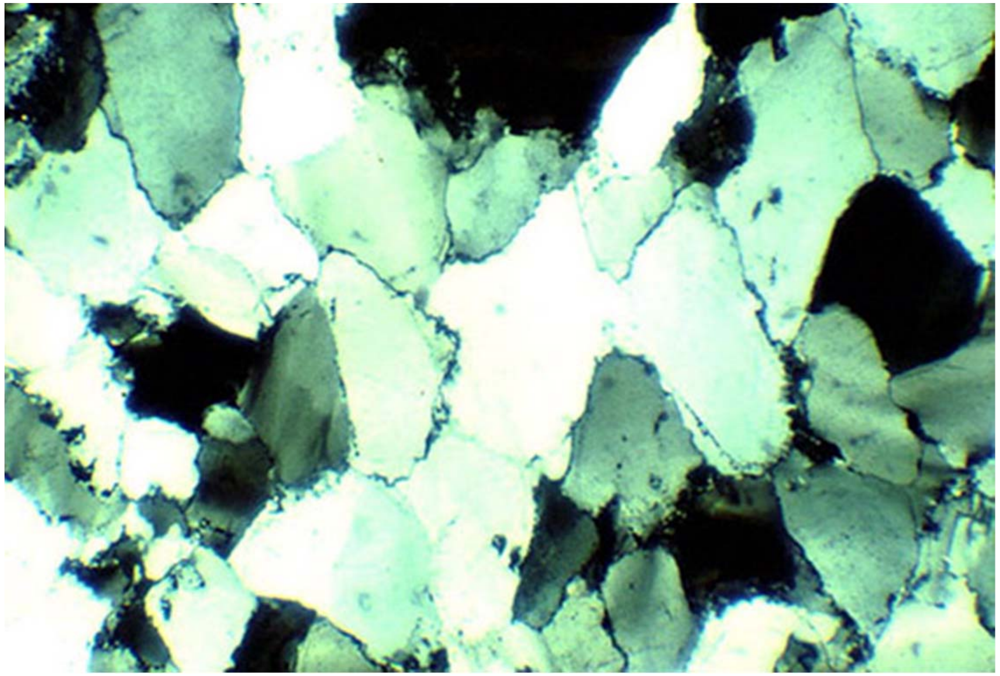
Four main criteria for naming metamorphic rocks (Yardley, 1989):
1. The nature of the parent material;
2. The metamorphic mineralogy;
3. The rock's texture;
4. Any appropriate special name.

Yardley, B. W. D. (1989) An Introduction to Metamorphic Petrology. Longman, Harlow. 248pp.

In contrast to igneous or sedimentary rocks there are relatively few special names or rigid divisions in classifying metamorphic rocks. With this flexibility a name should convey some information about the rock in question. This information could include: (1) the nature of the parent material; (2) the mineral assemblage; (3) the textures of the rock

## 1. Names indicating the nature of the parent material:

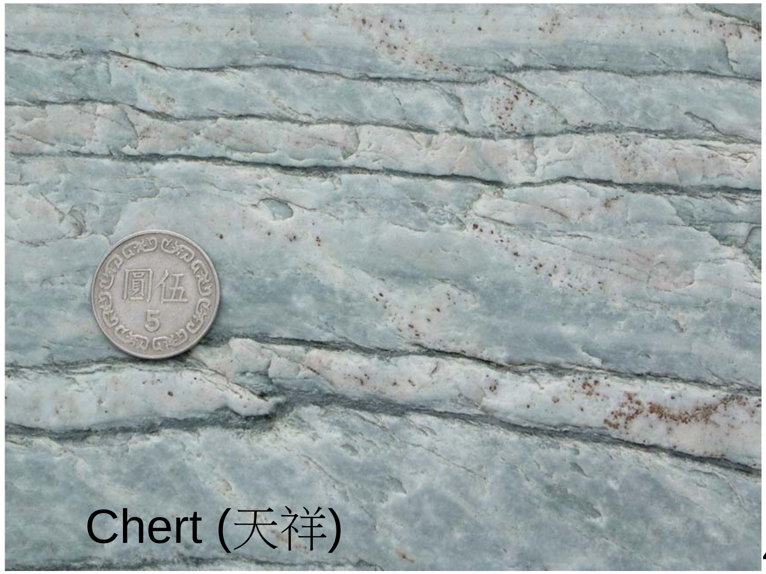
| **Original material** | Metamorphic rock type (noun/adjective) |
|---|---|
| Argillaceous or clay-rich sediment | Pelite (泥質岩)/pelitic |
| Arenaceous or sandy sediment | Psammite (砂屑岩)/psammitic or quartzofeldspathic (if appropriate) |
| Clay-sand mixture | Semi-pelite |
| Quartz sand | Quartzite |
| Marl | Calc-silicate/calcareous |
| Limestone | Marble |
| Basalt | Metabasite (變基性岩)/mafic |
| Ironstone | Meta-ironstone/ferruginous |



**Quartzite** in the Hsuehshan Range (白冷,中橫)

8.2 Photomicrograph of **Quartzite**

The interlocking quartz grains in the quartzite essentially are welded together by recrystallization during metamorphism. Compare the granular texture illustrated in this slide with the foliated texture exhibited in the photomicrograph of schist in Slide 8.3.



Chert (天祥)

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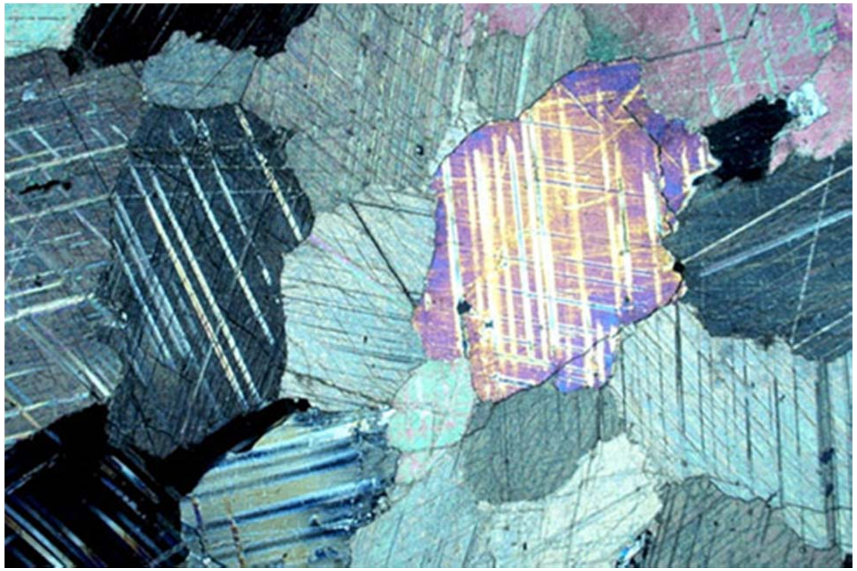

8.9 Photomicrograph of a **Marble**
Photograph by Peter L. Kresan

Photomicrograph of a marble (253), showing deformational twinning in the carbonate and a **granoblastic texture**. Note 120° grain boundary intersections.

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Marble (碧綠層,中橫)

## 2. Names indicating metamorphic mineralogy

The names of particularly significant metamorphic minerals that may be present are often used as qualifiers in the metamorphic rock names, e.g., garnet mica schist. Two possible conventions: (1) the mineral names are in order of abundance for the principal metamorphic minerals, this convention is commonly used by the field geologists; (2) the names of particularly significant minerals can be given, which indicate specific conditions of metamorphism, irrespective of their abundance. This convention is adopted by petrologists.

Some monomineralic rocks are named for their dominant mineral, e.g., quartzite, serpentinite, hornblendite (角閃石岩).

Compared with igneous petrology, relatively few mineral assemblages have been assigned specific names. Blueschist; eclogite; charnockite, are examples of such rock types.

## 3. Names indicating rock's texture

**Textural features of hand specimens**

There are two fundamental types of metamorphic rock-foliated and massive. These can be further subdivided using grain size, the presence or absence of porphyroblasts, color, the nature of foliation etc. Other structural elements such as folding, lineation, two or more 'S' planes, should also be recorded.

Foliation: a planar structure resulting from the parallel or subparallel arrangement of platy or fibrous minerals or from a mineralogical layering or from both of these. The term is equivalent to the 'S' surface of structural geologists – a plane of discontinuity within a rock. An initial subdivision of hand specimens of metamorphic rocks can be made on the basis of absence or presence or type (cleavage, schistosity, gneissic) of foliation.

Three types of foliation (葉理):

(a) Cleavage (劈理)– a perfect fissility defined by the parallel orientation of platy minerals in fine grained rocks (slates, phyllites).

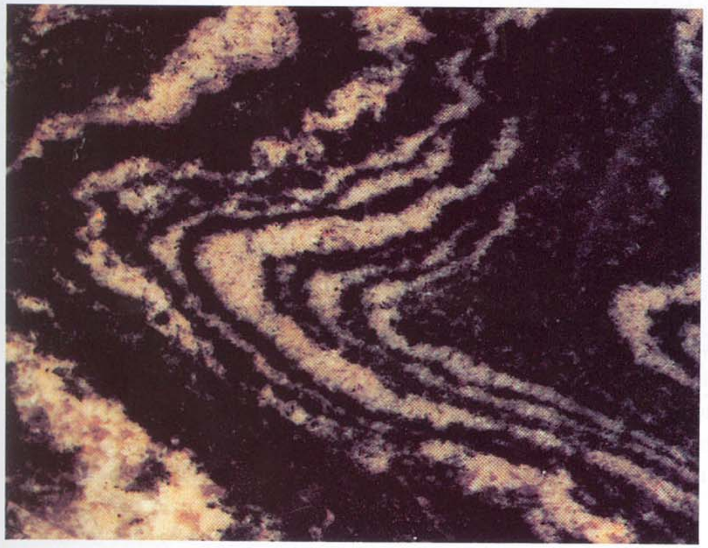
(b) Schistosity (片理) – a less perfect fissility defined by the parallel orientation of platy materials in somewhat coarser grained, recrystallised rocks (schists).

(c) Gneissic foliation (片麻狀葉理)– subparallel layers, streaks or plates of contrasting mineralogy (often consisting of lighter felsic layers and darker mafic layers) occurring in coarser grained rocks (gneisses).

A single specimen may show traces of more than one S surface and these can be described as S1, S2, S3 etc. if their relationships can be deciphered.

**A. Slaty Cleavage** is a type of foliation expressed by the tendency of the rock to split into thin layers. It results from the parallel orientation of microscopic grains of mica, chlorite, or other platy minerals. This photo shows the surface of a cleavage plane. Relic bedding can be seen as faint, reddish layers.

**B. Schistosity** is a type of foliation resulting from the parallel to subparallel orientation of large, platy minerals such as mica, chlorite, and talc. This photo shows the surfaces of the planes of schistosity. A section through the schistosity plane is shown in the specimen's left margin. The small, dark grains are garnet.



**C. Gneissic Layering** is a coarse-grained, foliated texture in which the minerals are segregated into layers that can be several centimeters thick. Light-colored layers commonly contain quartz and feldspar; dark-colored layers are commonly composed of biotite and amphibole.

**D. Gneissic Layering** in some rocks may be thin, discontinuous lenses that impart a distinctive fabric to the rock.

Deformation and metamorphism of clay-bearing clastic sediments give rise to the following sequence or rocks (slate to gneiss listed below):

A **slate** (板岩) is a fine-grained rock with perfect fissility (cleavage), independent of bedding, resulting from parallel orientation of micaceous minerals. It is a product of the regional or dynamic metamorphism of pelitic and semipelitic rocks.

A **phyllite** (千枚岩) is a rock resembling slate but coarser in grain size. The coarser grain size of the micaceous minerals imparts a lustrous sheen to the cleavage surfaces.

A **schist** (片岩) is a foliated, and sometimes lineated rock coarser than slate and phylllite. The foliation is accentuated by the occurrence of a fine mineral lamination resulting from metamorphic differentiation. Both phyllites and schists are the products of regional metamorphism.

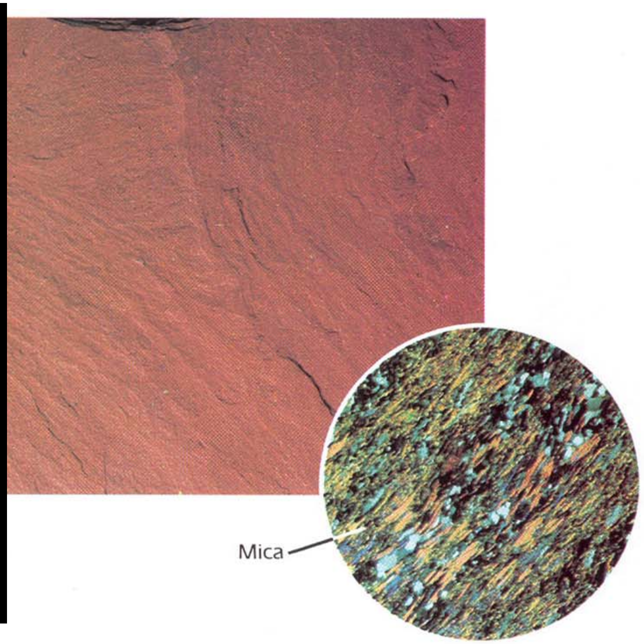
A **gneiss** (片麻岩) is a medium to coarse-grained rock consisting of mineralogically dissimilar laminae thicker than those of schists. The foliation tends to be ill-defined and discontinuous. Gneiss are products of regional metamorphism and/or migmatization (混成作用).

A **hornfels** (角頁岩) is a massive nonfoliated rock, generally fine-grained, composed of a mosaic of equidimensional grains (grano-blastic or decussate texture微交錯構造). It occurs almost exclusively, as the product of medium or high-grade contact metamorphism.

## Common metamorphic rock types

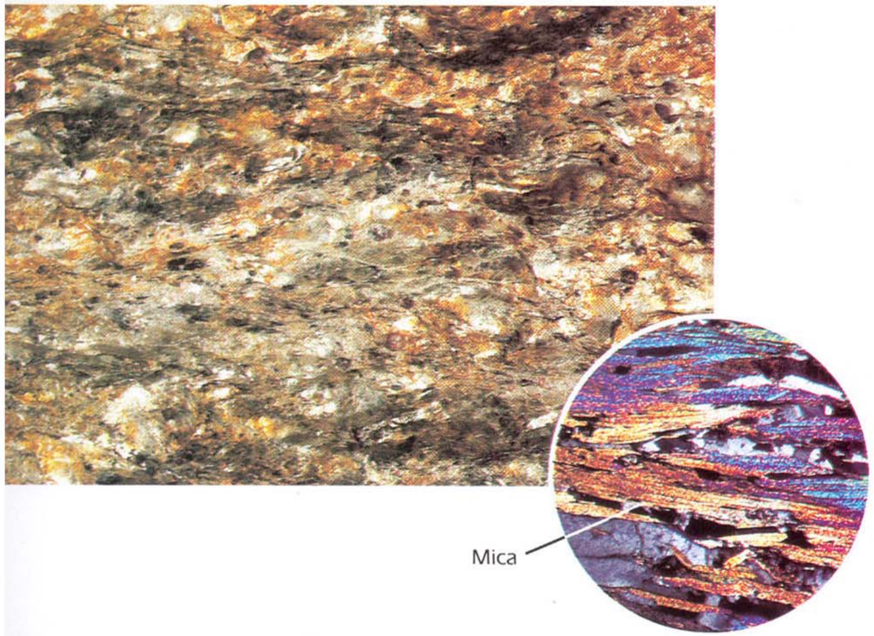
| ROCK NAME | TYPE | PARENT ROCK | CHARACTERISTICS |
|---|---|---|---|
| **SLATE** | foliated | shales and muds | prominent splitting surfaces |
| **PHYLLITE** | foliated | shales and muds | Similar to slate but with slightly coarser grains, silky appearance, cleavage surfaces less perfectly planar |
| **SCHIST** | foliated | fine grained rocks | mica minerals, often crinkled or wavy |
| **GNEISS** | foliated | coarse grained rocks | dark and light bands or layers of aligned minerals |
| **HORNFELS** | Non-foliated | Generally fine grained rocks | massive, composed of a mosaic of equidimensional grains |
| **MYLONITE** | foliated | Fine-grained rocks | Intense ductile deformation with deformed and recrystallized grains |

Slate (中橫盧山層)



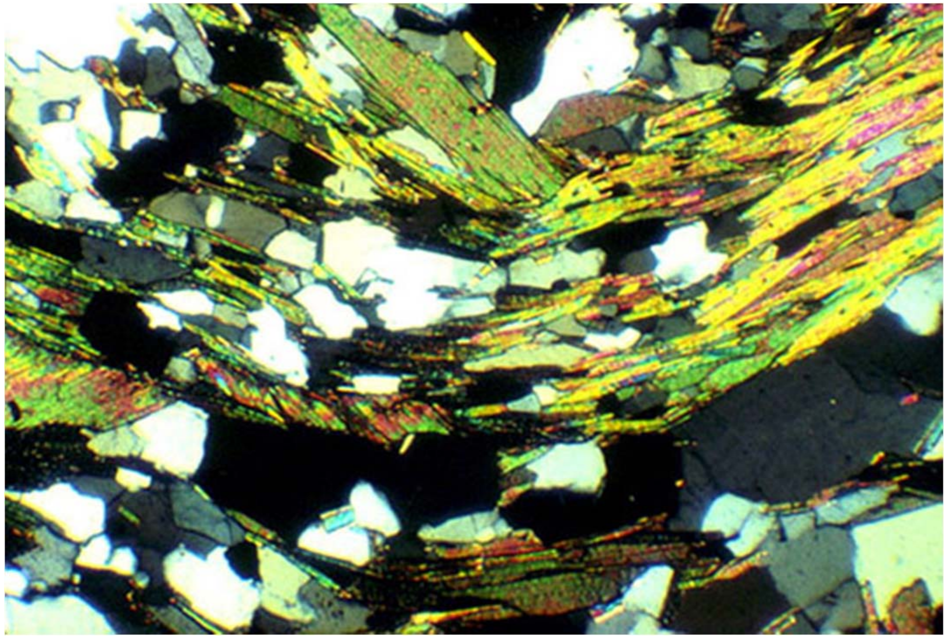

**A. Slate** is a fine-grained metamorphic rock, possessing a type of foliation known as slaty cleavage. In many slates, traces of the original bedding planes in the shale are expressed by subtle changes in color or grain size, but slaty cleavage is still the most obvious structure. The constituent minerals are commonly so small they can only be seen under high magnification. Slates are characteristically dense and brittle. Coloration may be gray, black, red, or green. They are low-grade metamorphic rocks, derived principally from the metamorphism of shale. (See also Figure 5.1A.)

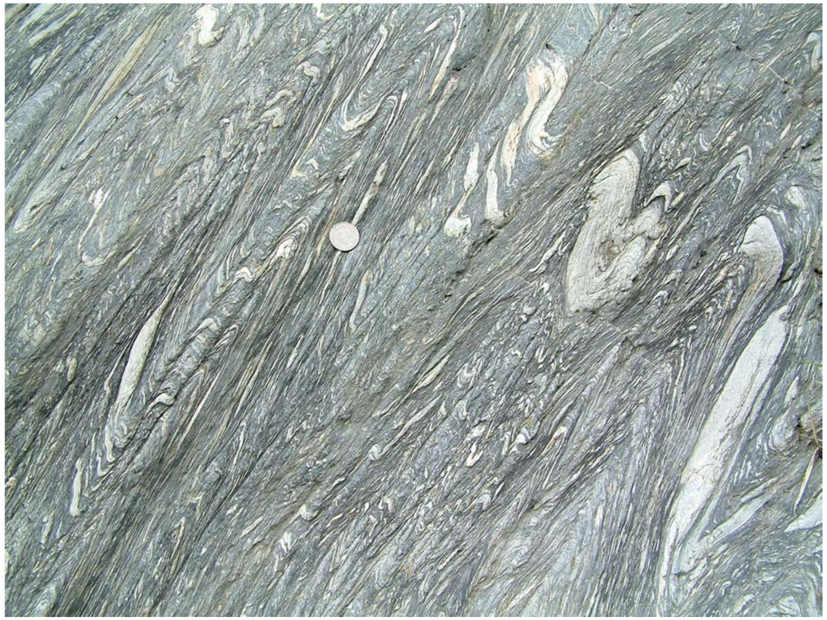
**Phyllite** is similar to slate but is distinguished by a satin luster, or sheen, developed on the planes of foliation. The luster results from the growth of larger mica crystals commonly found in slate.




**B. Schist** is a metamorphic rock in which foliation is due to the parallel arrangement of relatively large crystals of platy minerals. Muscovite, biotite, chlorite, and talc are the important platy constituents. Feldspars are rare, but quartz, garnet, and hornblende are common accessory minerals.

Schists may be further classified on the basis of the more important minerals present. The most common types are chlorite schists, muscovite schists, hornblende mica schists, and garnetiferous mica schists. The unifying characteristic, regardless of composition, is that foliation results from the parallel arrangement of relatively large, platy minerals. Schists are produced by a metamorphism of higher intensity than that which produces slates. Under such conditions, a variety of parent-rock types—including basalt, granite, sandstone, and shale—may be converted to schists.





8.3 Photomicrograph of Schist

Schist (天祥)

This is quartz-biotite-chlorite schist as it looks in thin section under a petrographic microscope at 3.53 magnification under polarized light. The well-expressed foliation in this high- grade metamorphic rock is due to the planar arrangement of minerals. Both physical (shearing/plastic flow) and chemical (recrystallization within the plane of least stress) reorientation of minerals is thought to contribute to the formation of foliation during metamorphism at elevated temperatures and pressure.

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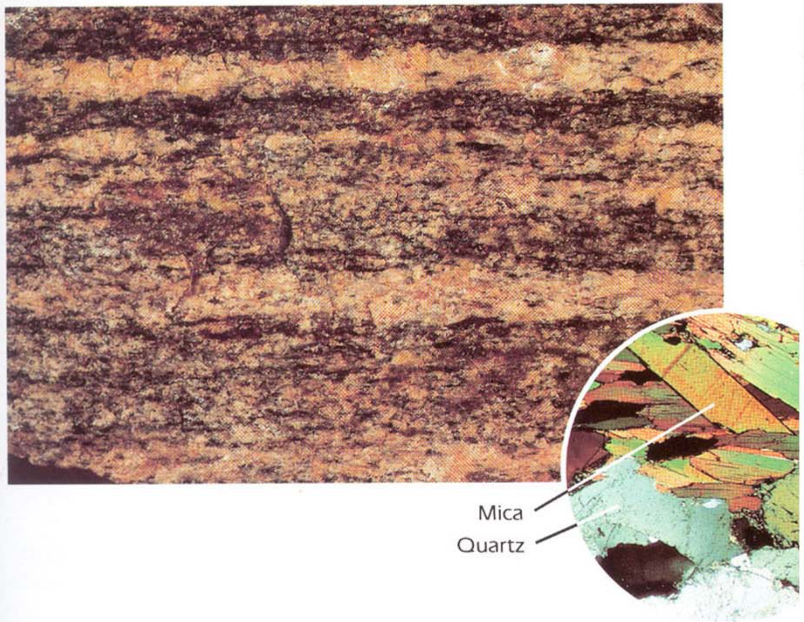
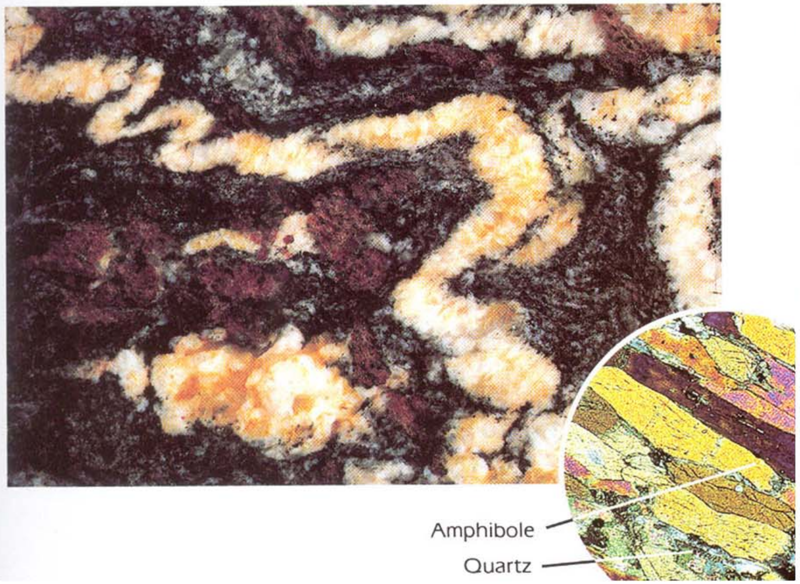
片麻岩(溪畔隧道,中橫)




**E. Gneiss** is a metamorphic rock in which foliation results from layers composed of different mineral groups. Feldspar and quartz are the chief minerals in gneiss, with significant amounts of mica, amphibole, and other ferromagnesian minerals. Gneiss has a coarse-grained, granular texture. It resembles granite in composition but is distinguished from it by the foliation. (See also Figures 5.1C and D.)




**F. Gneiss** may be foliated, with semicontinuous layers of light and dark minerals, as shown in Figure 5.4E (above), or with highly contorted, well-defined layers like those shown here. In many rock bodies, layers expressing foliation are several inches thick. Gneisses are among the most abundant metamorphic rocks. They represent a high grade of metamorphism and may originate from various granite-rhyolite rocks or from lower-grade metamorphic and sedimentary rocks.

## 4. Special names

Most special names are descriptive. The mineral associations indicated by the names may carry implications for the conditions of metamorphism.

| | |
|---|---|
| **Greenschist** | Green foliated metabasite, usually composed predominantly of chlorite, epidote and actinolite |
| **Blueschist** | Dark, lilac-grey foliated metabasite, owing its color to the presence of abundant sodic (富鈉)amphibole, typically glaucophane or crossite: seldom true blue in hand specimen |
| **Amphibolite** 角閃岩 | An essentially bimineralic dark green rock mad up of hornblende and plagioclase. Most amphibolites are metabasites (ortho-amphibolite) but some may be metamorphosed calcareous sediments (para-amphibolite) |
| **Serpentinite** 蛇紋岩 | Green, black or reddish rock composed predominantly of serpentine. Formed by hydration of igneous or metamorphic peridotites. |
| **Eclogite** | Metabasite composed of garnet and omphacitic clinopyroxene with no plagioclase feldspar. |
| **Granulite** 粒變岩 | With a texture of more or less equidimensional, straight-sided (polygonal) grains for all mineral species, and a mineralogy indicative of very high temperature metamorphism, closely akin to the mineralogy of calc-alkaline basic to moderately acid plutonic rocks. The **charnockite** suite constitutes a distinct variety of K-feldspar and hypersthene (紫蘇輝石) bearing granulites. |
| **Migmatite** 混成岩 | A mixed rock composed of a schistose or gneissose portion intimately mixed with veins of apparently igneous quartzo-feldspathic material. |

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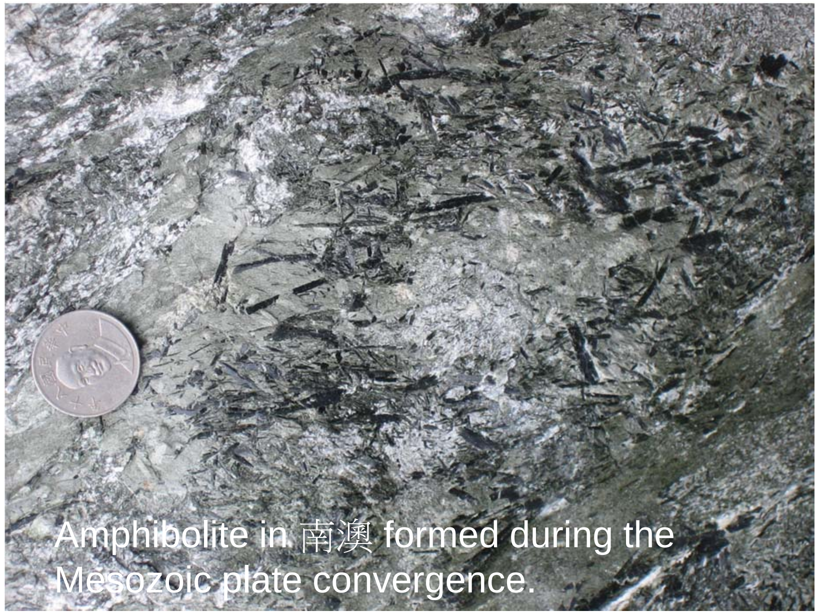
8.4 **Migmatite**

This outcrop of migmatite is exposed along the Bright Angel Trail in Pipe Creek, Grand Canyon, Arizona. Contorted pods of quartz and potassium feldspar-"granite"-interpenetrate the Vishnu schist. Because the deformed pegmatitic dikes follow the foliation of the schist, they must have formed during the metamorphism of the Vishnu complex, rather than intruding during the emplacement of the Zoroaster plutonic complex. The Vishnu schist complex is derived from interspersed sedimentary and volcanic rocks that were probably associated with island arc volcanoes, active on the seafloor about 2 billion years ago. An episode of high-grade regional metamorphism (temperature about 700 degrees Centigrade and a pressure of 34 kilobars) apparently partially melted the Vishnu complex and sweated out the low-melting-point quartz and feldspar to form the migmatite. Formed by partial melting, "metamorphic" migmatites support the idea that granites may originate from the melting of preexisting rocks, like clay-rich sediments and metamorphic rocks.

Migmatite in 南澳 formed during the Mesozoic plate convergence



Amphibolite in 南澳 formed during the Mesozoic plate convergence.

*Terms employed in describing the textures and mutual relations of metamorphic rocks.*

Crystallinity – coarse, medium or fine grained as in igneous rocks.
Crystoballatic – a general term applied to the textures of rocks formed by metamorphic recrystallisation.
Idioblastic (自形變晶) – describes a grain in a metamorphic rock which shows crystal faces.
Xenoblastic – describes a grain in a metamorphic rock which shows no crystal faces.
**Granoblastic** (花岡變晶狀)– (granular) – the texture of massive rocks when all minerals are about the same size c.f. – fels. (Fig. 4-19B)

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**Inequigranular textures:**

a. Porphyroblastic (斑狀變晶狀) – a texture in which large crystalloblasts are set in a finer grained matrix (Fig. 4-19C).

b. Poikiloblastic (變嵌晶狀) – a texture in which porphyroblastic minerals contain inclusions of another material (Fig. 4-19B). The descriptive term sieve texture is sometimes used.

c. Porphyroclastic (殘碎斑狀) – where the larger grains (porphyroclasts) are relics in a fine mylonitic groundmass (Fig. 4-19H).

d. Blastoporphyritic (變餘斑狀) – where the larger grains are relict phenocrysts of an igneous protolith (Fig. 4-19F).

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Mosaic texture (鑲嵌狀) – a granoblastic texture resulting from sub-grain formation in which the subgrain boundaries differ slightly in orientation.
Sutured texture – a granoblastic texture in which mutual grain boundaries have an irregular interlocking form.
Lepidoblastic (鱗片變晶狀) – the parallel or subparallel arrangement of platy minerals (micas, chlorites, etc.).
Nematoblastic (纖狀變晶) – the parallel or subparallel arrangement of fibrous minerals.

Trails – the regular, often parallel arrangement of inclusions within a poikiloblast. Trails may sometimes be curved, folded or spiral-like. In the latter case they are described as rotational texture. The trails are often the trace of a foliation and in petrofabric studies are described as Si (internal foliation), the foliation of the matrix being Se (external foliation).

**Foliated, schistose, cleaved** – parallel or laminated structures the detailed nature of which can be described from the thin section.

Maculose (斑結狀) or potted texture – porphyroblastic minerals developed in a granoblastic (often hornfelsic) matrix.

**Mylonitic texture** (磨變結構) – groundmass aphanitic or nearly so and typically foliated but generally not fissile; typically with angular or rounded relicts (porphyroclasts) of protolith.

**Cataclastic texture** (碎裂狀結構) – composed of brittle-fractured grains; unfoliated; typically the texture of a very poorly sorted breccia.

**TERMS USED IN DESCRIBING METAMORPHIC ROCKS**

Prefixes and Suffixes.

Meta- a metamorphic rock in which the original fabric, sedimentary or igneous, can still be recognized e.g. meta-greywacke, meta-basalt.

Ortho - A metamorphic rock derived from an igneous parent e.g. orthogenesis (正片麻岩).

Para - a metamorphic rock derived from a sedimentary parent e.g. paragenesis (副片麻岩).

-fels - a term used to describe massive metamorphic rock lacking a foliation e.g. hornfels.

Blasto - a residual texture or feature in a now metamorphosed rock e.g. blastophitic.

-blast or blastic a texture or feature which is metamorphic in origin. Used to qualify terms which might imply another mode of formation e.g. porphyroblastic-porphyritic, xenoblastic, xenomorphic, granoblastic-granular.

-clast or clastic a texture or feature of cataclastic origin e.g. porphyroclastic-porphyritic.

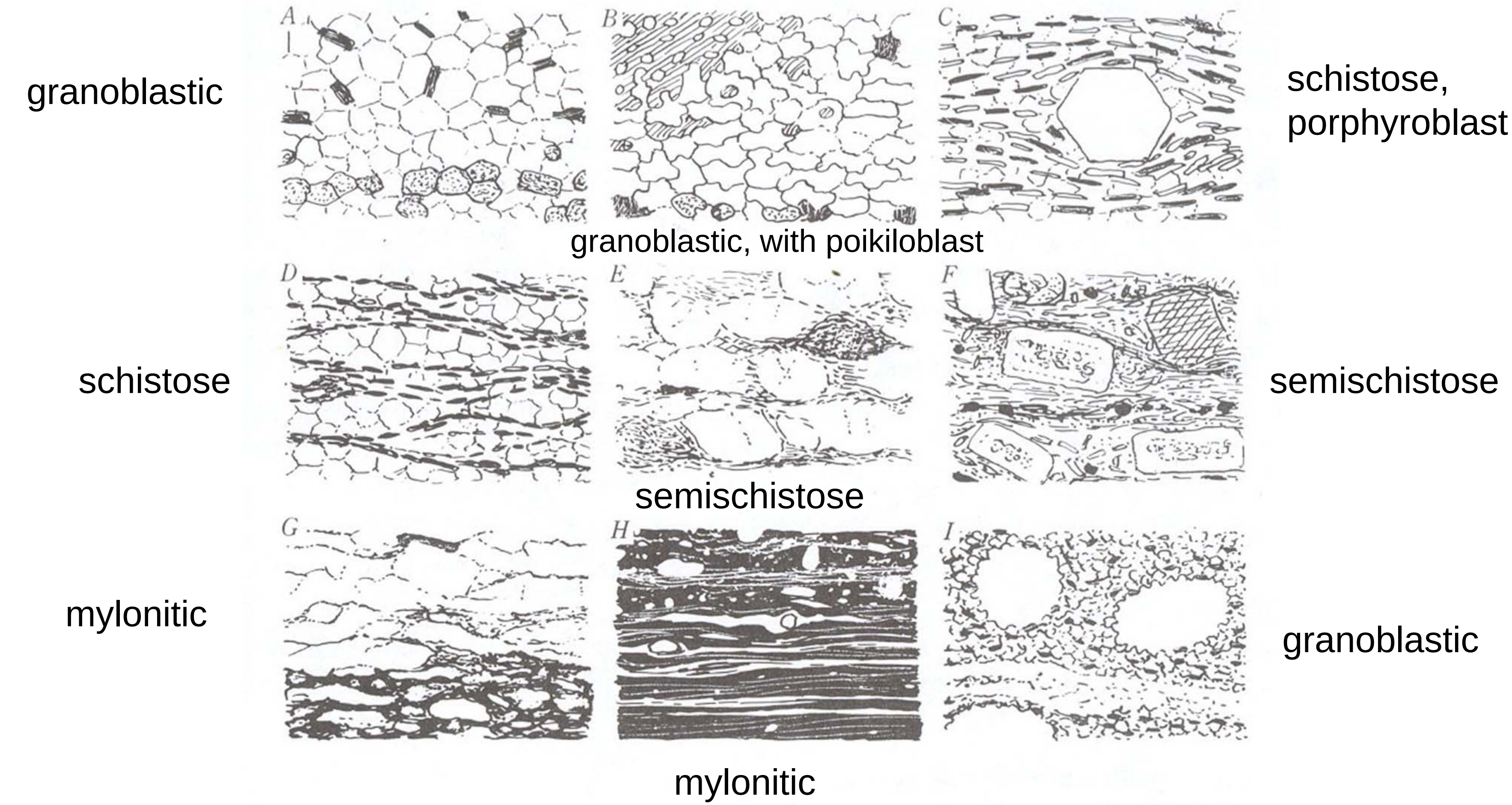


**Fig. 4-19.** Metamorphic textures, as seen through a hand lens. *A*. Granoblastic texture, in part a mosaic texture (with many triple junctions of grains with interboundary angles of around 120°). *B*. Granoblastic texture of irregular grains, with a large poikiloblast in the upper left. *C*. Schistose texture with a euhedral porphyroblast. *D*. Schistosity imparted by small flakes and lenticular granoblastic domains. *E*. Metasandstone with fine mica in the matrix, imparting a semischistose texture. *F*. Semischistose texture due to fine chlorite and actinolite in the groundmass of a blastoporphyritic metabasalt. *G*. Somewhat mylonitic granite passing downward into protomylonite. *H*. Orthomylonite passing downward into ultramylonite. *I*. Granoblastic texture in a blastomylonite, the latter indicated by the recrystallized margins of relict porphyroclasts (enlarged about 5 times relative to *H*).

Compton (1985)

8.1 **Metaconglomerate**
The "hotdog"-shaped features in this metaconglomerate are stretched quartz pebbles. This sample of metamorphosed Barnes conglomerate from the Tortolita Mountains near Tucson, Arizona, was cut and polished to show these stretched pebbles. The relatively unmetamorphosed Barnes conglomerate from central Arizona is shown in Slide 7.1 for comparison.

8.11 Outcrop of **4.03 Billion Year Old** Acasta Gneiss, Slave Province, Canada. Photograph by Clark Isachsen

This outcrop of Acasta **Gneiss** yielded a U-Pb radiometric date of about 4.0 billion years old. The darker bands are **amphibolite**, the gray is **tonalite**, and the white layers are **trondhjemite** (mostly quartz and plagioclase). Interpretations of this rock are still hotly debated. Its isotopic composition suggests that it was derived from a protolith of older continental crust, which means that continental crust existed on Earth by 4 billion years ago (Bowring, et. al. 1989).

8.14 **Limestone Breccia**, Titus Canyon,
Death Valley, California
Photograph by Peter L. Kresan

This mega breccia is exposed in the wall of Titus Canyon, Death Valley National Park, California. A careful look at the image shows that layering and other features continue across the white carbonate-filled fractures from one limestone block to another. This indicates that although the rock is highly shattered, possibly by movement along a fault nearby, the blocks have hardly moved.

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