Chapter 1 Definition of metamorphism, classification of metamorphic rocks

1.1 Definition of metamorphism

'Metamorphism' is a general name for processes of *change* of pre-existing igneous or sedimentary rocks. The original rock, before metamorphism, is called the parent rock or **protolith**.

The name metamorphism is derived from Ancient Greek μετα (meta) = *change* and μορφη (morphe) = *form, shape.*

Metamorphic changes take place in solid rocks with only a small volume of fluid present or sometimes none. Metamorphism is therefore a set of *solid-state* processes, in contrast to igneous processes that are solid-melt interactions. The temperatures and pressures of metamorphism are higher than those found at the surface of the lithosphere and this distinguishes metamorphism from sedimentary processes that are interactions between the atmosphere, hydrosphere and solid earth materials at or near the surface.

All metamorphic rocks were once igneous or sedimentary rocks

Because metamorphism is a process that occurs in solid rocks, metamorphic rocks must have formed from pre-existing igneous or sedimentary rocks. During the process of metamorphism, their original igneous or sedimentary minerals and microstructures broke down and new metamorphic minerals and microstructures took their place. There may have been more than one cycle of metamorphism, with metamorphic rocks forming from older metamorphic rocks of an earlier cycle. We call the original igneous or sedimentary rock the parent rock or **protolith**. If the process of metamorphism has been intense or if there have been several cycles of metamorphism, we may find it difficult to discover what kind of rock the protolith was.

Table 1.1 gives some examples of sedimentary and igneous protolith rock-types and the metamorphic rocks that they might change to. One kind of protolith can yield different types of metamorphic rock because it can undergo different kinds of metamorphism. Different kinds of protolith (e.g. sedimentary marls and volcanic tuffs) can yield the same type of metamorphic rocks because similar metamorphism produces rocks with similar characteristics.

Table 1.1

Protolith (parent rock)	Metamorphic rock
mudrock	slate
mudrock	schist
mudrock	gneiss
limestone	marble
limestone and chert	skarn
sandstone	quartzite
peridotite	serpentinite
basalt	greenschist
basalt	greenstone
basalt	amphibolite
basalt	pyroxene granulite
basalt	eclogite
granite	gneiss
granite	charnockite

1.2 Classification and nomenclature of metamorphic rocks

There are several systems for classifying metamorphic rocks and the one we use depends on our reason for studying them. If we are making a field geological survey or logging rocks from a borehole we must give them a name and short description so that we can study them in more detail later. If we are doing petrological or geochemical research, we shall make more detailed descriptions including study of thin sections and chemical analyses so we can use more preside schemes of classification. If we are investigating tectonics, we shall use metamorphic rocks to calculate temperatures and pressures deep in the Earth at some time during the tectonic evolution. If we are investigating a sedimentary basin, we may use metamorphic rocks to understand the evolution of the basin and the maturation of sediments that might be source rocks of oil and natural gas. In all these cases, we need to choose suitable metamorphic rocks and focus our study on them.

The system we use also depends on the equipment we have. Are we doing fieldwork with only a hammer, hand lens and penknife? Do we have facilities for making thin sections and studying them under a microscope? Are we fortunate enough to use a full range of analytical equipment for chemical analysis of rocks and minerals, optical and electron microscopy, stable and unstable isotope analysis (including age dating), mineral spectroscopy and determinations of crystal structure? Our descriptions and identifications will depend on our equipment.

1.2.1 A simple descriptive classification

The first scheme I introduce is mainly used during fieldwork, though you should check your conclusions if possible by studying thin sections of the rocks under a petrological microscope later. Table 1.2 gives an outline of the scheme. The first column lists protolith compositions, the second the main types of metamorphic minerals in the rock and the last four columns corresponding metamorphic rock types, subdivided according to their microstructure. For an alternative scheme see Fry (1984).

In my scheme, the main criteria for naming rocks are:

1. The composition of the protolith - pelitic, psammitic, semi-pelitic, marble etc.
2. The metamorphic minerals present in the rock.
3. Aspects of the rock microstructure: (1) grain-size, which distinguishes the members of the series slate→ phyllite→schist →gneiss for example and (2) the presence or absence of metamorphic banding.

The composition of rocks needs further explanation. If metamorphism has changed all the minerals in a rock, the kinds of minerals will depend on the rock's bulk chemical composition. But bulk compositions of rocks are usually not used for classifying sedimentary rocks and the chemical subdivisions of igneous rocks are often too detailed for the broad classification that we are making in our scheme. So we metamorphic petrologists use our own names for broad compositional categories of rocks, listed below noun first, adjective second.

Pelite, pelitic: rocks that were originally sedimentary mudrocks (shale), rich in Al.

Psammite, psammitic: rocks that were originally sedimentary sandstones, rich in Si.
Semi-pelite, semi-pelitic: rocks that were originally sandy shales, i.e. intermediate between pelites and psammites.
Metabasite, metabasic: rocks that were originally basic igneous rocks, basalt, dolerite (diabase) and gabbro, rich in Mg, Fe and Ca.
Limestone: rocks composed of carbonate minerals, especially calcite and dolomite.
Marl: rocks intermediate in composition between pelites and limestones.
Chert: rocks composed of very fine-grained SiO_2, i.e. chert or flint.

The microstructural subdivisions are based first of all on the grain-size of the metamorphic minerals. We take the size limit between fine-grained and medium-grained rocks at 0.125mm from the standard classification of sedimentary rocks. A grain 0.125mm across is approximately the smallest that you can see with your naked eye, without a hand-lens. 2mm is the limiting grain-size between medium and coarse-grained sedimentary rocks, approximately the diameter of this letter O.

Coarse-grained metamorphic rocks have undergone stronger metamorphism than finer grained ones and often develop a metamorphic layering or compositional banding, also called gneissosity (Fig. 1.1). Table 1.2 distinguishes two categories of coarse-grained rocks: those with gneissosity and those without.

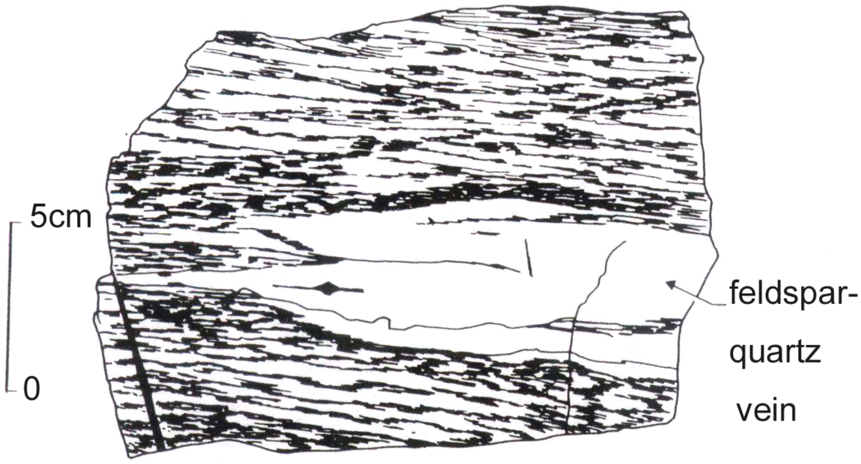


Fig. 1.1 Gneiss with mm scale banding, Myrdal, Norway

You can modify the names if there are obvious minerals in the rock, e.g. *kyanite schist*, *tremolite marble.*

To identify a metamorphic rock in the field, study it carefully using a hand lens in bright light. Identify as many kinds of minerals in the rock as you can, and estimate their grain-sizes and relative proportions. If you are used to identifying minerals or plutonic igneous rocks such as granite and gabbro in the lab, you will have to adjust to studying smaller crystals. As you gain experience you will be able to identify grains as small as 0.1mm across. If you cannot identify individual grains, test the bulk properties of the rock such as density, colour and hardness. You can identify a a rock composed of quartz crystals that are too small to see because it will scratch a knife blade. You can distinguish fine-grained metamorphosed rhyolite mainly composed of quartz and alkali feldspar from metamorphosed basalt mainly composed of amphibole and plagioclase feldspar by its lower density. It is usually lighter in colour as well. This kind of classification is not very accurate, but it is much better than no classification.

Table 1.2 Scheme of classification of metamorphic rocks

	Protolith composition	**Main minerals**	**Fine-grained <0.125mm**	**Medium-grained 0.125-2.0mm**	**Coarse-grained >2.0mm**
Foliated rocks	**Pelite**	sheet silicates, quartz, Al-silicates	slate	phyllite	schist, gneiss
	Semi-pelite	quartz, sheet silicates	sandy slate	quartz phyllite	quartz-schist
	Marl	sheet silicates, calcite, dolomite, epidote	calcareous slate	calcareous phyllite	calcareous schist or calc-schist
	Rhyolite, granite	alkali feldspar, quartz, sheet silicates	-	granitic gneiss	granitic gneiss
	Basalt, gabbro	plagioclase feldspar, amphiboles, epidote	greenschist	schistose amphibolite	schistose amphibolite
	Pyroxenite, peridotite, dunite	serpentine, talc, olivine, pyroxene	-	talc phyllite	talc schist, foliated peridotite
Massive rochs	**Psammite**	Q	quartzite	quartzite	quartzite
	Limestone	Cc, Dol	marble	marble	marble
	Limestone and chert	Cc, Q, Dol, Tc, Tr, Fo, Di	-	Tc-, Tr-, Fo-, Di-marble	Tr-, Fo-, Di - marble
	Rhyolite, granite	Af, Q, sheet silicates	-	augen gneiss	augen gneiss
	Basalt, gabbro	Pl, Am, Ep	greenstone	amphibolite	amphibolite, Px-granulite, eclogite
	Pyroxenite, peridotite, dunite	Serp, Tc, Ol, Px	soapstone, serpentinite	soapstone, serpentinite	Metapyroxenite, metaperidotite

Table 1.2 only contains a selection of metamorphic rock names. There are also special metamorphic rock names such as hornfels and protomylonite that we give to rocks from certain geological settings (see Section 1.1.2).

1.2.2 Classification of metamorphic rocks by their field settings

The geological setting of metamorphic rocks often tells us a lot about the processes that caused their metamorphism. Contact metamorphic rocks occur near the contacts of igneous intrusions, dynamic metamorphic rocks close to faults and thrusts. This gives rise to a three-fold classification, outlined below.

1.2.2A Contact metamorphic rocks

Contact metamorphic rocks occur adjacent to igneous intrusions. They occur over small areas (a few km^2), and formed by recrystallization of the original minerals in the igneous or sedimentary protolith because of the increase in temperature as heat flowed from the magma of the intrusion. Their mode of formation by heat from the intrusion is obvious from field study. The processes that transfer heat from the magma of the intrusion to cause metamorphism in the surrounding rocks are called contact metamorphism.

A small intrusion such as a dyke only bakes the country rock for a few millimetres. Around a larger intrusion, the contact metamorphic rocks form a contact metamorphic aureole that can vary in width from a few metres to kilometres. Therefore, contact metamorphic rocks outcrop over small areas ($<100km^2$). We can often see that the grain-size of the recrystallized minerals increases towards the intrusion, so that the largest grains are at the contact where the temperature of metamorphism was highest. The temperature of contact metamorphism also varies with the temperature of the intruded magma, being highest against ultra-basic igneous intrusions, intermediate against basic igneous intrusions and lowest against granitoid intrusions. At shallow levels in the Earth's crust (<7km) rocks are not usually deformed during contact metamorphism and thus do not display microstructures such as cleavage or foliation. They may inherit them from their sedimentary and igneous protoliths, or from earlier regional metamorphism. Because it is obvious that heat flowing from the intrusion in this type of metamorphism, some geologists call contact metamorphism *thermal metamorphism*. In this section, however, I am emphasising the field relationships of metamorphic rocks, so I prefer the older term **contact metamorphism**.

1.2.2B Dynamic metamorphic rocks

Dynamic metamorphic rocks occur near major faults and thrusts especially major fractures with large displacements at plate boundaries. Like contact metamorphic rocks, they therefore outcrop over small areas ($<10\ km^2$). They are the products of processes of fracture and plastic deformation that went on during the movement of the faults and thrusts.

1.2.2C Regional metamorphic rocks

The commonest metamorphic rocks outcrop over areas of hundreds of thousands of square kilometres. For example, over half the rocks outcropping in Canada are regional metamorphic rocks. Unlike contact and dynamic metamorphic rocks, the processes that caused their recrystallization from protoliths are not obvious from field study. There have been different theories about their origin since the beginning of geological research, and there still are. By describing these processes as **regional metamorphism,** we can classify the rocks without pre-judging their mode of origin, whereas if we use a term like *dynamothermal metamorphism* we are already expressing an opinion about the origin of the rocks. Using the prefix *dynamo-* (i.e. metamorphism associated with deformation) is wrong for many examples of regional metamorphism (e.g. burial metamorphism). Putting *dynamo-* ahead of *thermal* implies that deformation is more important than heat in the metamorphism of these rocks.

Modern research has shown that this is wrong, although many well-known geologists (e.g. Harker 1927) once thought otherwise. We call all rocks that are products of regional metamorphism, from sediments with only the smallest degree of metamorphism to ultra-high temperature gneisses **regional metamorphic rocks**.

This book is organised into sections based on this classification of metamorphic rocks.

1.2.3 Metamorphic facies

Metamorphic facies classifications divide metamorphic rocks with different protolith compositions into categories based on temperature and pressure at the peak of metamorphism. They rest on the application of equilibrium thermodynamic theory and the Phase Rule to metamorphic processes, which is explained and discussed in Chapter 2 of this book. Further explanation of metamorphic facies can be found in that Chapter.

1.2.4 Other classification schemes

There are other classifications of metamorphism in use, for example by their tectonic settings (e.g. subduction zone metamorphism, burial metamorphism, basin extension metamorphism). I shall describe these later.

1.3 The minerals of metamorphic rocks

The minerals in metamorphic rocks are new crystals formed by chemical reactions that occurred during the processes of metamorphism. Table 1.3 lists minerals that occur in metamorphic rocks, and is based on the textbook of Deer, Howie and Zussman (1992). You can see many minerals that are already familiar in sedimentary and igneous rocks (e.g. quartz, calcite, feldspar and mica). There are other minerals that only occur in metamorphic rocks (e.g. glaucophane, kyanite) or occur more commonly in metamorphic rocks (e.g. garnet, epidote). Kretz (1973) proposed a scheme of two or three letter abbreviations for metamorphic mineral names (e.g. Sph for sphene) and such schemes have since been widely adopted in both textbooks and research publications. The actual abbreviations used vary between different publications. In this book I follow Kretz (1994, Table 1.1) and Sang et al. (2005). I have added the minerals' Chinese names from Sang *et al.* (2005).

Table 1.3 Minerals of Metamorphic Rocks

(Deer, Howie & Zussman 1992, Kretz 1994, Sang *et al.* 2005)

Mineral Group	**Abbreviation and Chinese name**	**Chemical formula**	**Hand specimen properties**
SILICATE MINERALS			
Orthosilicates			
olivine group	**橄榄石族**		
olivine	Ol 橄榄石	$(Mg,Fe)_2SiO_4$	Orth. D 3.2-4.4 H 7, # None, Green, yellow.
forsterite	Fo 镁橄榄石	Mg_2SiO_4	Orth. D 3.2, H 7, # None, Yellow, colourless.
garnet group	**Gt 石榴石族**		
almandine	Alm 铁铝榴石	$Fe_3Al_2Si_3O_{12}$	Cub. D 3.6, H 6-7½, # None, Red-black
pyrope	Prp 镁铝榴石	$Mg_3Al_2Si_3O_{12}$	Cub. D 3.6, H 6-7½, # None, Bright red
spessartine	Sps 锰铝榴石	$Mn_3Al_2Si_3O_{12}$	Cub. D 3.6, H 6-7½, # None, Black
grossular	Grs 钙铝榴石	$Ca_3Al_2Si_3O_{12}$	Cub. D 3.6, H 6-7½, # None, Red, yellow
andradite	Andr 钙铁榴石	$Ca_3Fe^{3+}{}_2Si_3O_{12}$	Cub. D 3.6, H 6-7½, # None, Red
aluminium silicate group	**Al_2SiO_5 族**		
sillimanite	Sil 夕线石	Al_2SiO_5	Orth. D 3.3, H 6-7, #1, None, Grey
kyanite	Ky 兰晶石	Al_2SiO_5	Tric. D 3.6, H 5.5-7 variable, #2, Blue, grey
andalusite	And 红柱石	Al_2SiO_5	Orth. D 3.1, H 6-7, #2, Pink, grey
mullite	Mu 多铝红柱石	$3Al_2O_3.2SiO_2$	Orth. D 3.2, H 6-7, #1, None or pink, yellow
other orthosilicates	**其他正硅酸盐**		
sphene (titanite)	Sph 榍石	$CaTi[SiO_4](O,OH,F)$	Mon. D 3.5-3.6 H 5, #2, None, brown, black
chloritoid	Cld 硬绿泥石	$(Fe,Mg)_2(Al,Fe^{3+})(OH)_4$ $Al_3O_2[SiO_4]_2$	Mon., Tric. D 3.5-3.8, H 6½, #3, Green to black
larnite	Lar 斜硅钙石	$Ca_2[SiO_4]$	Mon. D 3.3, #1, White
spurrite	Spu 灰硅钙石	$2Ca_2[SiO_4].CaCO_3$	Mon. D 3.0, H 5, #1, White
Disilicates			
epidote group	**绿帘石族**		
epidote	Ep 绿帘石	$Ca_2Al_2O.(Al,Fe_{3+})OH$ $[Si_2O_7][SiO_4]$	Mon. D 3.4, H 6, #1, Yellow, green
zoisite	Zo 黝帘石	$Ca_2Al_2O.AlOH$ $[Si_2O_7][SiO_4]$	Orth. D 3.2-3.3, H 6-7, #2, Grey, green.
clinozoisite	Czo 斜黝帘石	$Ca_2Al_2O.AlOH$ $[Si_2O_7][SiO_4]$	Mon. D 3.2-3.4, H 6½, #1, None, pale green

other disilicates	**其他双硅酸盐**		
lawsonite	Lw 硬柱石	$CaAl_2[Si_2O_7](OH)_2.H_2O$	Orth. D 3.1, H 6, #2, None, bluish green
carpholite	Car 纤锰柱石	$(Mg,Fe^{2+})Al_2[Si_2O_6](OH)_4$	
pumpellyite	Pu 绿纤石	$Ca_2Al_2(Mg,Fe,Al)[Si_2(O,OH)_7](OH,O)_3$	Mon. D 3.2, H 5-6, #2, Green, brown
rankinite	Ran 硅钙石	$Ca_3[Si_2O_7]$	Mon. D 3.0, H 5½， # None, White
kilchoanite	Kl 斜方硅钙石	$Ca_3[Si_2O_7]$	Orth. polymorph of Ran
tilleyite	Til 粒硅钙石	$Ca_3[Si_2O_7].2CaCO_3$	Mon. D 2.8, #1, White
Ring silicates			
cordierite	Crd 堇青石	$(Mg,Fe)_2[Si_5Al_4O_{18}].n(H_2O,CO_2)$	(Hex.) D 2.5-2.8, H 7, #1, Dark blue, green-blue
tourmaline	Tur 电气石	$(Na,Ca)(Mg,Fe,Mn,Li,Al)_3[Si_6O_{18}](BO_3)_3(O,OH)_3(OH,F)$	Trig. D 3.0-3.2, H 7, # None, Black, blue, green, yellow.
Single chain silicates			
orthopyroxene group	**Opx 斜方辉石族**		
enstatite	En 顽火辉石	$Mg[SiO_3]$	Orth. D 3.2, H 5-6, #2, None, yellow
hypersthene	Hy 紫苏辉石	Orthopyroxene intermediate between $Mg[SiO_3]$ and $Fe[SiO_3]$	Orth. D 4.0, H 5-6, #2, Dark brown
clinopyroxene group	**Cpx 单斜辉石族**		
diopside	Di 透辉石	$CaMg[Si_2O_6]$	Mon. D 3.2, H 5½, #2, White, green
hedenbergite	Hd 钙铁辉石	$CaFe[Si_2O_6]$	Mon. D 3.6, H 6½, #2, Brown, dark green, black
omphacite	Om 绿辉石	$(Ca,Na)(Mg,Fe,Fe^{3+},Al)[Si_2O_6]$	Mon. D 3.2-3.4, H 5-6, #2, Green
jadeite	Jd 硬玉	$NaAl[Si_2O_6]$	Mon. D 3.2-3.4, H 6, #2, None, green, blue
other single chain silicates	**其他单链状硅酸盐**		
wollastonite	Wo 硅灰石	$Ca[SiO_3]$	Tric. D 2.9-3.1, H 4½-5, #3, White, grey
sapphirine	Sap 假蓝宝石	$(Mg,Fe^{2+},Fe^{3+},Al)_8O_2[(Al,Si)_6O_{18}]$	Mon. D 3.4-3.6, H 7½, #1, Light blue, green, grey
Double chain silicates	**双链状硅酸盐**		
Mg, Fe-amphibole group	**Mg,Fe 角闪石族**		
anthophyllite	Ant 直闪石	$(Mg,Fe)_7[Si_8O_{22}](OH)_2$	Orth. D 2.9-3.6, H5½-6, #2, White, grey
gedrite	Ged 铝直闪石	$(Mg,Fe,Al)_7[Si_6Al_2O_{22}](OH)_2$	Orth. D 2.9-3.6, H5½-6, #2, White, grey

cummingtonite	Cum 镁铁闪石	$(Mg,Fe)_7[Si_8O_{22}](OH)_2$	Mon. D 3.1-3.6, H 5-6, #2,Dark green, brown
grunerite	Gru 铁闪石	$Fe_7[Si_8O_{22}](OH)_2$	Mon. D 3.1-3.6, H 5-6, #2,Dark green, brown
Ca-amphibole group	**Ca 角闪石族**		
actinolite	Act 阳起石	$Ca_2(Mg,Fe)_5[Si_8O_{22}](OH)_2$	Mon. D 3.1-3.5, H 5-6, #2, Pale green, dark green
tremolite	Tr 透闪石	$Ca_2Mg_5[Si_8O_{22}](OH)_2$	Mon. D 3.0, H 5-6, #2, None, grey
hornblende	普通角闪石	$(Na,K)_{0-1}Ca_2(Mg,Fe^{2+},Fe^{3+},Al)_5[Si_{6-7.5}Al_{2-0.5}O_{22}](OH)_2$	Mon. D 3.0-3.6, H 5-6, #2, Dark green, black
Na-amphibole group	**Na 角闪石族**		
glaucophane	Gl 蓝闪石	$Na_2Mg_3Al_2[Si_8O_{22}](OH)_2$	Mon. D 3.1-3.2, H 6, #2, Blue, lavender blue
crossite	Crs 青铝闪石	Intermediate between Gl and Rie.	
riebeckite	Rie 钠闪石	$Na_2Fe_3Fe^{3+}{}_2[Si_8O_{22}](OH)_2$	Mon. D 3.2-3.5, H 5, #2, Dark blue, black
mica group	**云母族**		
muscovite	Ms 白云母	$K_2Al_4[Si_6Al_2O_{20}](OH)_2$	Mon. D 2.8-2.9, H 2½-3, #1, None, pale green, brown
paragonite	Pg 钠云母	$Na_2Al_4[Si_6Al_2O_{20}](OH)_2$	Mon. D 2.9, H 2½, #1, None, pale yellow
phengite	Phn 多硅白云母	$K_2(Al,Mg,Fe)_4[Si_6Al_2O_{20}](OH)_2$	Mon. D 2.8-2.9, H 2½-3, #1, None, pale green.
biotite	Bi 黑云母	$K_2(Mg,Fe^{2+})_{6-4}(Fe^{3+},Al,Ti)_{0-2}[Si_6Al_2O_{20}](OH)_2$	Mon. D 2.7-3.3, H 2-3, #1, Black, brownish black
phlogopite	Ph 金云母	$K_2Mg_6[Si_6Al_2O_{20}](OH)_2$	Mon. D 2.7, H 2, #1, Golden yellow
clay mineral group	**粘土矿物族**		
illite	Ill 伊利石	Complex, roughly Ms + H_2O	Mon. D 2.6-2.9, H 1-2, #1, White, pale colours
celadonite	Cel 绿鳞石	$K_{1.5-1.0}Al_4[Si_{6.5-7.0}Al_{1.5-1.0}O_{20}](OH)_4$	
carpholite	Car 纤锰柱石	$(K,Ca,Na)_{\sim 1.6}(Fe^{3+},Mg,Fe^{2+},Al)_4Si_{7.6}Al_{0.4}O_{20}(OH)_2$	
montmorillonite	Mm 蒙脱石	$(½Ca,Na)_{0.7}(Al,Mg,Fe)_4[(Si,Al)_8O_{20}]_4.nH_2O$	
smectite	Sm 蒙皂石	Minerals with similar composition to Mml	
other sheet silicates	**其他层状硅酸盐**		
serpentine	Ser 蛇纹石	$(Mg,Fe^{2+},Fe^{3+},Al)_{12}[(Si,Al)_8O_{20}](OH)_{16}$	Trig., Mon., Orth. D 2.6, H 2½-3½, Green, white
asbestos	石棉	Usually a fibrous form of serpentine	
prehnite	Prh 葡萄石	$Ca_2(Al,Fe3+)[AlSi_3O_{10}](OH)_2$	Orth. D 2.9-3.0, H 6-6½, #1, Pale green, yellow, grey

Framework silicates			
feldspar group	**长石族**		
K-feldspar	Kf 钾长石	$K[AlSi_3O_8]$	Mon., Tric. D 2.6 H 6-6½, #2, None, white, pink, green
plagioclase	Pl 斜长石	Ab-An	Tric.
albite	Ab 钡长石	$Na[AlSiO_3O_8]$ (An_0-An_{10})	Tric., D 2.6, H 6-6½, #2, None, white, pink
oligoclase	奥长石	$(An_{10}-An_{30})$	
andesine	中长石	$(An_{30}-An_{50})$	
anorthite	An 钙长石	$Ca[Al_2Si_2O_8]$ $(An_{90}-An_{100})$	Tric., D 2.8, H 6-6½, #2, None, green, black
perthite	条纹长石	Intergrowth of plagioclase in K-feldspar	
antiperthite	反纹长石	Intergrowth of K-feldspar in plagioclase	
zeolite group	**Zeo 沸石族**		
analcite	Anl 方沸石	$Na[AlSi_2O_6].H_2O$	Cub., D.2.2-2.3, H 5½, # poor, None, white, pink, grey
wairakite	Wr 斜钙沸石	$Ca[AlSi_2O_6]_2.2H_2O$	Mon., Ca equivalent of Anc
SiO_2 minerals	**SiO_2矿物**	SiO_2	
quartz	Q 石英	SiO_2	Trig., D 2.65, H 7, # None, None, white
coesite	Coe 柯石英	SiO_2	Mon., D 2.9
SINGLE ELEMENT MINERALS			
graphite	Gra 石墨	C	*Hex., H 1, #1,
diamond	Dia 金刚石	C	Cub., H 10, # None
OXIDE MINERALS			
spinel group	**尖晶石族**		Cub.
spinel	Sp 尖晶石	$MgAl_2O_4$	Cub. D 3.5, H 7½, # None, Variable
hercynite	Hr 铁尖晶石	$FeAl_2O_4$	Cub. D 4.4, H 7½, # None, Variable
magnetite	Mt 磁铁矿	$FeFe^{3+}{}_2O_4$	*Cub. D 5.2, H 7½, # None, Black [magnetic]
other oxide minerals	**其他氧化物矿物**		
ilmenite	Ilm 钛铁矿	$FeTiO_3$	*Trig. D 4.7-4.8, H 5-6, # None, Black
rutile	Rt 金红石	TiO_2	Tet. D 4.2-5.5, H 6-6½, #2, Reddish brown, black
perovskite	Pvs 钙钛矿	$CaTiO_3$	(Cubic) D 4.0-4.8, H 5½, # None

HYDROXIDE MINERALS			
brucite	Brc 水镁石	$Mg(OH)_2$	Trig. D 2.4, H 2½, #1, White, greenish, brownish
diaspore	Dsp 硬水铝石	α-AlO(OH)	Orth. D 3.4, H 6½-7, #1, White-colourless
SULPHIDE MINERALS			
pyrite	Pr 黄铁矿	FeS_2	*Cub. D 5.0, H 6-6½, #poor, Pale brassy yellow
pyrrhotite	Prt 磁黄铁矿	Fe_7S_8-FeS	*(Hex.) D 4.6, H 3½-4½, # None, Bronze yellow
chalcopyrite	Cpy 黄铜矿	$CaFeS_2$	*Tet. D 4.1-4.3, H 3½-4½, # poor, Brass yellow
CARBONATE MINERALS			
calcite	Cc 方解石	$CaCO_3$	Trig. D 2.7, H 3, #3, None, white
magnesite	Mgs 菱镁矿	$MgCO_3$	Trig. D 3.0, H 3½-4½, #3, White, none, yellow
dolomite	Dol 白云石	$MgCa(CO_3)_2$	Trig. D 2.9, H 3½-4, #3, White, none, yellow, brown
ankerite	Ank 铁白云石	$Ca(Mg,Fe^{2+},Mn)(CO_3)_2$	Trig. D 2.9-3.1, H 3½-4, #3, White, yellow, brown
aragonite	Arg 文石	$CaCO_3$	Orth. D 2.9, H 3½-4, #1, None, white
OTHER MINERALS			
apatite	Ap 磷灰石	$Ca_5(PO_4)_3(OH,F,Cl)$	Hex. D 3.1-3.4, H 5, # None, Green, white, brown
deerite	Der 迪尔石	$Fe^{2+}{}_{13}Fe^{3+}{}_7Si_{13}(OH)_{54}$	Rare mineral in high P metamorphic rocks
howieite	硅铁锰钠石	$Na(Fe,Mn)_{10}(Fe,Al)_2Si_{12}(O,OH)_{44}$	Rare mineral in high P metamorphic rocks
zussmanite	菱硅钾铁石	$KFe_{13}Si_{17}AlO_{42}(OH)_{14}$	Rare mineral in high P metamorphic rocks

Key to mineral properties in Table 1.3, Column 4

An asterisk * indicates a mineral that is opaque in thin section.
Crystal systems: Cub. = cubic, Tet. = tetragonal, Orth. = orthorhombic, Mon. = monoclinic, Hex. = hexagonal, Trig. = trigonal, Tric. = triclinic (brackets indicate that the true symmetry does not belong to that system, but the mineral appears to be in the system in hand specimen).
D: density or specific gravity measured in g cm^{-3}. SI density unit is kg m^{-3}, thus a density recorded here as D 2.65 is 2.65 g cm^{-3} = 2 650 kg m^{-3}.
H: hardness on Moh's scale.
#: number of cleavages described as perfect or good by Deer, Howie & Zussman 1992.
Colour: usual colour in hand specimen. 'None' means the mineral is colourless.

1.4 English mineral names

The English names of types of minerals are usually the same or almost the same as in other western European languages such as French, German, Swedish, Italian and Spanish. For example *garnet* is grenate in French and Granat in German. They are not as logical as Chinese names because European languages have taken names haphazardly from different languages for over 200 years. There are fewer names based on the composition or properties of minerals than in Chinese. The suffix *–ite* is used both for rocks (e.g. *granite, syenite, diorite*) and minerals (e.g. *fluorite, calcite, sillimanite*). Mineral names do not have an initial capital letter in English. They have several origins:

1. Traditional names: these come from many languages. The *–ite* suffix may be added to a traditional name, e.g. *calcite* from the prefix calc- meaning lime-bearing and *jadeite* from jade, the semi-precious gem stone. Feldspar comes from English field (as in *fieldwork*) and spar, another word meaning mineral, so feldspar is a type of mineral often found in the field. Other examples, *quartz, mica, galena, garnet, diamond.*
2. Place names: e.g. *dolomite, andalusite, muscovite, labradorite, bytownite, larnite, minnesotaite*. *Dolomite* is named for the Dolomites, a range of mountains on the international border between Austria and Italy. *Andalusite* is named after Andalucía, the southern province of Spain. *Muscovite* is from Moscow, the Russian capital, because at one time the mineral was sold in markets there. *Labradorite* is from Labrador, a large province of Canada, and *bytownite* is named after a Canadian city. *Larnite* is after Larne, a seaport on the NW coast of Ireland, and *minnesotaite* after Minnesota a large state in the mid-West of the USA. The names may not be the same as the present names of places on maps, e.g. the name of the Canadian capital has changed from Bytown to Ottawa, and in modern Spanish Andalucía is spelled differently from the mineral name. Igneous rocks with the suffix *–ite* are also often called after places and this causes a lot of confusion.
3. People's names: e.g. *sillimanite, forsterite, wollastonite, deerite, howieite, zussmanite*. The names of distinguished Earth scientists are preferred. Sillimanite is called after Benjamin Silliman, a pioneering American mineralogist who started the *American Journal of Science*, an Earth Science journal. Deer, Howie and Zussman are British editors of a series of mineralogy books.
4. Properties of minerals: e.g. *magnetite* is magnetic, *fluorite* is fluorescent, i.e. it lights up in ultra-violet light. *Kyanite* comes from the word cyan, derived from Ancient Greek and meaning blue. (In German, kyanite is called Disten, meaning two hardnesses.) *Glaucophane* comes from the Greek glaucos, also meaning blue.
5. Composition of minerals: e.g. cuprite from cuprum (Cu) the Latin name of copper, *magnesite* from magnesium (Mg) because it is an ore of magnesium.

Between 12 and 20 new minerals are discovered each year and their discoverers choose names for them. Scientists who discover a new mineral must publish their discovery in an international journal and submit their evidence to a committee of the International Geological Congress, who will approve the new name if they are convinced that the mineral is really new, and not (for example) a variety of a previously known mineral. The committee takes its task seriously, e.g. it disallowed the names *trafficlite* and *streikelite*, even though in the latter case the discoverers of the mineral protested that there was an Austrian mineralogist named Streikel. The committee also strikes out previous names of minerals that research shows are not real but (for example) intergrowths of two other minerals. Names like sericite, perthite, peristerite and chiastolite are not proper mineral names but informal names for microstructural combinations of minerals.

Units of measurement

You should use units of the Standard International System (SI), but other units used in international publications are included here with their SI equivalents. Approved SI unit symbols are shown in their definitions in bold type (e.g. **GPa**), other unit symbols are in normal type.

1. **temperature**	Degrees Celsius ("Centigrade", **^{o}C**) Also degrees Kelvin (or "degrees absolute") (1 **K** = ^{o}C + 273)
2. **pressure**	The Standard International unit is the pascal (**Pa**). Pressures of interest in geology are in kilopascals (1 **kPa** = 1000 Pa), megapascals (1 **MPa** = 1 000 000 Pa) and gigapascals (1 **GPa** = 1 000 000 000 Pa). English language publications use other units, especially in the United States of America, linguistically the most conservative English-speaking country. Some examples are: bar (bar) = 100 000 Pa or 100 kPa kilobar (kbar) = 100 000 000 Pa, 100 000 kPa, 0.1 GPa atmospheres (atm) approximately 1bar, 100kPa pounds per square inch (p.s.i.) approx. 7kPa degrees Fahrenheit (^{o}F) = ^{o}C x 9/5 + 32.

1.5 Description of thin sections of metamorphic rocks

To make a rapid and accurate description of a thin section, carry out the following observations. The order here is the sequence to be followed in your final written report. In practice, you will begin at section 2, and complete section 1 after you are sure that you have identified the minerals in the rock.

1) Make a list of the minerals you have found in the section. Distinguish the main minerals (>1%) from the accessory minerals (<1%). If you can recognise a mineral assemblage, give a list with the mineral names separated by + signs (e.g. biotite + muscovite + garnet + quartz + opaques).
2) Describe and identify the main minerals. Describe properties if they are either diagnostic or unusual, but omit the familiar or obvious (e.g. "Garnet is isotropic"). Here is a check-list of things to look out for:
   a) BEGIN IN PLANE POLARISED LIGHT. Relief + refractive index relative to the mounting medium (RI = 1.538)
   b) Colour and pleochroism, pleochroic scheme
   c) Form and habit of the crystals, presence or absence of cleavages

d) NOW CROSS THE POLARS. Birefringence
e) Extinction angle relative to crystal edges, cleavage traces, twinning planes or other features (state which)
f) Orientation; length fast or length slow
g) Interference figure in convergent light
h) BACK TO PPL. Signs of alteration of the mineral. What are the alteration products?
i) Are there inclusions in the mineral? If so, what are they?
j) NOW identify the mineral, noting any diagnostic properties.
k) Estimate the average grain-size of the mineral (e.g. 0.1mm)
l) Indicate the habit of the crystals of the mineral (Fig. 1.2)

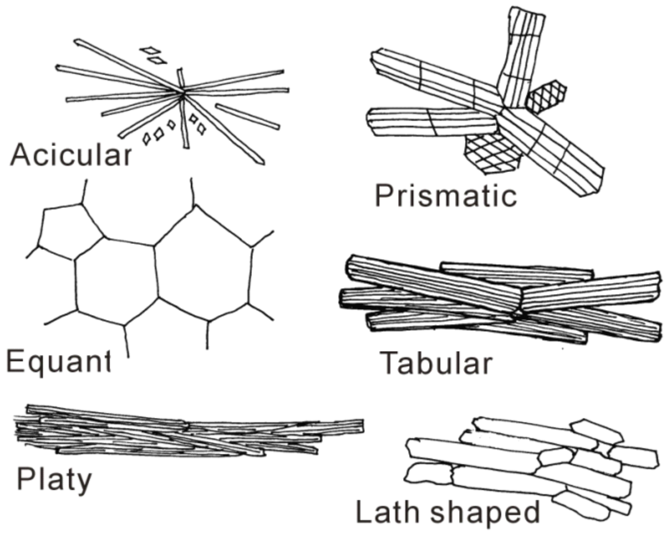


Fig.1.2 Shapes of minerals as they appear in thin section under the microscope.

3) Briefly describe the accessory minerals, giving the properties you used to identify them.
4) Describe the inter-relationships between the minerals. ILLUSTRATE THIS SECTION WITH A SKETCH DIAGRAM. Label the different minerals, and indicate the scale (a scale bar is best). In most cases, such a diagram should show the rock in ppl. Drawing the view between crossed polars does not usually add information (an exception might be, for example, sector twinning in cordierite). Despite what some books say, there is no such thing as cross-polarised light. Particular features to look for are:
   a) Which minerals are fresh, and which have been altered?
   b) Can you determine a sequence of mineral growth e.g. from one mineral growing over another, or from the relationships of minerals to a rock fabric?
5) Describe the microstructure (fabric or texture) of the rock. Illustrate it with a sketch diagram, or refer to the diagram you drew for section 3 above.
   a) Record any planar or linear preferred orientations (foliation and lineation microstructures) present in the rock.
   b) Record any microstructures surviving from the igneous or sedimentary protolith (e.g. bedding, porphyritic textures), and all metamorphic microstructures if any survive.

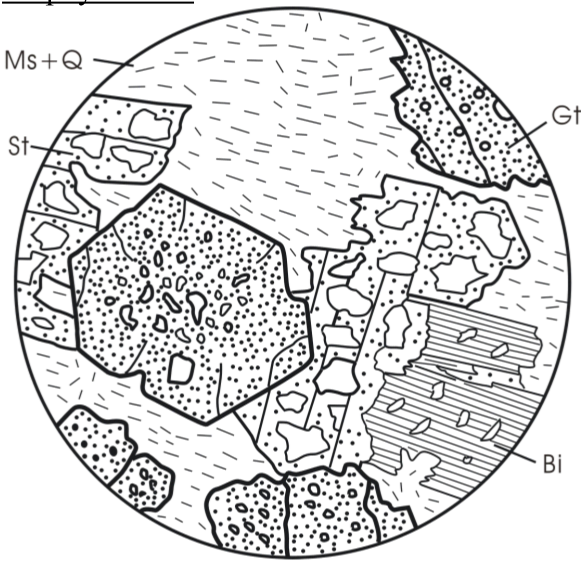
6) Give the rock a name (identify the rock) if you can. State its metamorphic grade, and describe its metamorphic history as far as you can.

Fig. 1.3 is an example of a thin section drawing and description of a regional metamorphic rock.

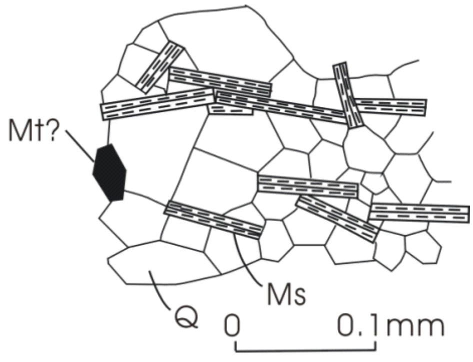
Thin Section C_{17}

Hand specimen: porphyroblastic schist

Porphyroblasts x40



Groundmass x400



（Dashes in left hand drawing indicate local direction of muscovite flakes）

Mineral proportions: garnet 10%, biotite 5%, staurolite 10%, quartz 50%, muscovite 25%.
Quartz: 70% groundmass. Unstrained crystals, flat grain boundaries, 120^o triple junctions (see groundmass drawing). Variable grain-size 0.02-0.5mm.
Muscovite: 30% groundmass. Platy habit, max length 0.1mm, 2nd order blue interference colours, parallel extinction. Local preferred orientation defines schistosity.
Biotite: large and small porphyroblasts that may cross-cut schistosity. Small porpyroblasts occur in the groundmass near large biotite porphyroblasts. Quartz inclusions with internal schistosity (s_i) sometimes preserved, see drawing. Max size 0.6mm.
Garnet: equant porphyroblasts with quartz inclusions concentrated in cores. Internal s_i sometimes preserved, rotated relative to external schistosity. Uniform size 0.6-1.0mm.
Staurolite: Sieve-textured porphyroblasts, not in matrix. Growing along grain boundaries between quartz crystals. Largest crystals >10.0mm. Pleochroic, pale yellow to yellow. 1st order int. colours, extinction parallel to crystal faces.
Accessory minerals: opaque minerals, some probably magnetite (see matrix drawing), zircon, tourmaline.

The groundmass microstructure of quartz and muscovite indicates an equilibrium mineral assemblage Qtz+Ms+Bi+Gt+St. The sieve texture of staurolite shows that it grew rapidly and enclosed slower growing garnet and biotite. The groundmass grain-size is variable, perhaps suggesting that the rock is an annealed mylonite.

Rock name: *staurolite-garnet schist*.

Fig.1.3 Specimen thin section description.

HOMEWORK

Study Table 1.2. Note that 'primary rock composition' means the name of the protolith sedimentary or igneous rock. Answer these questions:

1. What is the name of a metamorphic rock made of 90% calcite, and what is its protolith?
2. What is the name of a metamorphic rock with grains 0.8mm in size, formed from shale?
3. What are the main minerals in granitic gneiss?
4. What *volcanic* igneous rock is the protolith of halleflinta?
5. What are the main minerals in (a) quartzite and (b) amphibolite?