From mud to granite: The Cooma metamorphic sequence

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Summary of proposal

The mineral compositions and structural features of metamorphic rocks change when they are buried due to tectonic processes. How can geologists unravel the story that explains how these rocks were formed? A continuous sequence of rocks west of Cooma shows how the structure and mineral composition of an original mudstone was transformed to a granite as the rocks were exposed to increasing temperature and pressure.

Introduction

Metamorphic rocks are formed by transformation of sedimentary or igneous rocks by burial. During burial the rocks are exposed to increasing pressure and temperature in the interior of the Earth. The increase of pressure and temperature contributes to the formation of new minerals, many of which are not present in either sedimentary or igneous rocks. These new minerals are often aligned perpendicular to the main stress acting on the rocks as they are buried. This leads to a characteristic layering of aligned minerals in metamorphic rocks that is called a foliation. Therefore the structure and mineralogy are the main identification criteria of metamorphic rocks. Consequently, the study of metamorphic rocks always has a *structural component* as well as a *mineralogical component.*

The aim of geologists studying metamorphic rocks is to reconstruct the conditions that metamorphic rocks experienced as they formed. These conditions can include the depth and temperatures the rocks experienced, as well as the tectonic environments of formation such as collision or break-up of continents. Metamorphic rocks experience a complex evolution moving to great depths in the Earth and then back to the Earth's surface.

To unravel this history, relative timing of events as well as *absolute ages* are required. This case study will show how these fundamental concepts are used to understand the conditions and formation processes of metamorphic rocks. In a continuous sequence of rocks west of Cooma, the changes in structure and mineral assemblages with increasing temperature and pressure show the transformation of an original mudstone to a granite.

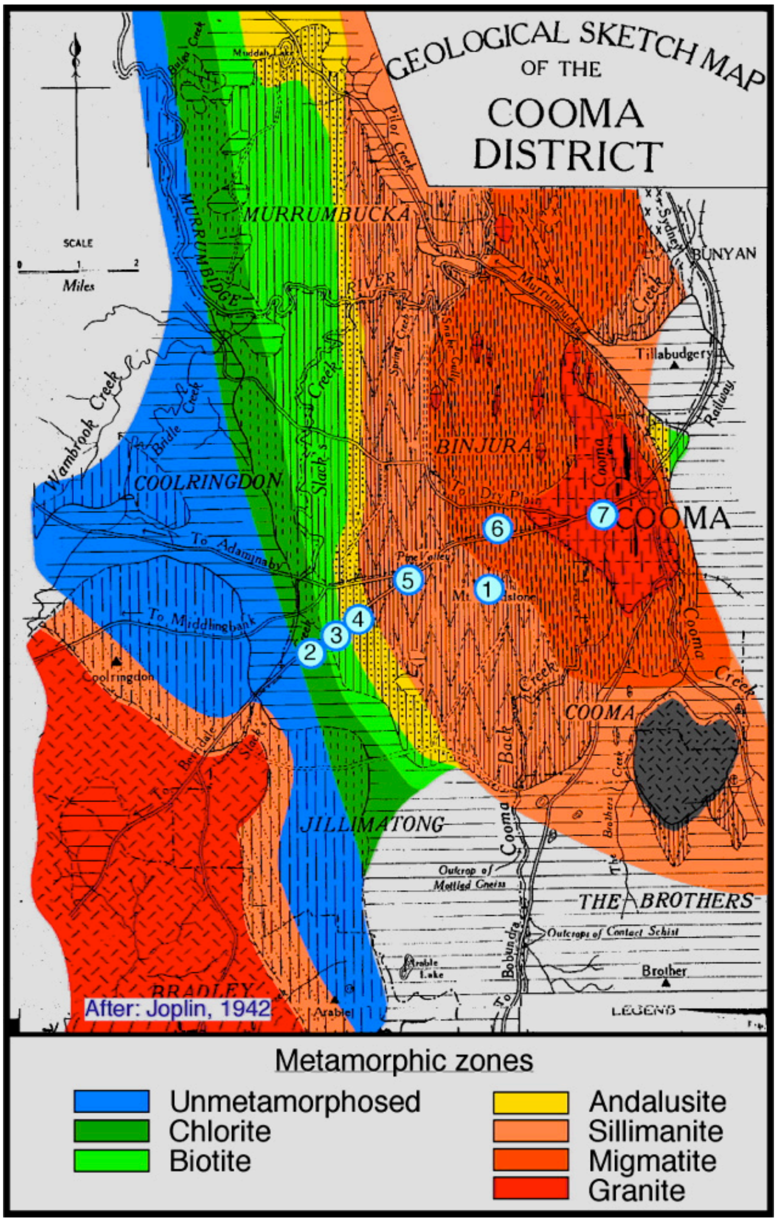

Figure 1. Geological Map of the Cooma region after Joplin (1942) and Hopwood (1976). With increasing metamorphic grade the rocks can be mapped as zones based on characteristic metamorphic minerals in the assemblage such as chlorite, biotite, andalusite and sillimanite. The highest-grade zones are mapped as the first occurrence of melting (migmatite zone) and as the granite intrusion. The numbers 2-7 represent easy accessible stops where the rocks crop out along the main road. Stop 1 refers to the Mt. Gladstone lookout, which is an excellent viewpoint of the whole sequence.

Geological setting

Cooma is located in the south-eastern part of the *Lachlan Fold Belt*, the Palaeozoic terrain over 700 km wide that forms the eastern 20% of the Australian continent. The basement rocks in the region are Ordovician (488-444 Ma[1]) sediments, which were strongly deformed at low metamorphic grade[2] in the late Ordovician. Granites and related volcanic rocks make up over 25% of the outcrop in the Lachlan Fold Belt. Most measured ages are in the range early Silurian (~435 Ma) to mid-Devonian (~370 Ma): the oldest rocks occurring in the Snowy Mountains region of southern New South Wales and the youngest mostly in central Victoria and along the east coast.

The Cooma Metamorphic Complex has an outcrop area of more than 300 km^2. The geological map based on the original study by Joplin (1942) and Hopwood (1976), shows that over a distance of less than 10 km west of Cooma, a complete sequence of metamorphic rocks ranging from un-metamorphosed sediments to high-grade metamorphic gneisses can be studied (Figure 1). There are rock outcrops along the Snowy Mountains highway that provide easy access. The complex is elongate North-South, parallel to the regional structure and the elongation of plutons of the Murrumbidgee Batholith immediately to the north, to which the metamorphic complex is probably related (Richards & Collins, 2002).

Rock cycle

The Cooma metamorphic sequence provides an outstanding illustration of the rock cycle with sedimentary, metamorphic and igneous rocks that are directly related to each other cropping out over a very short distance.

The *sedimentary rocks* west of Cooma (Fig. 1) consist of decimetre-thick layers of mudstone, siltstone and sandstone that are related to the deposition of the sediments (Fig. 2). In the sandstone layers, graded bedding[3] and cross bedding related to the deposition environment are preserved. The sedimentary rocks originated from 'turbidites', which were formed from submarine sand and mud avalanches at the transition from the continental shelf to the deep ocean floor. The Ordovician turbidites are part of a huge 'mud pile' that once extended along the eastern margin of the Gondwana supercontinent from South America and Africa, through Antarctica to New Zealand and north Australia. Similar deposits are formed today in the Bay of Bengal related to the erosion of the Himalayas.

Moving towards the east (Fig. 1), the sediments are replaced by *metamorphic rocks* that show a pronounced preferential orientation of minerals. The compositional layering that derives from the sedimentary rocks is visible throughout most of the metamorphic transformation of the rocks, providing evidence that the metamorphic rocks formed from the sedimentary turbidites (Fig. 2). New metamorphic minerals formed as a consequence of increasing temperature and pressure.

Around the township of Cooma, the pressure and temperature conditions are high enough for the metamorphic rocks to start melting. Melting is first visible in the formation of small veins and dykes (Fig. 2d), then the rocks are intensively interlayered between molten parts and residual parts (called a migmatite; Fig. 2e). In the layers that were partially molten, coarse grained, un-oriented minerals crystallized (Fig. 2k). Finally, only relics of the metamorphic rocks are present in a dominant association of coarse grained, un-oriented minerals (Fig. 2f). The metamorphic rocks have transformed to an *igneous rock*—a granite.

The Cooma granite is only fresh in road cuts and in exposed riverbeds. Generally the granite is highly weathered and breaks into single minerals close to the surface. These minerals are transported away and ground down to smaller grains, providing material that is washed down in the creeks and rivers to form a sediment again. The rock cycle is closed.

Textures of the Cooma metamorphic rocks

The textures of the rocks change with increasing metamorphic grade. In low-grade metamorphic rocks many minerals have a shape similar to sheets, resulting in a preferred orientation (like stacked sheets) that forms a foliation in the rocks. The foliation in low-grade rocks is very closely spaced and the rocks break into thin plates called *slates* (Fig. 2a). The grain size in the slates is very small, typically only a few tens of microns (2g). With increasing metamorphic grade, the rocks become *phyllites*. The grain size in phyllites is still very small (less than 100 µm; Fig 2h) and the foliation is still closely spaced, but the rocks break into thicker plates than the slates (Fig. 2b). With increasing grainsize, the rocks break into centimetre-thick slabs called *schists* (Fig. 2c).

Further coarsening of the minerals leads to a less pronounced foliation and more massive *gneisses* (Fig. 2d). With the onset of partial melting these gneisses are called *migmatites* (Fig 2e). The decrease in the intensity of foliation is related to a decreasing amount of minerals that have a flat, flaky shape (called platy) such as chlorite, muscovite and biotite. The examples in Figure 2 show that the change in texture of rocks and the increase in grainsize can be used as a first indicator for the metamorphic grade of a rock.

Figure 2. Outcrop photos of the metamorphic rocks with increasing grade (a-f). In green the name of the rock is shown. The names Slate, Phyllite, Schist and Gneiss refer to the texture of the rocks. Migmatites mark the occurrence of partial melts, represented by white veinlets. The granite is the final product of this melting process and occurs at the highest metamorphic conditions. Note the compositional banding between original muddy and sandy layers of the metamorphosed sediment that is visible in all metamorphic rocks, but then disappears in the granite. The main minerals in the rocks are given. Minerals in bold are used to define the mineral zones mapped in Figure 1. Photos of thin sections of the same rocks under the petrographic microscope using polarized light are shown in panels g-l. The scale bar represents 0.5 mm. Note the increase of grain size with increasing metamorphic grade.

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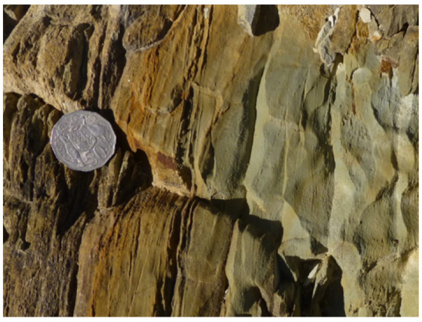
[1] Millions of years old

[2] The grade of metamorphic rocks provides a general indication of the degree of metamorphism they have been exposed to.

[3] In a graded bed there is a systematic change in grain size from the bottom to the top. Usually the coarser sediments would occur at the bottom of the sequence and finer sediments at the top.



a)

Slate
Muscovite
Chlorite
Quartz

b)

Phyllite
Muscovite
Chlorite
Biotite
Quartz

c)

Schist
Muscovite
Biotite
Cordierite
Andalusite
Quartz

d)

Gneiss
Muscovite
Biotite
Cordierite
Sillimanite
K-feldspar
Quartz

e)

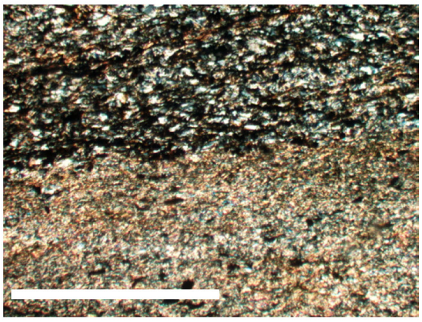
Migmatite
Biotite
Cordierite
Sillimanite
K-feldspar
Plagioclase
Quartz

f)

Granite
Biotite
Cordierite
Sillimanite
K-feldspar
Plagioclase
Quartz

Increasing metamorphic grade

g)



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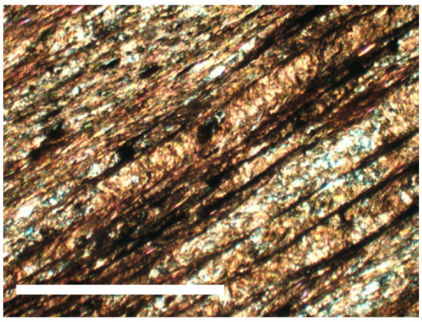
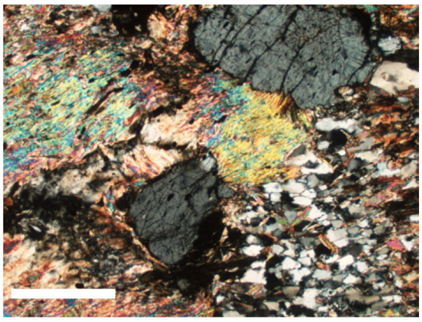


i)



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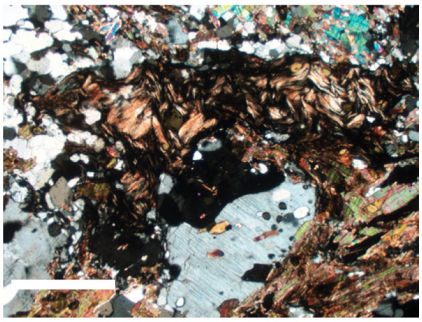

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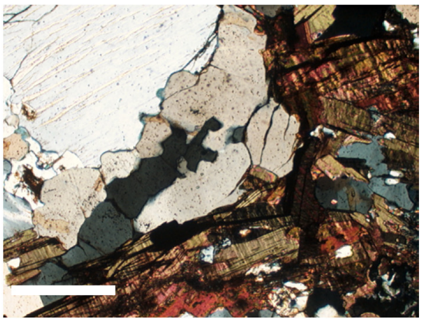

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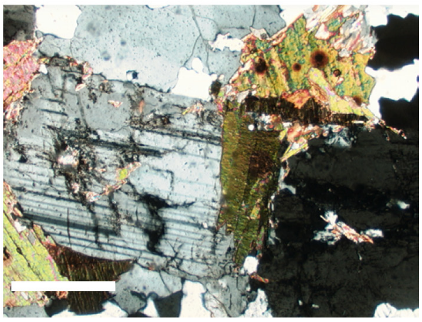

Mineralogy of the Cooma metamorphic rocks

In the Cooma area, the increase in metamorphic conditions can be seen in the change of mineral assemblages. In the slates, chlorite, muscovite and quartz are the dominant minerals. As chlorite is the most typical mineral in this assemblage the rocks have been classified as 'chlorite zone'. Biotite joins muscovite, chlorite and quartz in the mineral assemblage in the phyllites, and these rocks are labelled as coming from the 'biotite zone' (Fig. 1).

The next metamorphic stage is manifested by the growth of much larger minerals in the rocks. Up to centimetre-sized grains of andalusite and cordierite are wrapped into a finer grained matrix of muscovite, biotite and quartz. Such large, newly formed minerals are called porphyroblasts. Chlorite has disappeared. These rocks are labelled by the new occurrence of andalusite as 'andalusite zone'.

An interesting observation is that grain growth is not equal in all layers of the previous sedimentary sequence. Andalusite and cordierite form exclusively in the muddy (pelitic) layers of the former sediment, whereas the sandy layers mainly consist of quartz and minor biotite. This highlights the fact that the mineral assemblage in metamorphic rocks is not only dependent on the metamorphic grade (pressure and temperature conditions) but also on the chemical composition of the rocks. The muddy layers derive from clay minerals, which are very rich in aluminium, promoting the growth of aluminium-rich minerals such as andalusite and cordierite.

In the gneisses, andalusite is replaced by sillimanite and thus classified as 'sillimanite zone'. K-feldspar is starting to form at the expense of muscovite. Biotite is the only remaining platy mineral in the assemblage resulting in a much weaker fabric of the gneisses.

The migmatites contain the mineral assemblage of biotite, quartz, plagioclase, K-feldspar, sillimanite and cordierite. Muscovite has disappeared and the minerals are much coarser. It is interesting to note that the sandy layers of the sediment are still visible in places because the extent of melting is much smaller than in the more pelitic layers. The Cooma granite displays the same mineralogy as the migmatites, but the minerals are no longer aligned. Also the sandy layers have disappeared.

The different mineral zones are defined by the observed mineralogy and texture. The pelitic layers display a greater variety in minerals than the sandy layers, thus the classification of zones is entirely based on assemblages found in the former. The extent of each zone can be mapped (Fig. 1) by comparing the rocks through several sections. This provides a powerful tool for the interpretation of the metamorphism. Each boundary between the zones should represent comparable metamorphic conditions (called *isogrades*) and thus the distribution of isogrades can inform us about the heat distribution in the crust.

Metamorphic conditions

The texture and mineralogy of the rocks provides a relative scheme to distinguish between low-grade and high-grade metamorphic rocks, but they can't be used to reconstruct the exact conditions of formation. To solve this problem, researchers conducted many laboratory experiments in which mud rocks were exposed to variable pressure and temperature conditions. Figure 3 shows a compilation of key reactions in the metamorphism of pelitic rocks. The x-axis shows the temperature and the y-axis the pressure, which can be converted to depth of the rocks within the crust. In a stable continental crust, pressure and temperature both increase with increasing depth in a regular way as shown by the red curve. The average thickness of continental crust in Australia is about 35 km and thus in areas that are not disturbed by any tectonic activity, the temperature at the base of the continental crust is about 600°C.

In the Cooma rocks the minerals andalusite and sillimanite occur. Both these minerals have the same composition (Al_2SiO_5) but their mineral structure changes as a function of pressure and temperature. There is also a third mineral – kyanite – in that mineral family. The experiments have now shown that each of these minerals is only stable in a specific pressure-temperature field and the fields are delineated with reaction curves. Andalusite is stable at low-pressure, sillimanite at high-temperature and kyanite at high-pressure conditions. Figure 3 shows where the experimentally determined reactions for the three minerals are situated. As andalusite is a stable mineral in the cordierite-andalusite schists from Cooma, we can infer that the rock must have formed within the pressure-temperature stability field of andalusite. This demonstrates that the pressure in the Cooma rocks was about 3-4 kbar, which translates to a depth of about 10-14 km. The Cooma rocks thus must have been buried from the surface where the sediments have been deposited to the middle of the continental crust. On the other hand the gneisses and migmatites contain sillimanite, providing evidence that they formed at temperatures higher than 600°C. In a similar way, researchers have also experimentally determined what pressures and temperatures are needed to partially melt mudstones. For the 10-15 km depth of the Cooma metamorphic sequence, temperatures must exceed 700°C in order to melt the rocks (Fig. 3). In a similar way the temperature and pressure conditions can be estimated for all the observed metamorphic stages using other metamorphic reactions. The position of each stage is shown in the pressure-temperature diagram. The result shows that the Cooma metamorphic rocks were heated up from less than 300°C to more than 750°C! It is interesting to note that the Cooma metamorphic sequence experienced much hotter temperatures than what is found in an undisturbed continental crust and thus must have formed in a tectonically active zone.

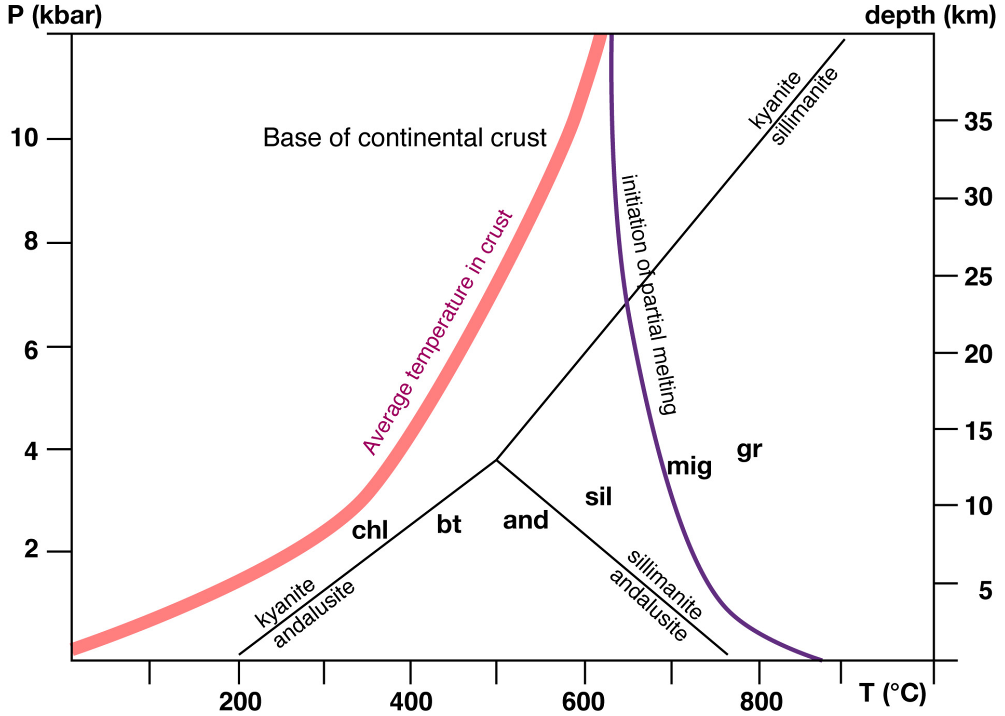

Figure 3. The metamorphic conditions of the Cooma rocks for the chlorite (chl), biotite (bt) andalusite (and), sillimanite (sil), migmatite (mig) and granite (gr) zones in a pressure-temperature diagram. The experimentally determined stability fields of kyanite, sillimanite and andalusite as well as the conditions needed to initiate partial melting provide a framework to determine the metamorphic conditions of the Cooma rocks. The red curve shows the average temperature distribution in a steady state crust. The average continental crust extends typically to 35 km depths. It is evident that the Cooma rocks formed not in a steady state crust but in a tectonically active environment that produced much hotter temperatures.

Relative time and absolute ages

The Cooma migmatites formed from sediments that were deposited at the Earth's surface then buried to depths of about 12 km. They were deformed, experiencing temperatures of about 750°C. Such complex metamorphic rocks often document multiple events of their evolution. How a *relative sequence of events* can be deduced is explained on an example from the migmatites (Fig. 4a). The oldest feature observable in the migmatite is a foliation that is marked by aligned biotite. This foliation is overprinted by a first set of veins related to partial melting that are sub-parallel but locally discordant to the foliation. The foliation and the first set of veins are then folded in upright folds. Finally, a second set of partial melts with large, un-oriented minerals cuts across the folds. This picture illustrates that four events can be distinguished in this small outcrop. It is interesting to note that all these events are related to the heating history of the rocks and not much is seen of the evolution related to the exhumation of the migmatites back to the surface.

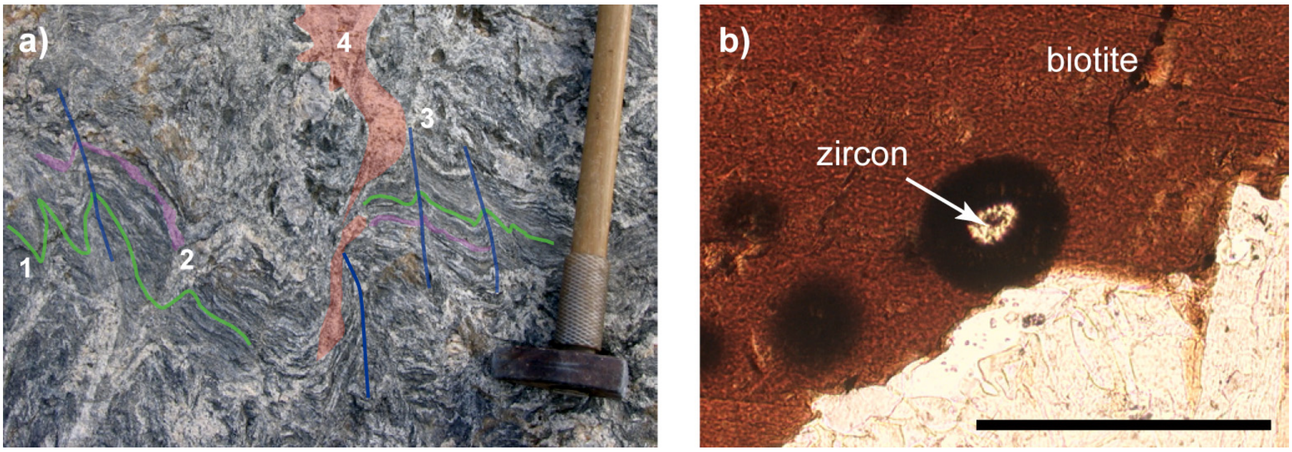

Figure 4a. Relative timing of different events in a migmatite. The oldest event (1) is a gneissic foliation marked by biotite. A first generation of partial melts partly crosscuts this foliation (2). Both features are folded during a later event (3). The folds are crosscut by a second event of partial melting (4). A zircon inclusion in a biotite displays a dark halo that is related to damage caused by the decay of Uranium and Thorium that were incorporated into the zircon. Radioactive decay is used to determine the absolute age of metamorphic rocks. The scale bar represents 0.5 mm.

The determination of *absolute ages* relies on minerals that can be dated using radioactive decay. Occasionally minerals incorporate radioactive elements such as Uranium (U) and Thorium (Th) in their mineral structure. These elements decay through time to Lead (Pb). By measuring U, Th and Pb in a mineral, the age can be determined by assuming that no Pb was present at the formation of the mineral.

The accessory minerals monazite and zircon satisfy these conditions. During the radioactive decay from U or Th to Pb, alpha particles are emitted. These particles can damage the minerals that host zircon or monazite. Figure 4b shows a biotite in thin section that displays an extensive halo related to this radioactive damage. A detailed study on the Th-U-Pb systematics of monazite and zircon from the Cooma metamorphic complex showed that the migmatites as well as the granite formed 430-435 Ma (Williams, 2001).

Interpretations

The mapped isogrades wrap around the Cooma granite (Fig. 1) and suggest that there is a causal relationship between the formation of the granite and the surrounding metamorphic rock suites. This is supported by the indistinguishable age of the migmatites and the granite. There are two opposite ways to interpret these findings.

The metamorphism could be caused by the intrusion of a hot magmatic rock (the Cooma granite) and thus would be regarded as a contact metamorphism. Alternatively, the Cooma granite could represent the pooling of melt that was produced by heating of the sedimentary rocks during a regional metamorphism. Many metamorphic minerals are aligned along a foliation in the lower grade region that is older than the granite formation (Richards and Collins, 2002). Thus, structural arguments support the regional metamorphism hypothesis.

Also the Cooma granite and migmatite took about 30-40 Ma to cool to temperatures below 350°C (Williams 2001). Such a rate of cooling is much slower than would be expected from an intruding granite. Therefore, structure and cooling ages provide evidence that the Cooma granite is the product of a regional metamorphic event rather than the cause of a metamorphic contact aureole (Williams, 2001).

This conclusion has some important implication for the genesis of granites. The example of Cooma provides evidence that progressive melting of sediments can lead to granite formation. Such granites have been labelled S-type granites, to highlight that they derive from a sedimentary source rock (Chappel and White, 1992). Because the relationship between metamorphism, partial melting and granite formation are so well exposed, the Cooma granite is one of the type examples of such S-type granites. The mineralogy and composition of S-type granites is distinct and different from granites that are generated by the partial melting of pre-existing igneous rocks (so called I-type granites; Chappel and White, 1992).

Now that the Cooma granite can be eliminated as the cause for the metamorphism, how do we explain how the Cooma rocks were formed? Figure 3 shows the average thermal gradient in continental crust. In steady state, the temperatures at the base of a 30 km thick continental crust are only about 600°C. This contrasts with the observed temperatures of 750°C at 12 km depth in the Cooma rocks. Therefore, the Cooma rocks are far too hot.

Thinning of continental crust during extension with the input of hot (1200°C) magmas in the lower crust is the most effective way to raise temperatures in the middle crust significantly. The Cooma rocks were situated close to the Australian continental margin at 430 Ma. The most likely tectonic setting is that the Cooma rocks were situated above a west-dipping subduction zone. Subduction related magmatism delivered hot magma to the lower crust (Collins, 1998) and crustal extension and thinning might be related to episodes of eastward retreat of the subduction zone.

The Cooma metamorphic sequence shows how the structure and mineralogy of rocks changes when sedimentary rocks are heated up from 300 to 750°C related to subduction zone tectonics. Such processes occur today in Indonesia. While we are able to study the volcanic activity related to such processes, we don’t have access to deeper rocks such as the metamorphic sequence in Cooma. It is only by the combination of observations from tectonic activities today with the study of exposed rocks from the deeper Earth in the past that we can learn how Earth works.

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Water in metamorphic rocks

Water plays a crucial role in the metamorphism of rocks. Water can be incorporated into minerals as structural hydroxyl (OH). For example, the chemical formula of muscovite is $KAl_3Si_3O_{10}(OH)_2$, showing that some amount of water is bound in minerals. During metamorphic reactions, such water can be released as a metamorphic fluid. The study of metamorphic fluids is very important as many of the economic ore deposits are related to metamorphic fluid activity in the crust.

In this exercise we will estimate how the water content of the Cooma rocks changes as a function of metamorphic grade. We will do this in the typical way of how scientists approach such problems. First we formulate a working hypothesis, where we have a guess at the outcome (question 1). Then an experiment is designed to see what is happening (question 2). In the next step, we quantify the results (question 3). Finally we apply the findings of the experiments and calculations to the interpretation of the metamorphic rocks.

Guess how much water is incorporated into 1kg of slate, phyllite, schist, gneiss and granite? Fill beakers with that amount of water and compile the results from the whole class in a table.

Experiments on the dehydration of clays: Take 100g of pottery clay from the shops. This is essentially a mudstone. How can we test how much water is in the mudstone? We can determine water loss by heating the clay up gradually and measure its weight after each step. Water is present in two different states in pottery clay. Some proportion of water is adsorbed to the surface of the clay. This can be driven off by heating the clay just above 100°C where water evaporates. The water that is incorporated in the structure of the clay will be released at 800-1000°C. If you have an oven to fire pottery at your school you can use this. Alternatively, if you don't have access to such a hot oven, you can also use modelling materials that dry up in air. These are availably in any arts and craft shop. Again it is important that you measure the weight before and after.

The main hydrous minerals in the Cooma metamorphic rocks are chlorite, muscovite and biotite. Use the website webmineral.com to find out how much H_2O in weight % is present in these three hydrous minerals. Now calculate the water content of the Cooma rocks using the following proportion of minerals in the rocks:

	Slate	Phyllite	Schist	Gneiss	Granite
Muscovite	30	20	20	5	
Chlorite	30	20			
Biotite	0	20	20	15	10

Compare the calculated results with the estimates you made in question 1. Then plot the results in a diagram, where the x-axes is the temperature (you can get this information from Figure 3) and the y axes represents ml of water in 1kg of rock. Can you see any trend?

Where does the water go that is liberated during metamorphism of the sediments? How could this finding be used to explain that we find high-grade metamorphic rock at the Earth's surface today?