Practical Notes

Mineralogy and Petrology 2

Mike Sandiford

May 18, 1994

1 Metamorphic rock descriptions

One of the aims of this practical course is to develop the ability to recognise and describe metamorphic rocks, both in hand specimen and thin section. While there are no hard and fast rules about how metamorphic rocks should be described these notes should provide some basic guidelines for your initial descriptions.

To set about describing metamorphic rocks we must have some preconceived notion about what is interesting and therefore worth describing (and conversely what is boring and not worth describing). In the study of metamorphic rocks we are interested largely in determining:

- the original nature of the rock (i.e., was it sedimentary or igneous, what type of sediment, i.e., calcareous or clastic, psammitic or pelitic etc.),

- the pressure-temperature conditions of formation or grade of the rock,

- the deformation history of the rock.

We can only make correct interpretations about these three facets of a metamorphic rock if we make good observations in the first place. It is

absolutely important therefore to be able to observe and describe rocks independently of, and without being prejudiced by, our interpretation. A rock description should present our own observations in such a way that another person can independently interpret the evolution of that rock. Whatever the format of a metamorphic rock description the following aspects must be addressed:

- mineralogy,

- fabric,

- microstructure.

1.1 Mineralogy

Because many metamorphic minerals have a limited stability in pressure - temperature space, the minerals in a metamorphic rock give us information concerning the temperature and pressure conditions or grade of metamorphism. The minerals in a metamorphic rock also give us information about the bulk composition of the rock (i.e., whether the rock is aluminous or calcic or potassic etc.) from which we can make inferences about the premetamorphic nature of the rock. So a description of a metamorphic rock must include a list of the minerals in the rock. Normally the most abundant as well as the most interesting metamorphic minerals in the rock are incorporated in the rock name. For instance the name *garnet-biotite-quartz schist* is applied to rock consisting mainly of garnet, biotite and quartz which shows a schistose fabric. Normally the minerals which convey the most information about the metamorphic grade are listed first, and thus the order of the minerals in a name is not indicative of the abundance of the minerals. Some idea of the proportion of the minerals should however be included in the description. Accessory phases (i.e., those phases which constitute $< 5\%$ of the rock) are not included in the rock name, unless they are of some special significance. However all accessory minerals should be listed in the description.

1.2   Fabric

The fabric of a metamorphic rock is defined by the three dimensional arrangement of the minerals within the rock, and reflects in large part the deformation (or strain) history of the rock. Metamorphic rocks that have been deformed pervasively during metamorphism commonly have anisotropic fabrics. Standard terms are generally applied to such anisotropic fabrics and are usually incorporated in the name of the rock. For rocks which contain planar fabrics defined by platy minerals (normally sheet silicates such as chlorites and micas) we differentiate between slates (or phyllites) and schists on the basis of the grainsize of the platy minerals. A useful rule of thumb is that if the individual platy minerals can be seen in hand specimen we use the term schist, whereas if they are too fine to be seen in hand specimen we use the term slate. Coarse grained metamorphic rocks which show layering of the metamorphic minerals, but do not have platy minerals defining a schistosity, are termed gneiss (pronounced nice not neice). Coarse grained metamorphic rocks showing no layering are distinguished from gneisses by the term granofels .

In addition to the fabric component used in the name, the description should include any other fabric forming elements present in the rock, for example, lineations. Intersection lineations should be distinguished from mineral elongation lineations.

It is important to realise that although for any given rock type there will generally be a coarsening of grain size with increasing metamorphic grade, there is no direct correlation between grade and grainsize. The grainsize of metamorphic rocks is controlled by a number of variables other than grade. Two important additional influences on grain size in metamorphic rocks are:

- the presence of dispersed impurities in the rock. For instance, dispersed carbonaceous matter which turns to graphite on metamorphism is very effective at pinning grain boundary migration during metamorphim and thus prohibits grain coarsening. Car-

bonaceous or graphitic slates can therefore exist to very high grades of metamorphism without loosing there slatey fabric (i.e., without turning into schists).

- the strain rate during deformation. Metamorphic rocks deformed at very high strain rates are typically very fine grained independent of the grade of metamorphism. Such high strain rate rocks which are characteristic of shear zones (the deep level extension of fault zones) and have very characteristic microstructures. Such rocks are termed mylonites. Thus you should be wary of interpretations about the grade of a metamorphic rock on the basis of fabric considerations alone.

1.3 Microstructure

The microstuctural or textural relationships between the individual minerals of a metamorphic rock gives us information about the relative timing of growth of the minerals and about the relationship between metamorphism and deformation. Importantly, microstructures which indicate the sequential growth of different minerals may provide invaluable information concerning the way in which pressure and temperature have changed during the evolution of the rock, that is, about the pressure-temperature-time path of the rock.

Important terms used to describe the texture of metamorphic rocks include:

- porphyroblast: for any crystal which is very large compared to the average crystal size of the rock.

- poikiloblast: for porphyroblasts which contain inclusions of other minerals.

- granoblastic: for even grained polygonal textures.

1.4   Example description with sketch

Sample 891-011, staurolite-kyanite amphibolite, Harts Ranges

Sample 891-011 (from the Harts Range, central Australia) is a coarse grained staurolite-kyanite amphibolite. Two distinct textural domains are recognisable:

- Aluminous enclaves consisting of staurolite-kyanite aggregates surrounded by moats of plagioclase (see Figure below).

- texturally equilibrated intergrowths of hornblende- plagioclase-quartz that form the bulk of the rock and surround the individual aluminous enclaves.

Hornblende is never observed in contact with either kyanite or staurolite from which it is always separated by a moat of plagioclase. There is no preferred orientation of individual crystals either within of between individual enclaves. Kyanite forms large (up to 5mm) subhedral grains and aggregates of small grains that are corroded and embayed. Kyanite grains are commonly rimmed by epitaxial overgrowths of staurolite (1mm in width). Optical zoning in the plagioclase moats shows an increase in anorthite content towards the aluminous enclaves. In the less aluminous parts of the sample, coarse (8-30mm) hornblende, plagioclase and quartz which have straight to slightly curved grain boundaries with common triple junctions indicative of a high degree of textural equilibration. Quartz generally shows undulose extinction.

..

2 Practical 1: Pelitic rocks

The aim of this practical is to gain familiarity with the mineralogy
and textures of pelitic schists and gneisses. Using illustrative sketches
and giving a list of the minerals and their approximate modal propor-
tions briefly describe the following sections, taking note of the listed
features:

- A171-71 : staurolite schist,

- 171-70 : andalusite schist,

- 83 : garnet-sillimanite gneiss with cordierite-spinel reaction coro-
  nas,

- 171-170 : biotite schist with crenulation cleavage,

- 1a : biotite schist with crenulation cleavage and late chlorite.

Make sure you can recognise the following minerals in both thin section and hand specimen

- biotite

- muscovite

- chlorite

- andalusite (see examples in both veins and schists)

- garnet

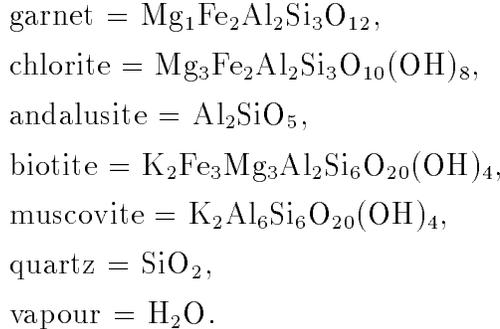- sillimanite (both fibrolite and prismatic forms)

- staurolite

- cordierite

also view the hand specimen of kyanite.

3 Balancing reactions

An important skill involved in understanding the reaction history of metamorphic rocks is writing balanced reactions. Many simple reactions may be balanced by inspection but more complicated reactions need to be tackled in a more systematic fashion. The basic strategy is to establish a set of simultaneous equations that express the conservation of matter. To illustrate we will use an example involving the reaction that marks the andalusite-in isograd at the boundary between the garnet- and andalusite-zones in the Buchan facies series. By inspection of simple chemographic relationships in AFM (see next section on compatibility diagrams) the reaction must have the form:

$$\text{gt} + \text{chl} + \text{mu} \Rightarrow \text{and} + \text{bt} + \text{H}_2\text{O}$$
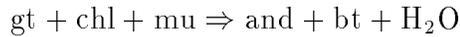
Quartz is also likely to be involved, however, it is not easy to see which side of the reaction it is on without first balancing. We assume the following compositions $X_{Fe,gt} = 0.66$, $X_{Fe,bt} = 0.5$ and $X_{Fe,chl} = 0.4$, which gives the full mineral formulas:

garnet = $\text{Mg}_1\text{Fe}_2\text{Al}_2\text{Si}_3\text{O}_{12}$,
chlorite = $\text{Mg}_3\text{Fe}_2\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_8$,
andalusite = Al_2SiO_5,
biotite = $\text{K}_2\text{Fe}_3\text{Mg}_3\text{Al}_2\text{Si}_6\text{O}_{20}(\text{OH})_4$,
muscovite = $\text{K}_2\text{Al}_6\text{Si}_6\text{O}_{20}(\text{OH})_4$,
quartz = SiO_2,
vapour = H_2O.

The method recommended for balancing reactions is as follows:

Let the reaction coefficient of phase i be r_i. The equation expressing the conservation of Si is then:

$$3\,r_{gt} + 3\,r_{chl} + r_{and} + 6\,r_{bt} + 6\,r_{mu} + r_{qtz} = 0 \qquad (1)$$

Similarly, the following equations apply for the conservation of Fe, Mg, Al, K, and H:

$$2\,r_{gt} + 2\,r_{chl} + 3\,r_{bt} = 0 \qquad (2)$$

$$1\,r_{gt} + 3\,r_{chl} + 3\,r_{bt} = 0 \tag{3}$$

$$2\,r_{gt} + 2\,r_{chl} + 2\,r_{and} + 2\,r_{bt} + 6\,r_{mu} = 0 \tag{4}$$
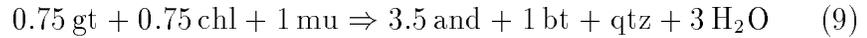
$$2\,r_{bt} + 2\,r_{mu} = 0 \tag{5}$$

$$8\,r_{chl} + 4\,r_{bt} + 4\,r_{mu} + 2\,r_v = 0 \tag{6}$$

We now need to determine a set of reaction coefficients that satisifes the constraints expressed by Eqn (1)-(6). Given that any multiple of a solution is also a solution we can normalise against an arbitary coefficient for any one of the phases. Letting $r_{bt} = 1$, then from Eqn (5) we have $r_{mu} = $ -1. Eqns (2) and (3) now give:

$$2\,r_{gt} + 2\,r_{chl} = -3 \tag{7}$$

$$r_{gt} + 3\,r_{chl} = -3 \tag{8}$$

Solving for r_{chl} gives $r_{chl} = $ -0.75, and hence $r_{gt} = $ -0.75. Substituting into the remaining equations gives $r_v = 3$, $r_{and} = 3.5$ and $r_{qtz} = 1$. Thus, the balanced reaction is:

$$0.75\,\text{gt} + 0.75\,\text{chl} + 1\,\text{mu} \Rightarrow 3.5\,\text{and} + 1\,\text{bt} + \text{qtz} + 3\,\text{H}_2\text{O} \tag{9}$$

The problem and procedure outlined above is of a type common in linera algebra and those of you with a passing knowledge of linear algebra should see that we have set up the equation:

$$\mathbf{A} . \mathbf{r_i} = \mathbf{0} \tag{10}$$

where $\mathbf{A}$ is the coefficient matrix:

$$\begin{pmatrix} 3 & 3 & 1 & 6 & 6 & 1 & 0 \\ 2 & 2 & 0 & 3 & 0 & 0 & 0 \\ 1 & 3 & 0 & 3 & 0 & 0 & 0 \\ 2 & 2 & 2 & 2 & 6 & 0 & 0 \\ 0 & 0 & 0 & 2 & 2 & 0 & 0 \\ 0 & 8 & 0 & 4 & 4 & 0 & 2 \end{pmatrix}$$

and $\mathbf{r_i}$ is the vector of unknown reaction coefficients:

$$\begin{pmatrix} r_{gt} \\ r_{chl} \\ r_{and} \\ r_{bt} \\ r_{mu} \\ r_{qtz} \\ r_v \end{pmatrix}$$

With more than a passing knowledge of linear algebra you may know that the solution is given formally by

$$\mathbf{r_i} = \mathcal{N}(\mathbf{A})$$

where $\mathcal{N}(\mathbf{A})$ is the nullspace of $\mathbf{A}$. For rather more complicated examples (which you will not be expected to do) procedures such as Gaussian elimination are often needed to solve the set of simultaneous equations. Such methods can be found in any standard text on linear algebra. (Note that before applying Gaussian elimination it is necessary to reduce Eqn **??** by assigning an arbitrary coefficient for one of the phases, thus defining a problem with as many equations as unkowns.)

Once a reaction has been balanced it is a relatively simple step to calculate the change in molar proportions of the phases invoved in the reaction, given some knowledge of the molar (or modal) proportions of the phases prior to reaction.

4   Compatibility diagrams

Compatibility diagrams provide a useful way of visualising the chemical relationships amongst mineral phases in metamorphic rocks, and are particularly useful in helping us to visualise what reactions may take place between the minerals. The compatibility diagram that we will use in this practical is the AFM diagram, which is particularly useful for illustrating the *chemographic relationships* in pelitic schists.

The AFM diagram entails a projection onto a compositional space defined by two independently variable components (and therefore, unlike the AKF and ACF diagrams that you might read about in various texts, constitutes a valid compatibility diagram). The composition of phases to be shown on the AFM diagram must be projected from a complex multidimensional composition space (usually at least 5-dimensions) onto a two dimensional space defined by the ternary system Al_2O_3-FeO-MgO, abbreviated to AFM.

To achieve this projection mineral compositions are projected from the saturating phases (phases that are always present in pelites such as quartz, muscovite or K-feldspar, H_2O) onto the AFM plane. To obtain the projecting co-ordinates of any phase we wish to display on the AFM diagram we simply need to write a balanced reaction between the phase to be plotted, the compositions of the three apices of the plot (namely, Al_2O_3, FeO and MgO) and the saturating phases that are always assumed to be present (namely, muscovite, quartz and H_2O fluid). The plotting co-ordinates are then given by the three coefficients for Al_2O_3, FeO and MgO normalised to unity.

A simplified procedure, illustrated below with an example involving biotite, achieves the same result as writing the full balanced reaction with *much less effort*. In this simplified procedure, for assemblages containing muscovite the projection co-ordinates are given by the proportions of (Al_2O_3 - 3 x K_2O), FeO and MgO in the phase to be projected, normalised to unity (in assemblages with K-feldspar instead of muscovite the projection co-ordinates are given by the proportions of (Al_2O_3 - K_2O), FeO and MgO normalised to unity).

Biotite has the limiting composition $K_2(Fe, Mg)_6Al_2Si_6O_{20}(OH)_4$. So that ($Al_2O_3$-3 x K_2O) defines a negative number. This is no problem, it simply means, that when projecting biotite from muscovite it plots further away from the A-apex of the AFM diagram than the line connecting the F- and M- apices. For instance, for a biotite with an Mg:Fe ratio of 2:1, the projection co-ordinates are calculated as follows:

11

$(Al_2O_3 - 3 \times K_2O) = 1 - 3 = -2$

$FeO = 2$

$MgO = 4$

$(Al_2O_3 - 3 \times K_2O) + Fe0 + MgO = 4$

co-ordinates of A = -0.5

co-ordinates of F = 0.5

co-ordinates of M = 1.0

5 Practical 2

5.1 Part 1: Balancing a reaction

Balance the reaction marking the staurolite-out isograd which involves the phases staurolite, kyanite, biotite, garnet, muscovite, quartz and H_2O-vapour assuming the following compositions for the ferro-magnesian phases: $X_{Fe,gt} = 0.8$, $X_{Fe,st} = 0.75$ and $X_{Fe,bt} = 0.6$.

5.2 Part 2: Projecting onto AFM

Using a projection from muscovite, quartz and H_2O, plot the following phases on an AFM diagram assuming the Mg : Fe ratio as specified:

- garnet = 1:4

- staurolite = 2:7

- kyanite -

- cordierite = 3:2

- chlorite = 2:1

- biotite = 1:1

Figure 1: Schematic representation of the AFM compatibility relations for the garnet-zone.

5.3 Part 3

The use of compatibility diagrams provides a powerful insight into the narture of the reactions that take place in real rocks. For instance, in the Kanmantoo metamorphics in the Mount Lofty Ranges (a terrain transitional between Buchan and Barrovian facies series) the lowest grade pelitic rocks have the assemblage biotite + chlorite + muscovite + quartz (and, presumably, H_2O).

With increasing grade garnet makes its first appearance as a very Fe-rich phase. At this grade the assemblage biotite + garnet (+ muscovite, quartz, H_2O) is stable in Fe-rich pelites while biotite + chlorite is stable in the most Mg-rich pelites, and garnet + chlorite is stable in more Al-rich or less K-rich pelites (see Figure 1).

What is the significance of the stipled region in Figure 1?

With increasing grade the assemblage staurolite-biotite becomes stable in rocks of intermediate Mg/Fe ratio. At this grade, biotite + garnet (+ muscovite, quartz, H_2O) is stable in more Fe-rich pelites while biotite-chlorite is stable in Mg-rich pelites.

Draw the appropriate AFM diagram and determine the reaction that causes staurolite to appear.

The next isograd is marked by the appearance of andalusite which

coexists with biotite and staurolite or biotite and chlorite.

This is followed in turn by the disappearance of staurolite which is coincident with the first appearance of the stable association garnet, andalusite and biotite.

The final zone, at highest grades, is marked by the appearance of cordierite which can coexist with biotite and andalusite in rocks of intermediate Fe-Mg composition and with biotite and chlorite in the most Mg-rich rocks.

Sketch the AFM diagrams appropriate to each of these metamorphic zones and describe the reactions which define the zone boundaries.

6   Practical 3

This practical is designed to illustrate the concept of equilibrium as it applies to metamorphic phase equilibria and to provide an introduction to phase diagrams

The principal aim is *to reinforce the notion of Gibbs energy as the thermodynamic function that is minimized at equilibrium.*

6.1   Part 1:

Using the G-T figures shown on page 24 of the lecture notes and the P-T information listed below construct the Al_2SiO_5 phase diagram in P-T space:

Figure 9, P = 2 kbars

$T_1 = 300°C$

$T_2 = 440°C$

$T_3 = 690°C$

Figure 9, P = 8 kbars

$T_4 = 400°C$

$T_5 = 690°C$

$T_6 = 850°C$

At what temperature and pressure does the triple point occur?

Due to uncertanties in the basic thermodynamic data there is an uncertainty of 50°C on the position of the andalusite = sillimanite reaction and an uncertainty of 10°C on the kyanite = sillimanite and

kyanite = andalusite reaction. In what range of temperatures and pressures can we realistically place the triple point?

6.2 Exercise 2

Using the G-X diagrams on the accompanying sheet, draw the compatibility diagrams for each temperature, $T_1 - T_4$, for the binary system involving the phases α, β and γ. Using the compatibility diagrams for each temperature, construct a T - X diagram (assume that the temperature intervals are equal and that $T_4 > T_3 > T_2 > T_1$). For a bulk composition consisting of equal proportions of the two components defining this binary system, calculate the approximate modal proportions of each phase in the equilibrium assmblage at each temperature. What reactions occur in the interval $T_2 - T_3$.