



A user's guide to migmatites



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**Geological Survey of South Australia,
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INTRODUCTION

Migmatites are complex, high-grade rocks that have formed by partial melting. They have been recognised across most of geological time, develop in various tectonic settings, and can affect a wide range of protoliths. Consequently migmatites are commonly encountered in the field where their complexity can confuse and intimidate the geologist. These rocks are particularly common in basement areas of South Australia and are therefore likely to be encountered by geologists working in this state.

The aim of this report is to provide an understanding of the terminology applied to migmatitic rocks, the processes that form them, and their usefulness. To achieve this, the report is divided into three main sections. The first section is conceptual and provides the background that is necessary to understand and describe these rocks. This will include how they form, the parts of a migmatite, and the different types of migmatitic rocks and what they mean. The second part will provide some practical information including what information can be extracted from a migmatite, dating of these rocks, their relationship to mineralisation, and some ideas on how to deal with migmatitic rocks in the field. The final section includes a collection of case studies from South Australia which will give the reader some idea of what information can be extracted from migmatitic rocks.

The first part of this review is largely based on the *Atlas of Migmatites* by E.W. Sawyer (2008a), which is an excellent, amply illustrated account of the description and origin of migmatitic rocks. This book also has a very comprehensive background section with a bibliography of the more detailed literature and is highly recommended.

WHAT IS A MIGMATITE?

A migmatite is a rock found in medium- and high-grade metamorphic areas that can be heterogeneous at the microscopic to macroscopic scale and consists of two, or more, petrographically different parts, which are petrogenetically related to each other, and to their protolith, through partial melting or segregation of the melt from the solid fraction (Sawyer 2008a).

The partially melted part of a migmatite will often, but not always, contain pale-coloured rocks that are quartzofeldspathic or feldspathic in composition, and dark-coloured rocks that are enriched in ferromagnesian minerals. These two parts essentially represent the liquid and solid products of the melt reaction respectively, but this will be explained in the next section. In some cases however, the partially melted part may have changed mineralogy, microstructure and grain size without segregating into separate light or dark parts. This can make recognition in the field difficult and would most likely require petrographic analysis (the petrographic study of migmatites will not be covered in this report book but readers are directed to Sawyer 2008a).

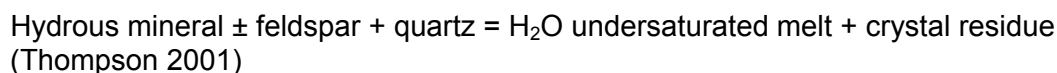
HOW DO MIGMATITES FORM?

Partial melting, or anatexis, of crustal rocks is a complex process controlled by a number of variables including the temperature (T) and pressure (P) conditions, the fertility or composition of the rock protolith, and the presence or activity of water or other volatile phases.

Partial-melting, like all metamorphic reactions, is controlled by the chemical stability of a given mineral assemblage at particular P-T conditions. As a rock moves through the crust, the P-T conditions change bringing about disequilibrium conditions and inducing the mineral assemblage to alter in order to minimise the Gibbs free energy of the system (Spear 1993). Because most melt-

producing reactions have a steep slope (i.e. a large $\Delta P/\Delta T$) in P-T space, the temperature of a system has a major control on inducing partial-melting and the amount of melt produced.

The melt fertility, or propensity for a given rock to start melting at given P-T conditions, is controlled by the bulk composition of the rock (Spear 1993). Partial-melting reactions in crustal rocks are strongly controlled by the modal proportions of quartz and feldspar and the amount of hydrous minerals present such as muscovite, biotite and hornblende (Thompson 1996). Melting initially occurs through the process of dehydration-melting reactions that generally take the form:



Typically for felsic crustal rocks this involves muscovite and biotite to produce either a ferromagnesian (e.g. garnet or cordierite) or aluminosilicate (e.g. sillimanite) mineral and melt, for example via the reactions:



At progressively higher T conditions, or as hydrous phases are consumed, melt-production will continue via the breakdown of more refractive minerals such as:



Because dehydration reactions are so important for producing melt at lower temperatures, rocks which contain more hydrous mineral phases, such as mica-rich schists, will generally tend to be more fertile and melt at lower temperatures. In comparison, comparatively dry rocks such as quartzites and marbles will generally require higher temperatures to begin melting. However, because of the compositional complexity and open system behavior of most rock packages this generalisation may not always hold true.

The availability of water in the system also has a major effect on controlling the temperature at which partial-melting may begin. Many natural and experimental observations have demonstrated that free water can considerably lower the temperature of the solidus and affect the stability of many hydrous mineral phases (Holland and Powell 2001; White et al. 2001, Thompson 2001). In rocks of typical pelitic composition, H₂O-saturation can lower the solidus to temperatures of c. 650°C at 5 kbar (Fig. 1) producing a H₂O-saturated melt. The control of water on the solidus can be demonstrated using phase-equilibria modelling and varying the amount of H₂O in the system. Figure 2 is a temperature-molar% H₂O pseudosection generated using the program THERMOCALC (Powell and Holland 1988) for a pelitic rock from Shoal Point on southern Eyre Peninsula (Dutch 2009). The bulk composition has been kept the same but the molar proportion of H₂O varies from 7 mol% on the left to 2.5 mol% on the right. At 7 mol% H₂O the rock begins to melt at <700°C. Free water leaves the system at ~6 mol% H₂O, with the temperature of the solidus jumping to ~775°C. As H₂O content decreases the solidus continually increases to nearly 850°C at 2.5 mol% H₂O.

When the conditions are met to start melting, small isolated patches and tubes of melt will form at the junctions and along grain boundaries of the reactant phases (Mehnert et al. 1973). Less than 2% melt volume is required in felsic systems to allow the melt pockets to join and for the rock to become permeable (Vigneresse et al. 1996; Lupulescu and Watson 1999). Melt can then begin to segregate out and move through the solid framework, beginning the formation of migmatites.

The formation and migration of melt out of a rock body is vital for the preservation of anhydrous granulite facies mineral assemblages. Because water is strongly partitioned into the melt phase, in the absence of melt loss in an open system, the water content of the system would remain constant and the rock package would undergo significant retrogression during recrystallisation of the melt phase and the subsequent re-hydration of the rock package. The amount of melt loss required to preserve granulite mineral assemblages is strongly dependent on the composition of

the rock package. Modeling of an aluminous metapelitic assemblage suggests the removal of nearly all the melt is required to preserve the peak mineral assemblage, while in a subaluminous metapelite, the melt loss required is roughly half that for an aluminous assemblage (White and Powell 2002). The fact that we still see preserved granulite facies mineral assemblages indicates that a significant amount of melt has been lost from the system by the process of melt segregation into leucosomes and subsequent migration from the system. In fact, the concept of melt loss and open system behaviour is fundamental to the preservation of weakly retrogressed granulite facies rocks.

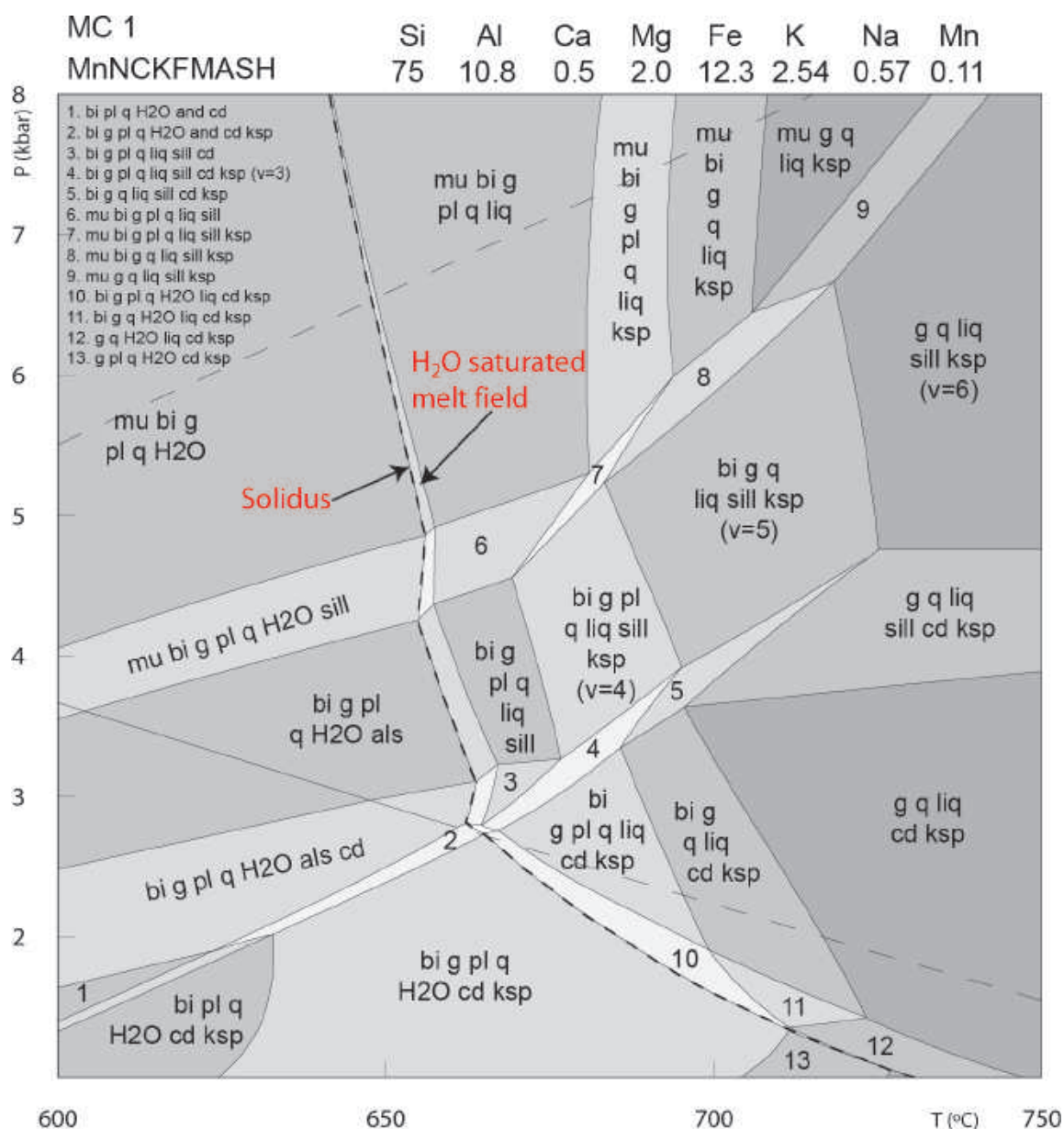


Figure 1. P-T pseudosection for a metapelitic rock from the southern Eyre Peninsula calculated with a H₂O saturated bulk composition using the phase-equilibria modelling program THERMOCALC (Powell and Holland 1988) in the chemical system MnNCKFMASH (bulk composition on the figure is in Molar%). V refers to variance, or degrees of freedom within a given stability field. The dashed line is the solidus, the univariant line where the first melt occurs. The narrow field to the up temperature side of the solidus is the small stability field with H₂O saturated silicate melt. At 5 kbar the first melt occurs through dehydration reactions involving muscovite while at lower pressures (below 4 kbar) it occurs via biotite break down reactions, which occur at slightly higher temperatures.

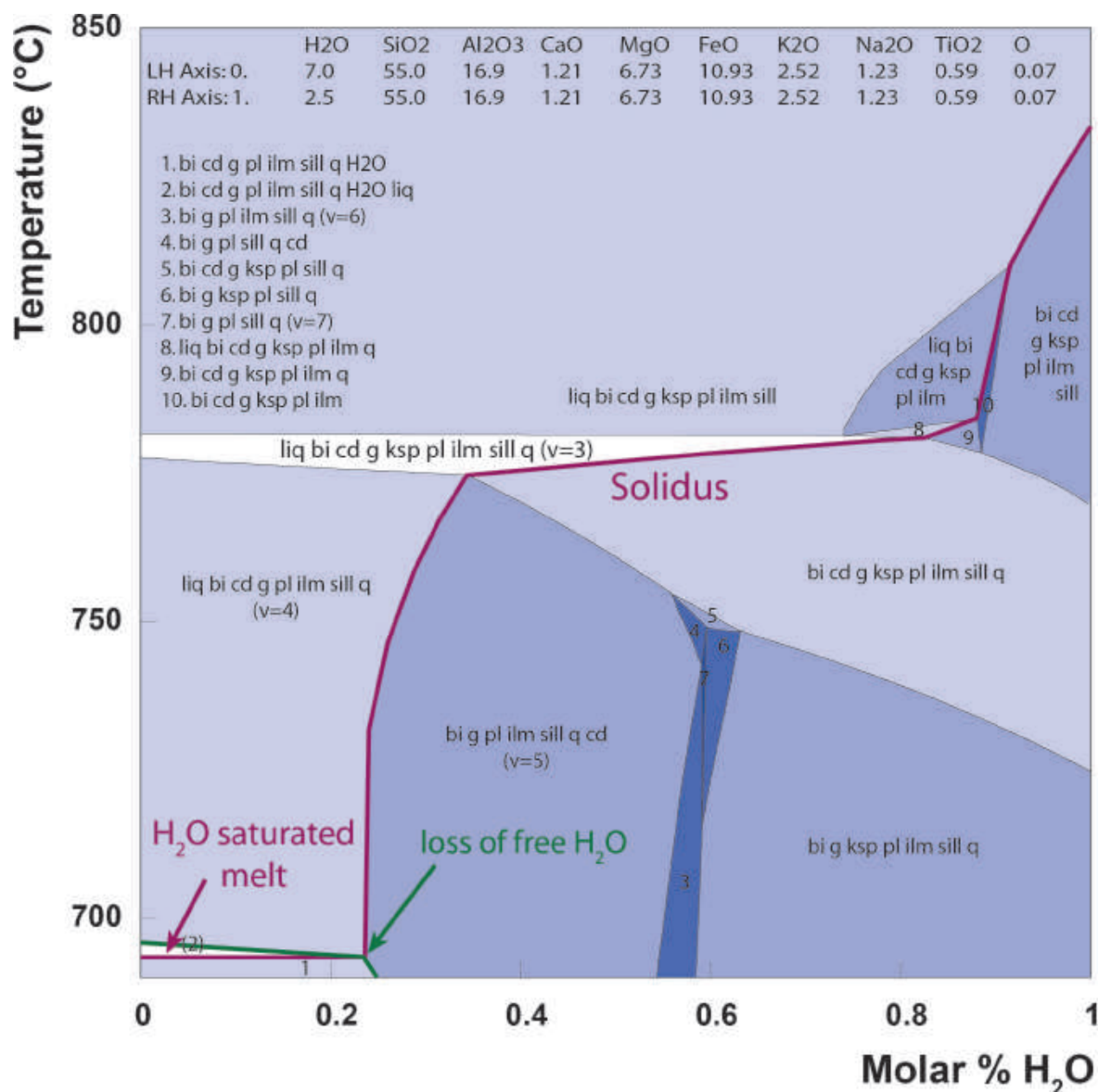


Figure 2. Temperature-Molar% H₂O pseudosection calculated for a pelitic metasediment from Shoal Point on the Eyre Peninsula. Calculated using the phase-equilibria modelling program THERMOCALC (Powell and Holland 1988) in the chemical system NCKFMASHTO (bulk composition on the figure is in Molar%). V refers to variance, or degrees of freedom within a given stability field. Molar% H₂O in the bulk rock composition varies along the x-axis from 7.0 mol% at 0 (left) to 2.5 mol% at 1 (right). The solidus (purple line) represents the first appearance of melt. The field labelled 1 is H₂O-saturated and the solidus is at <700°C. The first melt produced here (field 2) are H₂O-saturated, liberating free H₂O. Free H₂O leaves the system along the green univariant lines. At H₂O-undersaturated conditions the temperature of the solidus jumps to c. 775°C. As the rock is made progressively more anhydrous towards the right of the pseudosection, the temperature of the solidus progressively increases.

Evidence of removal of material from a rock mass may not be easily recognised, and so melt loss from the system can be difficult to identify. However, a good example of this process can be found in the metapelites at Round Hill, just to the east of Broken Hill. The rocks in this area contain two types of leucosomes (White et al. 2004); some are dominated by very large garnets that are up to 15 cm in diameter (Fig. 3a), whereas others are coarse-grained and garnet-poor (Fig. 3b). The garnet-bearing leucosomes have been interpreted as in situ melts, with the garnet representing the residuum, and the garnet-poor leucosomes are interpreted as segregated and migrating melt (White et al. 2004). Both types of leucosome are generally parallel to a composite, layer-parallel solid-state foliation, although locally discordant leucosomes can form a network. In places, the large garnets form augen structures with the leucosome preserved in pressure shadows (Fig. 3c).



Figure 3. Migmatites from Round Hill, near Broken Hill. a) Stromatic metatexite migmatite with large garnet porphyroblasts in the in situ leucosomes. **b)** Migmatite following melt extraction with the in situ leucosome only preserved adjacent to the large garnet porphyroblasts. There is an oblique, garnet-poor leucosome in the lower part of the photograph which has segregated from its source and is interpreted as an in-source leucosome. **c)** Detail of a migmatite from which most of the melt has been extracted. Remnants of the stromatic leucosomes are preserved in the pressure shadows next to the large garnet porphyroblasts, resulting in augen structures. (Photos 413510–413512)

It is likely that the melt originally formed more extensive layer-parallel leucosomes, prior to the extraction of melt that was locally squeezed out from between the foliation planes, leading to volume loss in the rock. The garnet-poor leucosomes would be part of a more extensive melt migration network (White et al. 2004). The removal of the melt from around the garnets was important for the textural and mineralogical evolution of the rock, as it prevented the rehydration reactions that would have caused the garnet to breakdown, thereby leading to their preservation at Round Hill (White et al. 2004).

Since rock packages are commonly chemically inhomogeneous at a variety of scales, the process of migmatization is correspondingly inhomogeneous throughout a rock package and across a metamorphic complex. This inhomogeneity is particularly evident within metasedimentary packages, where subtle compositional variation between different lithologies permits some layers to melt at lower temperatures than adjacent layers. The melting of more fertile lithologies within a rock package may liberate water and other volatile phases which may then migrate into less fertile lithologies nearby and induce partial-melting there, further propagating the production of melt within the larger system.

THE PARTS OF A MIGMATITIC ROCK

The following descriptions are based on Sawyer (2008a).

PALAEOSOME

The palaeosome is the part of a migmatitic rock that was not affected by partial melting (Fig. 4) and which preserves structures (e.g. foliations, folds and layering) that are older than the partial melting event. The microstructure of the rock may be unchanged, or there could be minor changes in the size, form, and orientation of the grains (i.e. changes that would reflect sub-solidus metamorphic processes).

RESISTERS

These are rocks in the palaeosome that are especially resistant to partial melting or microstructural change. These are typically competent and can include quartzites, calc-silicates, and metamafic rocks.

Palaeosome and resisters can be important for unraveling migmatites, as they may represent the original layering (e.g. bedding), thereby forming marker units. Furthermore, because they are rigid and competent, they can provide information about strain. For example layers can be boudinaged or folded, or blocks can be rotated to form asymmetric features that are often analogous to porphyroclasts in mylonites, e.g. s- and d-porphyroclasts, and mica fish (see Passchier and Trouw 2005 for microscopic examples).

PROTOLITH

Protolith is the name given to the original rock that undergoes partial melting. Strictly speaking, this term is applied to the pre-anatectic lithology, because once melting starts, the rock will be converted to neosome. For example, a migmatite that was derived by partial melting of a pelite can be considered to have a pelitic protolith.

NEOSOME

The neosome comprises the parts of a migmatite that are newly formed by, or reconstituted by, partial melting of the protolith. The neosome essentially includes the solid (i.e. residuum and melanosome) and liquid (i.e. leucosome) components of the melt-producing metamorphic reaction. The parts of the neosome may, or may not, have undergone segregation into separate melt and solid fractions.

There are several parts to the neosome (Fig. 4), including the residuum, the melanosome and leucosome.



Figure 4. Migmatite from Kirton Point, Port Lincoln, showing two components of the neosome. The paler material represents the leucosome, the dark selvage (composed of mafic minerals) adjacent to the leucosome would be the melanosome (a type of residuum), and the mesocratic host would be the palaeosome. The rock is part of the Donington Suite which underwent partial melting during the c. 1730–1690 Ma Kimban Orogeny (Hand et al. 2012). (Photo 412904)

Residuum

The residuum forms the part of the neosome that is predominantly the solid fraction left after partial melting and extraction of some, or all, of the melt fraction. Microstructures may indicate that partial melting has occurred.

Melanosome

The melanosome is the darker-coloured part of the neosome in a migmatite, which is rich in dark minerals such as biotite, garnet, cordierite, orthopyroxene, clinopyroxene, amphibole and even olivine. The melanosome is the solid, residual fraction (i.e. residuum) left after some, or all, of the melt fraction has been extracted. Microstructures indicating partial melting may be present.

The definitions for residuum and melanosome are quite similar, which can be a little confusing. The easiest way to think of them is that they are both the solid product of the melt reaction, with residuum a more general term, whereas melanosome specifically refers to residuum that is composed of dark (ferromagnesian) minerals.

Leucosome

The leucosome is the lighter-coloured part of the neosome in a migmatite, consisting predominantly of feldspar and quartz. The leucosome is derived from segregated partial melt and it may contain microstructures that indicate crystallisation from a melt or magma. The leucosome may not necessarily have the composition of an anatectic melt, as fractional crystallisation and separation of the fractionated melt may have occurred.

Leucosomes can be subdivided, depending on whether they are in situ, or they have segregated and migrated from their source (more on this below). In situ leucosomes may be distinguishable by the presence of a darker selvage, comprising mafic minerals plus other minerals such as garnet or cordierite, which would represent the solid products of the melt reaction. In contrast, these features may be absent from injected leucosomes, where the melt has moved away from its source.

THE MARGINS OF LEUCOSOMES

The following is a list of informal terms that can be used to describe the margins of leucosomes. The different types have been picked up from field observations but we are not sure if they have been formally described. However, they are considered to be important as they provide information about the rheological contrasts between the leucosomes and their host, and the timing of the leucosome relative to anatexis and deformation. These observations can enable the geologist to understand the development of the migmatite.

Sharp margins

There are several types of sharp margins with each type providing information about the history of the rock. The context of the injected body is important in understanding the process.

- A sharp, stepped margin that follows the edges of crystals suggests the host was not completely crystallised, i.e. there was a film of silicate melt at the grain boundaries, which permitted the rock to 'crack' along the boundaries of individual grains (Fig. 5), rather than fracturing across the grains (as can happen in crystalline rocks).
- In stromatic (or layered) metatexitic gneisses, leucosomes with a sharp, straight margin parallel to the gneissosity can indicate that the leucosome formed relatively early in the anatectic event and was subjected to more solid-state strain, and transposition, relative to the later leucosomes (Fig. 5).

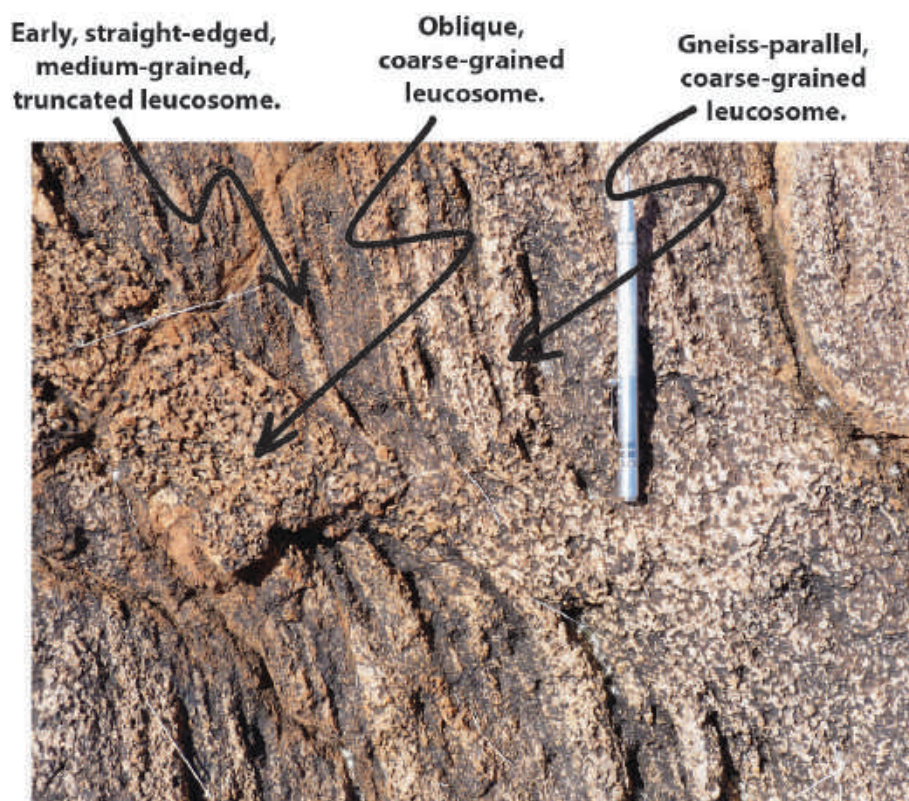


Figure 5. Close-up of a shear band from the eastern Musgrave Province illustrating the difference between early, straight-edged leucosomes, and parallel, later, coarser grained leucosomes that have sharp stepped margins that follow grain boundaries. It is possible to distinguish the two generations of parallel leucosomes by cross-cutting relations. The straight-edged leucosomes are deflected and cut by the oblique shear band which is filled with leucosome that is texturally continuous with the coarser grained leucosome (suggesting they are the same generation). This is a close-up of part of Figure 36. (Photo 412929)

- A sharp, straight margin can also indicate that the host was relatively solid, with the grains sufficiently bound that the vein or dyke is associated with brittle fracturing and cracking of the crystals (Fig. 6). There will not necessarily be any solid-state strain associated with the intrusive sheets.



Figure 6. An example of a sharp, straight-edged dyke intruding a solid rock from the East Albany Fraser Orogen, Western Australia. A rapakivi granite is cut by a pale microgranite dyke which has sharp margins that cut across the large mantled feldspar grains in the host. This suggests that the host rock was completely crystallised and able to crack when the microgranite intruded. (Photo 413513)

- Alternatively, parallel veins or dykes with sharp, straight margins may indicate that originally oblique or sub-parallel leucosomes, veins or dykes were subjected to a later solid-state structural overprint that led to their transposition. It should be possible to distinguish this, as the leucosome, vein or dyke will tend to have a solid-state foliation that is parallel to a similar foliation in the host. In some cases, the partitioning of simple shear into a leucosome, vein or dyke may cause an angular relationship with the foliation in the host.

Diffuse/gradational

These terms are applied to the margin when it is difficult to precisely pinpoint the edge of the leucosome (Fig. 7). This may be due to the transition from a leucosome to the residuum via a zone where melt fills the grain boundaries in the residuum.

Feathery

Leucosomes with feathered margins have fine apophyses that can be traced into the foliation in the host, leading to a 'feathered' or comb-like geometry (Fig. 8). This feature suggests local derivation, with the melt moving along the foliation planes, and into the 'low-pressure site', possibly represented by a shear band. This can be a relatively small-scale feature with the apophyses at the mm-scale.

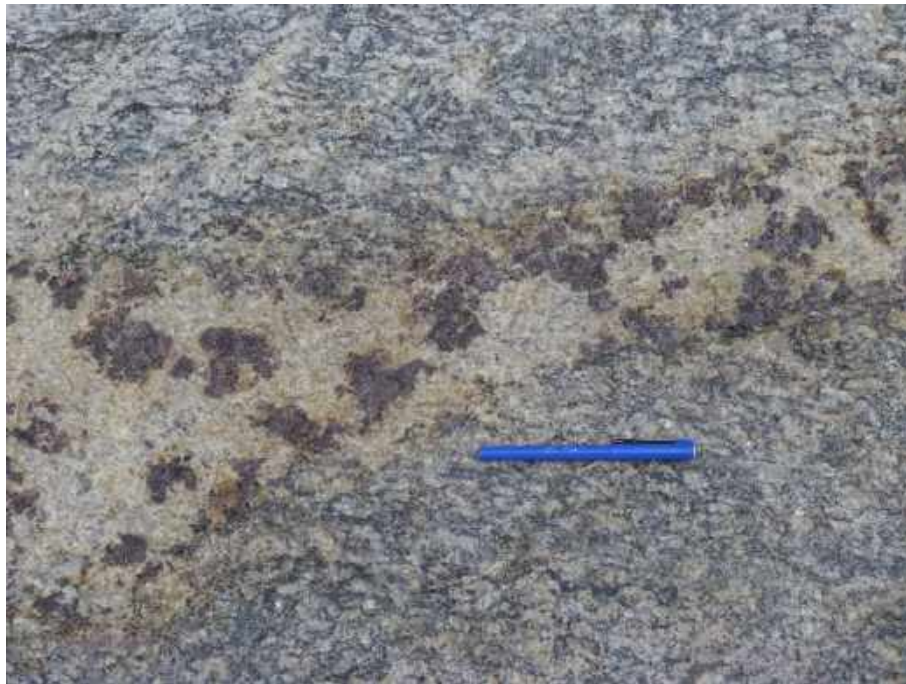


Figure 7. Garnet-bearing leucosome from Cape Carnot, Port Lincoln, showing a diffuse/gradational margin. (Photo 413514)



Figure 8. Small melt patches from Wanna, Port Lincoln, showing feathery margins where fine apophyses can be traced into the host rock. (Photo 413515)

LEUCOSOME SEGREGATION AND MIGRATION FEATURES

The leucosome can be divided into several groups depending on the degree of separation from the site of melt production (Sawyer 2009). The distance travelled from the source can also affect the textural evolution of the leucosome, causing it to progress from something that is a minimum melt composition, to something that resembles a true granite. These groups also represent a progression in scale, from melt that is locally segregating at the grain-scale, up to large-scale magma, or melt, migration (Fig. 9).

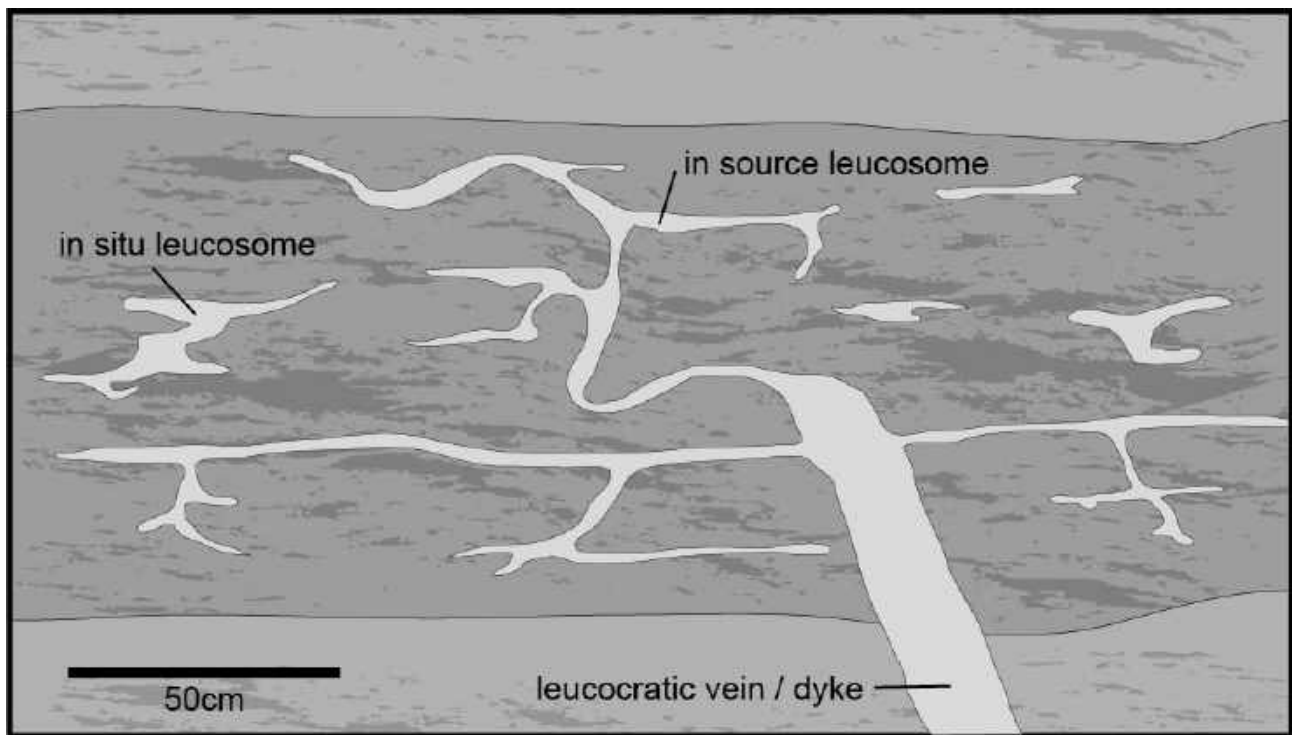


Figure 9. Schematic representation of a migmatite layer showing the difference between in situ, in-source and leucocratic vein or dykes (modified from Sawyer 2008b).

In situ leucosome

This is the product of crystallisation of an anatectic melt, or part of a melt, that has segregated from the residuum but has remained at the site where the melt formed.

In-source leucosome

The product of crystallisation of an anatectic melt, or part of a melt, that has migrated away from the place where it formed but is still within the confines of its source layer.

Leucocratic vein or dyke

The product of crystallisation of an anatectic melt, or part of a melt, that has migrated out of its source layer and has been injected into another rock, which may be nearby or farther away, *but is still in the region affected by the anatectic event*.

Granite dyke, sill, pluton, etc

The product of crystallisation of a felsic melt that has migrated out of its source region completely and is *injected into host rocks of lower metamorphic grade or into non-metamorphosed rocks*.

The last three types may be parallel to the strictly in situ leucosomes (depending on the strain), but it is also likely that these are transgressive and will cut across 'earlier' migmatitic structures as they migrate. As well as the context, the examination of the margin of these features can help the geologist to understand the degree of segregation and migration. For example:

- The in situ and in-source leucosomes will likely have a feathery or diffuse/gradation margin as there may still be melt between the grains of the host. If the residuum has a relatively low melt fraction then the leucosome may be sharp and stepped, following the margins of the crystals in the host.
- The margin of a leucocratic vein or dyke will vary from sharp and stepped, to sharp and straight, depending on the proportion of melt in the residuum.

- The felsic melt that has been injected to a lower grade, or non-metamorphosed rock to form a dyke or sill will tend to have a sharp, straight intrusive contact, since the host will likely crack (e.g. Fig. 6). If the temperature contrast is great enough there may also be a chilled margin.

SOME ADDITIONAL CONCEPTS

ANATEXIS

A general term used to describe partial melting of the continental crust. It does not specifically refer to the degree of partial melting, and can therefore be applied to all stages, from incipient partial melting to complete fusion. Crustal anatexis is generally accompanied by deformation which will facilitate a series of physical processes including melt segregation, melt migration, fractional crystallisation, and magma flow.

SEGREGATION

Segregation is the process whereby the anatectic melt phase is separated from the residuum in the neosome. Note however, that not all neosome has undergone segregation of the melt.

MELT OR MAGMA?

The liquid component of the neosome can also be subdivided into melt and magma.

Melt is a silicate liquid without crystals.

Magma is a silicate liquid that contains crystals. The crystals may have either crystallised from the melt (i.e. liquidus phases), or they are the solid product of the melt reaction (i.e. known as peritectic products).

Rheology

Magmas can have complex rheological behavior as they are non-Newtonian fluids.

Rheology is essentially the deformational behavior of material, and examines the relationship between stress and strain (Stüwe 2007). Newtonian fluids are substances that have a linear, proportional relationship between differential stress and shear-strain rate. This means that the viscosity of the fluid will not change regardless of any external stresses.

In contrast, non-Newtonian fluids are characterised by a non-linear relationship between shear stress and the rate of shear strain. As a result, the viscosity of the fluid will change, i.e. it will become 'thinner' or 'thicker', when external stresses are applied.

Magmas can exhibit **shear thickening** behaviour, where the viscosity increases as strain rate increases (i.e. rate of change in the material with respect to time). This behavior occurs because the magmas are a mix of fluid and rigid particles. At low velocities, the fluid dominates the behavior as it is able to flow and fill the spaces between the particles because they are not moving fast. At higher velocities, the fluid cannot keep up with the particle movement and it is unable to fill the spaces between them, so the particles rub against each other creating friction between them. As a result, a crystal mush can crack if it is stressed or flows too quickly, explaining apparently brittle features such as syn-plutonic dykes in magma chambers and volatile 'de-watering' structures. This behavior is further complicated as a cooling and crystallising magmatic body is constantly changing the crystal fraction over time. There will also be spatial variation, as greater crystallisation occurs at the boundary of the body where it loses heat, leading to crystal zonation, and thereby variable rheology within a single body, at the same time.

While the paragraph above generally deals with a crystallising magma, the rheology of a melting rock is similarly complex and will vary depending on several factors. These include the proportion of melt, the distribution of melt and any external stresses. Shear thickening can also affect migmatites, where the melt can be pervasively distributed at the grain-scale, resulting in the

development of dilational features such as small-scale shear zones. The rheology of a melting rock will be further examined in the section “The transition from a metatexite to a diatexite”.

Magmatic versus sub-magmatic flow

The terms ‘magmatic flow’ and ‘sub-magmatic flow’ can be applied to the different types of migmatites described below.

Magmatic flow

This is inferred from the preferred orientation (magmatic foliation) of minerals in a rock derived from a magma, which was acquired during flow when the crystals were suspended in the magma and free to rotate with ***no, or very little interaction*** with nearby crystals. Experiments and models have indicated that this will occur when the magma contained <45% crystals (Vigneresse et al. 1996).

Sub-magmatic flow

This is inferred from the preferred orientation of minerals in a rock that was acquired when the magma had sufficient crystals that ***interactions commonly occurred*** between them as they rotated in the flow (sub-magmatic foliation). Experiments and models have indicated that this will occur when the magma contained >45% crystals (Vigneresse et al. 1996). Indicators of sub-magmatic flow include the tiling (or imbrication) of crystals and the healing of cracked crystals by a silicate liquid.

These thresholds are approximate and will vary depending on strain, cooling rate and other factors.

The concept of magmatic and sub-magmatic state foliations does not just apply to partially melted rocks. It is also an important concept to keep in mind when looking at syn-tectonic/syn-kinematic granites. The systematic alignment and tiling of euhedral to subhedral phenocrysts in an igneous body indicates that stresses were being applied to the body while it was still in the magmatic state, with the minerals able to freely rotate and align. As well as providing important structural information (e.g. foliation, lineation, kinematic indicators, stress directions), these are excellent targets for geochronology as the age of the igneous rock will also constrain the age of the deformation.

THE DIFFERENT TYPES OF MIGMATITES

Migmatites can be divided into two first-order groups; metatexites and diatexites. Metatexites are migmatites that preserve coherent, pre-partial melting structures in the palaeosome and residuum, whereas diatexites have disaggregated and lost structural coherency. The differences between these two types and the second order division are described below, following a brief discussion of the processes that will result in the different types of migmatite. These are end-members and outcrops may display characteristics of several types.

A flow chart for distinguishing between the various types of migmatites is included as an appendix at the end of this report.

THE TRANSITION BETWEEN THE DIFFERENT TYPES OF MIGMATITES

The transition from a metatexite to a diatexite is largely based on two factors; the proportion of melt in the rock and degree of strain that the rock mass is subjected to (Fig. 10).

The actual melt proportion at which the framework of a metatexite will break down to form a chaotically arranged diatexite is difficult to quantify (Fig. 10). Some experimental models treat the solid crystals as uniform, rigid spheres (the URS model in Fig. 10) and suggest that the breakdown of the solid crystal network will occur at a melt fraction of 0.26 (which is very precise, but may not be realistic as crystals do not tend to be uniform spheres). More realistic models which treat the

crystals as solid particles of non-uniform in size and shape (the non-uniform particle model; NUP in Fig. 10), has determined that transition from a metatexite to diatexite will occur over a melt fraction range of 0.16–0.6 (Renner et al. 2000).

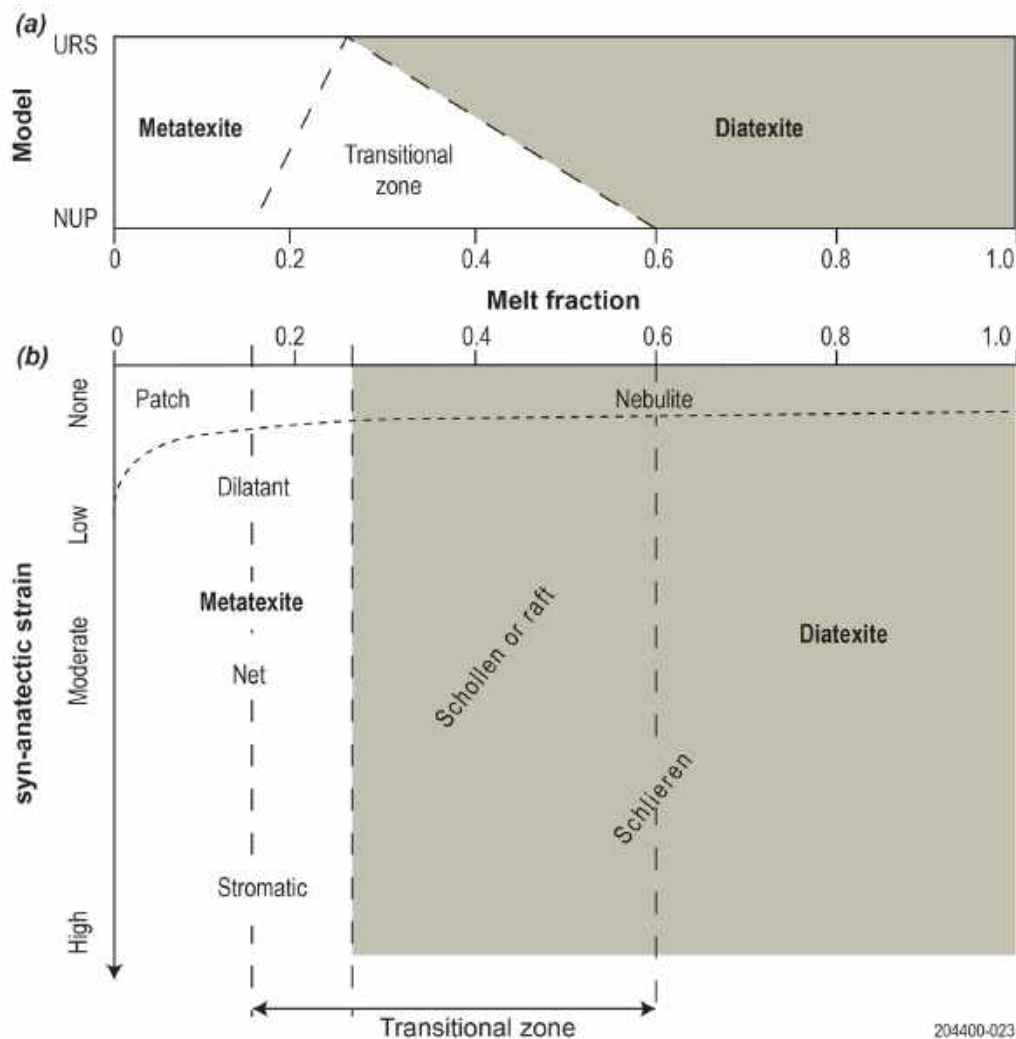


Figure 10. Classification scheme for migmatitic rocks modified from Sawyer (2008a).

a) First-order division of migmatites into metatexite and diatexite migmatites as a function of the fraction of melt and the properties of the solid grains in the partially melted rock. This will depend upon the nature of the crystal model which include the uniform, rigid spheres (URS) model, and the non-uniform in size and shape (NUP) model. See the text for description. **b)** Second-order morphologies of metatexite and diatexite migmatites on a plot of syn-anatectic strain versus melt fraction. The diagram is shaded for the URS model but the vertical dashed lines indicate where the boundaries are for the transitional zone in a NUP model.

The transition will be affected by several factors. As shown in the “How do migmatites form?” section, the distribution and degree of partial melting will be affected by the composition and thereby the melt fertility of the protolith. This can be extremely variable in the case of well-bedded metasedimentary rocks.

Strain can also be an important influence as higher strain, or increased strain rates, can lead to disaggregation at relatively lower melt fractions. The difference in syn-anatectic strain also tends to be an important factor in the second order subdivisions (Fig. 10). High shear strain will also generate better alignment of minerals, schollen (rafts), and schlieren in diatexites, often leading to the development of compositional layering or foliations (see Fig. 24) which can be truncated during shear flow (Fig. 11). Deformation during anatexis can also enhance the segregation of the melt phase.



Figure 11. Layering defined by sub-parallel leucosomes in a migmatite from the Birksgate Complex in the eastern Musgrave Province, which are locally cut at a low-angle by melt-filled shear bands that developed during shear flow. (Photo 413516)

METATEXITE

A metatexite is a migmatite that is heterogeneous at outcrop scale with coherent, pre-partial-melting structures preserved in the palaeosome. In these rocks the neosome is *generally* segregated into leucosome and melanosome. Essentially, a metatexite is a migmatitic rock that preserves structural integrity, whether this is primary layering in the protolith, earlier structural elements, or syn-anatectic structures, such as layering.

Sawyer (2008a) describes four main second order divisions of metatexite; patch, dilational, net and stromatic. However it is important to remember that there is a progression and there can be overlaps between these structural types. For example, the development of shear bands can cause a stromatic migmatite to develop net type structures. The following descriptions are based on Sawyer (2008a).

PATCH METATEXITE MIGMATITE

This texture is seen when melting occurs at discrete sites to form small, scattered patches of non-foliated in situ neosome. The neosome are generally round or oval in shape and are characteristic of the incipient stages of partial melting. The earliest stages of partial melting can be difficult to distinguish in some lithologies (e.g. a coarse-grained, non-foliated granite), however as the melt fraction increases, the neosome grows and the patches can coalesce to form irregular, lobed shapes (Figs 12 and 13).

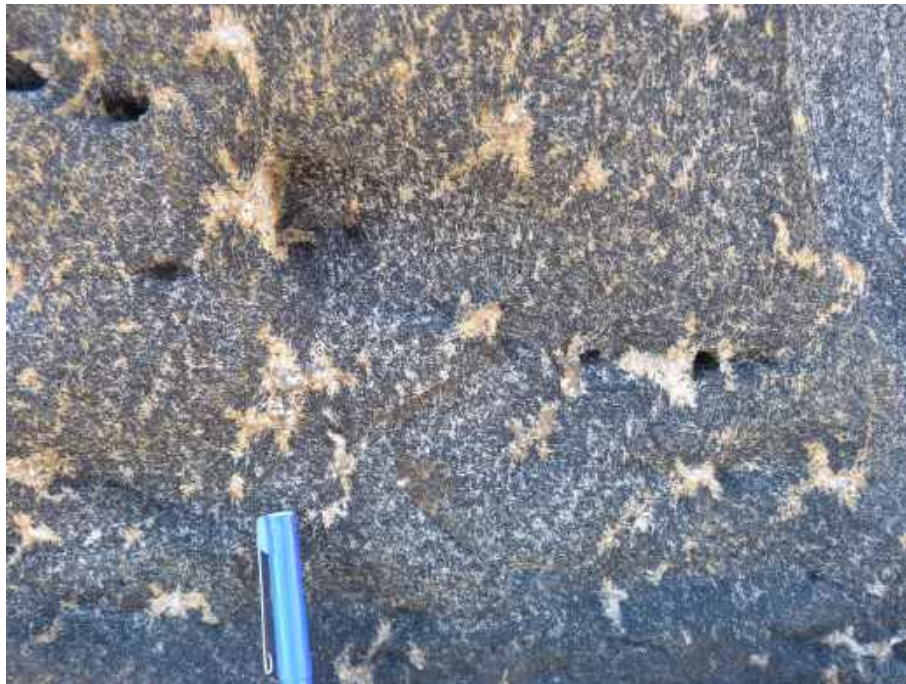


Figure 12. Patch metatexite migmatite from Wanna, Port Lincoln, showing the irregular, discontinuous leucosomes in migmatized orthogneisses of the Donington Suite. The leucosomes have feathered margins with fine apophyses that can be traced into the host suggesting local derivation. (Photo 412905)



Figure 13. Patch metatexite migmatite from Kirton Point, Port Lincoln, showing the irregular, generally discontinuous leucosomes in migmatized orthogneisses of the Donington Suite. The well-developed melanosome selvages indicate in situ partial melting and the relatively large size of the leucosomes, and the lobate boundaries suggests a relatively high melt fraction and the coalescence of melt patches. Locally, they have connected to form stromata that would have accommodated melt migration. There are also some discrete stromata with well-developed melanocratic selvages (right of centre). (Photo 413517)

DILATION METATEXITE MIGMATITE

The leucosomes occur within dilatant (i.e. relatively low pressure) sites, such as boudin necks, pressure shadows, or fractures in more competent layers (Figs 14–18). Typically, the dilational sites are comparatively short and restricted to particular, relatively competent layers and do not form large-scale features. These structures imply that there is a competency contrast in the host rock, with the more competent layers often less fertile (e.g. greywacke in a pelite), or resistant or refractory lithologies (e.g. calc-silicates, quartzites, metamafic rocks, pegmatites). They could also be newly formed residual layers that are rich in strong minerals such as garnet or pyroxene. Dilational sites can also form in and around the hinges of folds that developed in rocks with a strong planar anisotropy.

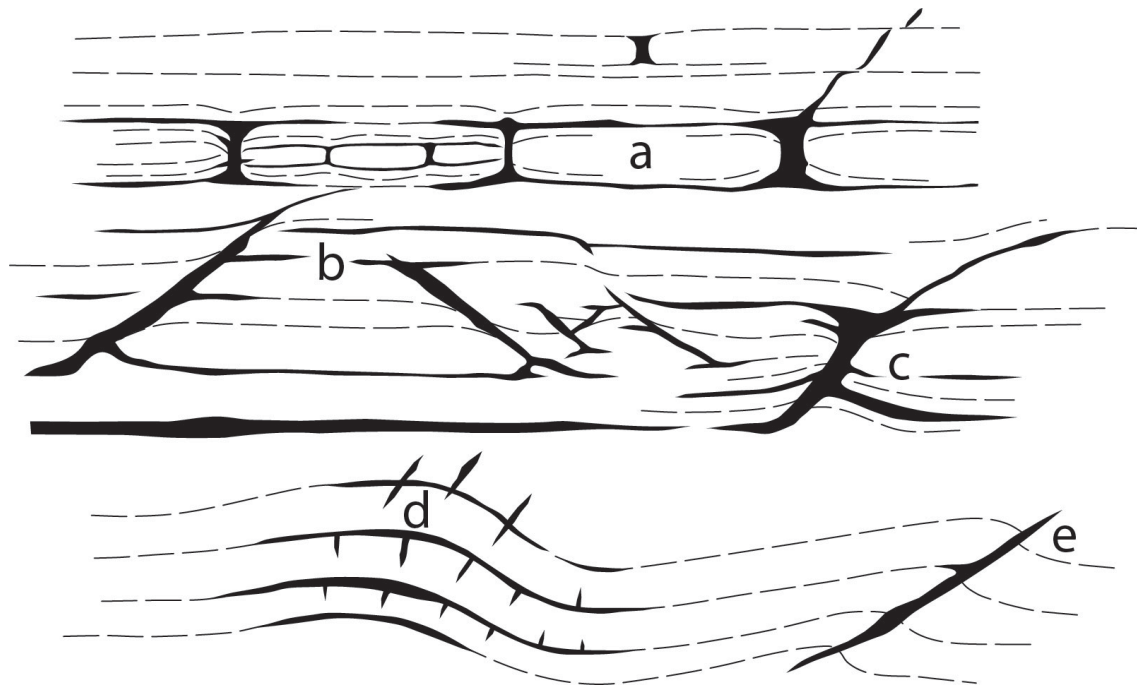


Figure 14. Diagram showing some of the structural sites that can host the leucosome in dilation metatexite migmatites. The solid areas represent the leucosome and the dashed lines represent the traces of bedding or a solid-state foliation. **a)** The melt can pond in the necks of boudins that develop in the more competent layers, such as palaeosome resisters or melanosome. **b)** The melt can pond in extensional shear bands with both synthetic and antithetic shears shown in the figure. **c)** Melt ponding in asymmetrical boudins. **d)** The melt can pond in several sites that are associated with parallel folds. The melt can migrate into fold hinges to form layer parallel leucosomes. The melt can also form oblique leucosomes that are either parallel to the axial plane of the fold (if the layer is less competent), or in extensional cracks that are perpendicular to the folded layer (if the layer is more competent). **e)** Melt can flow into the shear zones that can often develop in the hinge zones during folding of migmatitic rocks. The figure is modified from Sawyer (2008a).



Figure 15. An example of a dilation metatexite migmatite from the Shaw Granitoid Complex, Pilbara Craton. A relatively competent mafic layer within tonalitic orthogneisses has been boudinaged with melt ponding in the boudin neck. There also appears to be more melt accumulated on the right side of the mafic layer (the east side) relative to left (the west side), suggesting that this is also an asymmetric vein cluster that indicates way-up was to the west during partial melting. (Photo 413518)



Figure 16. An example of a dilation metatexite migmatite from the Shaw Granitoid Complex, Pilbara Craton. A more mafic (darker, finer grained) layer in tonalitic orthogneisses has sheared parallel to the axial plane of a small-scale 'z' fold. At a smaller scale, fine, discontinuous leucosomes are cutting some of the thin, more competent mafic layers. At first glance, the mafic layers appear to be boudinaged, but on closer inspection the leucosomes are not divergent, but instead they are parallel to the axial plane of the fold. (Photo 413519)



Figure 17. An example of a dilation metatexite migmatite from Fishery Bay, Gawler Craton. The melt is ponding to form a series of vertical sheets in the sheared axial planes of upright folds. The folded layering also contains layer-parallel leucosomes that are 1) locally deflected and truncated by the shears, and 2) texturally continuous with the melt in the shears. This indicates a progression from earlier, layer-parallel leucosome development to folding with flow most likely occurring from later leucosomes into the axial plane parallel shears. (Photo 413520)



Figure 18. Migmatite from the East Albany Fraser Orogen, Western Australia, where the melt is ponding in an extensional shear band that is at a moderate angle to the foliation and parallel leucosomes. The leucosome in the shear band has a very irregular, 'feathered' edge and is texturally continuous with the layer parallel leucosomes. This suggests that the melt is moving along the foliation planes and into the low-pressure 'tear' represented by the shear band. This photograph gives an indication of the difficulties that can arise when looking at migmatites. At the scale of

the photo, the feature would represent a dilation metatexite migmatite, however if the shear bands are common across the outcrop, then it could be described as a net-structured migmatite. In fact, there is a sinistral shear zone at the top left corner of the photograph making it likely that it would be a net-structured metatexite migmatite at the outcrop scale. Elsewhere, the rock could be dominated by the layer parallel leucosomes, and it would be described as a stromatic metatexite migmatite. (Photo 413521)

NET-STRUCTURED METATEXITE MIGMATITE

This type contains leucosomes that occur in two or more systematic sets which intersect to form a net-like pattern that outlines polygonal blocks of darker rock (Figs 19 and 20). The sets commonly include leucosomes that are parallel to the compositional layering or foliation and extensional shear bands that host the melt. This relationship can be distinguished by the deflection of the compositional layering or foliation into the shear bands and may indicate that the bulk rock underwent layer-parallel extension.

A range of progressive textural development can be recognised in the net-structured migmatites:

- At the early stages of partial melting, the leucosome is narrow with a high aspect ratio, and bordered by melanosome. The centres of polygon blocks are palaeosome (i.e. have not melted).
- With further partial melting, the blocks become progressively dominated by neosome, and they can be either melanocratic if the melt is extracted, or mesocratic if melt is injected into the blocks out of the oblique leucosomes.
- With increased melt fraction, the net-structured migmatites will progress into a schollen diatexite migmatite.



Figure 19. An example of a net-structured metatexite migmatite from the Shaw Granitoid Complex, Pilbara Craton, showing the two systematic sets of leucosome. Relatively earlier, foliation parallel, sharp-edged leucosomes (parallel to the hammer head) are deflected by shear bands with diffuse margins (sub-parallel to the hammer handle). (Photo 413522)



Figure 20. An example of a net-structured metatexite migmatite from Red Banks, Port Lincoln, showing the two systematic sets of leucosome. The relatively earlier, foliation parallel, sharp-edged leucosomes (parallel to the pen) are deflected at a moderate angle by shear bands with diffuse margins. The two sets are texturally continuous indicating their development was progressive. (Photo 412907)

STROMATIC METATEXITE MIGMATITE

This type contains numerous thin and laterally continuous bands of leucosome that are oriented parallel to the major plane of anisotropy in the palaeosome, which are typically compositional layering or a solid-state foliation (Figs 13 and 21). The individual leucosome bands can have melanosome on both sides, only on one side, or it can be absent. Several models have proposed for the origin of stromatic migmatites. Some, particularly those with melanosome selvages, are interpreted to be in situ partial melts (e.g. Sawyer 1991; Oliver and Barr 1997), whereas others are considered to be injection migmatites, where there is *lit par lit* (literally bed by bed) intrusion of migrating melt (e.g. Lucas and St-Onge 1995).

To help distinguish between these two processes, the contacts of any oblique leucosomes should be examined. If the rock was partially melted, any oblique leucosomes would have diffuse, feathery margins that would reflect the fine-scale migration of melt along the foliation planes and into the dilational sites. Furthermore, the in situ leucosomes may have a darker selvage that could represent the solid products of the melt reaction (Figs 4 and 13). In contrast, if the leucosomes were injected into a non-melted rock, then the oblique (dilational) leucosomes may have relatively sharp, intrusive boundaries.

DIATEXITE

A diatexite is a migmatite dominated by pervasive neosome. Pre-partial-melting structures are absent from the neosome, and commonly replaced by syn-anatectic flow structures or isotropic neosome. The neosome is variable in appearance as it typically includes leucosome and melanosome in varying proportions. The palaeosome can occur as rafts or schollen, or it may be absent.



Figure 21. An example of a stromatic metatexite migmatite from the Birksgate Complex, eastern Musgrave Province. The rock is characterised by parallel gneissosity and leucosomes, with the later forming continuous coarse- to medium-grained layers. (Photo 412908)

Sawyer (2008a) describes four main second order divisions of diatexite; nebulite, schollen (raft), schlieren, or diatexite (Fig. 10). However, it is important to remember that these represent transitional stages as the rock progresses to high degrees of partial melt and complete disruption of the protolith.

NEBULITE DIATEXITE MIGMATITE

Nebulite diatexite migmatites have neosome that is diffuse and difficult to differentiate from the palaeosome. This happens when patch metatexite migmatites reach higher melt fractions in the absence of any external strain (Fig. 10). External stresses will lead to structural control on the distribution of the melt phase, resulting in systematically arranged leucosomes (i.e. a metatexite), or possibly flow banding if the rock is disrupted and it forms a diatexite.

SCHOLLEN DIATEXITE MIGMATITE

Schollen, or raft-structured diatexite migmatites, are characterised by the presence of raft-like blocks within leucocratic to mesocratic neosome. The blocks can be either remnants of palaeosome, resistant lithologies, or melanosome (Figs 22 and 23).

Schollen diatexite migmatites commonly occur at the transition from metatexite to diatexite, and represent the disaggregation of the palaeosome, melanosome and resistant lithologies into discrete blocks thereby disrupting the structural continuity (Figs 22 and 23). Initially, the blocks are large, have high aspect ratios (reflecting the compositional layering and foliation) that have typically not undergone rotation, and often have rounded ends. Farther into the transition zone there is a progressive decrease in the size, aspect ratio, and number of rafts, which typically become more rounded, rotated and dispersed throughout the leucocratic neosome. The leucocratic neosome generally has a flow foliation defined by the alignment of platy or tabular minerals.

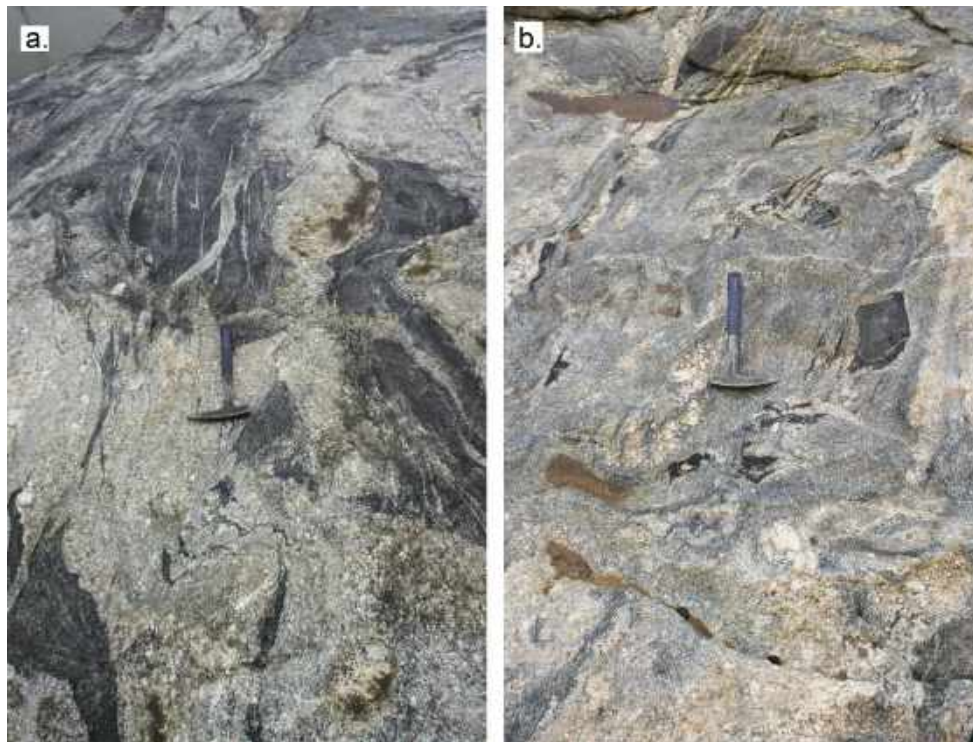


Figure 22. **a)** An example of a schollen diatexite migmatite from the Shaw Granitoid Complex, Pilbara Craton, containing large blocks of melanosome. The tips of some of the blocks are being attenuated to form schlieren. **b)** A schollen diatexite migmatite from the same outcrop which has undergone further disaggregation resulting in scattered, smaller blocks of melanosome in a groundmass of heterogeneous, leucocratic to mesocratic neosome. The rock also contains relatively common schlieren defined by trains of mafic minerals. There is a broad layering, extending from top right to bottom left, defined by aligned schollen and schlieren, as well as compositional layering in the neosome which would likely be a flow foliation. (Photos 413523 and 413524)



Figure 23. Schollen diatexite migmatite from the Birksgate Complex, eastern Musgrave Province. The residuum and palaeosome form common isolated blocks that have been rotated so that there is no structural coherence. The blocks are relatively equant and do not appear to be aligned suggesting there was little to no magmatic flow at this outcrop. (Photo 412909)

SCHLIERIC DIATEXITE MIGMATITE

Schlieric diatexite migmatites are characterised by well-developed, flow-induced structures, defined by thin layers of aligned platy, tabular, or prismatic minerals, which are known as schlieren (Fig. 24). The schlieren are most commonly defined by biotite, but can also include plagioclase, sillimanite, orthopyroxene, or amphibole, and likely represent entrained and attenuated neosome, most commonly the residuum.

The schlieren tend to be parallel (Figure 24), although in some outcrops the foliation, compositional layering, or schlieren, can be truncated at a low angle by similar looking, but often more leucocratic (i.e. melt-rich) layers (Figure 11). These features are evidence of syn-magmatic shear zones, or flow discontinuities in the partial melted rock, with greatest strain partitioned into the zones with the highest melt fraction. Folding can also occur during syn-magmatic flow, resulting in rootless, isoclinal folds, and sheath-like geometries.

Schollen of the palaeosome, resister lithologies, or melanosome may also be present, but they are less abundant than in schollen diatexite migmatites. The transition from schollen migmatites to schlieric migmatites represents an increase in the melt fraction, or neosome:palaeosome ratio. Strain is interpreted to have little effect on this transition, although the increased melt fraction will reduce the viscosity of the system, leading to a greater tendency to flow and attenuation of the residuum.



Figure 24. A schlieric diatexite migmatite from the Shaw Granitoid Complex, Pilbara Craton, showing the irregular mesocratic to melanocratic layers and lenses defined by trains of mafic minerals. The layering is locally defined by leucocratic lenses of coarse-grained feldspar and quartz (in the centre of photo) which likely represents attenuated leucosomes. The layering would be the result of magmatic flow which has drawn out and disaggregated the neosome. (Photo 413525)

DIATEXITE MIGMATITE

Diatexite migmatites are dominated by neosome, and relicts of palaeosome are rare, or absent. Pre-melting structures are restricted to the scattered schollen, and schlieren are rare (Figs 25 and 26). Instead, the neosome can contain a magmatic or sub-magmatic state flow foliation defined by the alignment of platy, tabular, or prismatic minerals, such as mica and feldspar. There may also be a flow banding defined by variable mineral proportions, grain size, or microstructure.

Diatexite migmatites are gradational from schollen and schlieric migmatites through an increase in melt fraction (i.e. neosome:palaeosome ratio), and from nebulitic migmatites through an increase in syn-anatectic strain (Fig. 10).

At the extreme end of the range are the diatexites that are well on their way to becoming a granite. These can be relatively homogeneous with granitic textures, although the presence of rare schollen and mafic schlieren, thin, leucocratic, coarse-grained layers that likely represent late-stage melts, and xenocrysts, indicate its origin as a migmatitic rock (Fig. 26). This paragraph may appear to be redundant as granites are considered to be derived by partial melting of the crust (e.g. Brown 2013). However, it is important to stress that the diatexite migmatites represent an early stage of the process. Subsequent migration and flow of the magma is necessary for the continued disaggregation of these features which will lead to homogenisation of the magma and the development of 'true' granite.



Figure 25. An example of a diatexite migmatite from the Shaw Granitoid Complex, Pilbara Craton, showing the dominance of the neosome. Rare pre-melting textures are preserved as layering on the right side of the photo, but the rock is dominated by a broad-scale, sinuous, magmatic or sub-magmatic state flow foliation and layering. The flow foliation is frequently truncated by magmatic flow or magma injection. The latter is best developed on the left hand side of the photo, where a sheet of more evolved, blue-grey, flow-banded 'granitic' material (likely monzogranite) has intruded the diatexite and truncated the layering. (Photo 413526)



Figure 26. An example of a diatexite migmatite from the Birksgate Gneiss, Musgrave Province that is well on the way to becoming a granite. The outcrop is generally

homogeneous with granitic textures although the origin as a migmatitic rock is suggested by rare mafic schlieren and thin, leucocratic, coarse-grained layers that likely represent late-stage leucosomes. Equally important is the local context as there is a spectrum of migmatitic textures ranging from metatexite, to diatexite, to 'dirty' granites in this area. (Photo 413527)

SYNTHESIS OF MIGMATITE CONCEPTS

An important point to remember is that all of these processes and features are interrelated, with something affecting one likely to change another. Furthermore, the processes can be progressive, as migmatitic rocks are not static. Figure 27 illustrates the relationships between the different parts of a migmatite, the effect that protolith composition can have on melt generation, and how the migmatite can evolve through the process of partial melting.

- a. For this example, the starting point (Fig. 27a) is a sequence of folded rocks which includes inter-bedded psammite (units 1 and 4), pelites (2 and 6) and calc-silicate rocks (units 3 and 5).
- b. With the onset of anatexis (Fig. 27b), the pelitic units have started to melt with neosome developing in these layers, forming neosome patches in unit 2 and stromatic neosomes in unit 6 (the dotted pattern in units 2 and 6). As the neosomes are in situ, it is likely that these neosomes would be composed of both leucosome and residuum/melanosome. In this scenario the pelitic rock would be the protolith, and the psammitic and calc-silicate rocks that did not partially melt (they would be considered infertile) would be the palaeosome. The rock is now a metatexite migmatite.
- c. At more advanced stages of partial melting (Fig. 27c) things have changed considerably. The psammitic units (units 1 and 4 in a and b) have now partially melted — so that they also form protolith — with the psammitic and pelitic layers now dominated by neosome. The calc-silicate rocks still have not melted and remain as palaeosome or resisters. Partial melting was accompanied by dextral shearing that has led to the destruction of the pre-existing structures. The resister layers have been disrupted so that they form disaggregated blocks, or schollen. The less melt fertile parts of the psammite and pelite layers have also been disaggregated to form schollen, which can retain the stromatic metatexite texture that developed during stage b. The various schollen are contained within neosome that was derived by partial melting of the more melt fertile psammites and pelites. The neosome will be characterised by magmatic-state structures that developed during shear flow, such as the schlieren (the black dashed lines) and asymmetric schollen. The neosome derived from the psammite and pelite layers will have similar meso- and microstructures, but it should still be possible to distinguish between them on the basis of the different mineralogy. The rock is now a diatexite migmatite.

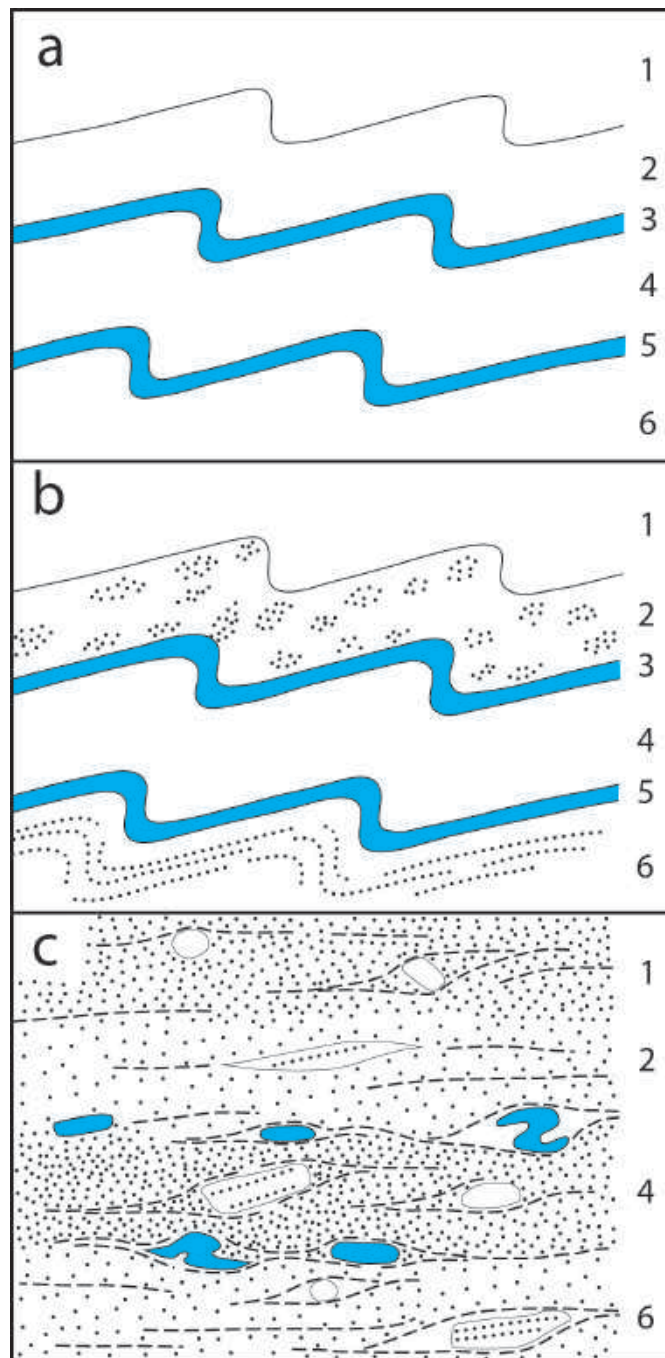


Figure 27. Diagram showing the transition from un-melted rock, via metatexite, to diatexite, and the effects that melt volume and lithology will have on this process. See the text for an explanation. The figure is modified from Sawyer (2008b).

OTHER INFORMATION THAT CAN BE EXTRACTED FROM A MIGMATITE

THE DATING OF MIGMATITES

Dating of migmatitic rocks usually will focus on constraining either the formation age of the metamorphosed protolith or the timing of partial melt formation. Any migmatitic zircon-bearing rock can be dated using U-Pb isotopic methods via standard analytical methods like sensitive high resolution ion microprobe (SHRIMP) or laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS). Zircons extracted from migmatitic rocks typically preserve evidence for either solid state recrystallisation or new zircon growth and, with in situ methods like SHRIMP, it is

possible to target both the inner portion of zircon grains that are part of the protolith and metamorphic rims formed during partial melting. In this way, zircon-bearing migmatites can be very useful rocks to date, providing information on the primary rock type, be it sedimentary or igneous, and on the timing of metamorphism.

An example is from the Christie Domain of the Gawler Craton. Mount Christie drillhole CD-1 intersected magnetite gneiss and into migmatitic metapelitic rocks. A sample of garnet-cordierite migmatitic gneiss (R1562985) was taken for SHRIMP geochronology and the data is presented in Jagodzinski et al. (2009). The zircons in this sample preserve small, oscillatory-zoned cores surrounded by metamorphic rims (Fig. 28). Sector zoning is ubiquitous in the rims. SHRIMP dating of core and rim populations from this sample reveal that the cores have a range of ages, from as old as c. 2980 Ma to as young as c. 2480 Ma. This range of ages suggests that the protolith is sedimentary in origin with a maximum depositional age of 2480 Ma. The metamorphic rims have ages ranging from 2470 Ma to 2415 Ma, which suggest that metamorphism was not a single event, but resulted from progressive stages of zircon growth, presumably linked to different P-T conditions.



Figure 28. a) Photograph of core from CD-1, sample R1562985. (Photo 413528)
b) Representative cathodoluminescence image of zircons from sample R1562985 showing the difference in age between metasedimentary cores and metamorphic rims.

In other studies where leucosomes can be seen to form discrete markers in a sequence of structural events, samples of the leucosome material alone has been taken in order to place constraints on the timing of different structural elements. An example is from the Albany Fraser Orogen by Kirkland et al. (2011) who dated 1) leucosomes aligned parallel to the gneissosity which were folded into northwesterly trending isoclinal folds, and 2) leucosomes that were aligned parallel to the axial planes of the folds. The SHRIMP zircon age data from the folded leucosomes shows they crystallised at 1676 ± 6 Ma, while the cross-cutting leucosomes formed at 1679 ± 6 Ma (Kirkland et al. 2011). Hence the two different leucosome generations can be shown to be within geochronological uncertainty, and the structures bracketed by these leucosomes were formed during sequential deformation during a single orogenic event.

WAY-UP INDICATORS IN MIGMATITIC ROCKS

Several studies have shown that migmatitic structures can be used as 'way-up' indicators, as well as provide information about the palaeohorizontal, during partial melting (Burg 1991; Burg and Vanderhaege 1993). The way-up indicators are primarily driven by the buoyancy contrast between the melt and the surrounding rock, with the buoyant ascent of the melt resulting in asymmetric features including asymmetric vein clusters, cauliflower structures and branching fractures (Fig. 29).

ASYMMETRIC VEIN CLUSTERS

Asymmetric vein clusters are collections of parallel leucosome veins that have accumulated and crystallised beneath the lower contact of a more competent layer, such as palaeosome or resisters (Fig. 29a). They are interpreted to be melts that have buoyantly ascended — either at the grain-scale via percolation, or as in-source leucosomes or leucocratic veins — and been trapped below the impermeable, more competent layer (Burg 1991; Burg and Vanderhaege 1993).

The more competent layer may be disrupted during deformation, for example it may be boudinaged, in which case the buoyant melt would start to flow through the breached layer (Burg 1991; Burg and Vanderhaege 1993). This would also result in the asymmetric distribution of the leucosomes, where crystallised melt would occur below the layer, in the boudin neck, and also possible forming a vein that continues upwards from the neck.

An example of asymmetric vein clusters and boudinaging can be seen in Figure 15 which is taken from an outcrop on the western side of the Shaw Granitoid Complex, a granite dome in the eastern Pilbara Craton. At this location, tonalitic orthogneisses contain a mafic layer that is aligned parallel with the granite–greenstone contact. The mafic layer is acting as a resister, with melt ponding on the eastern side, i.e. the side closest to the core of the granite dome (on the right side of Fig. 15), resulting in a zone of melt that contains discontinuous layers of the mafic rock and the host orthogneiss. The mafic layer has been boudinaged and breached with melt migrating into the boudin neck (one can be seen just above the note book) and locally flowing along the top side of the layer. Towards the top of the photograph, the melt is locally starting to overwhelm and disaggregate the mafic sheet resulting in a series of rafts within the leucosome. These observations suggest that the melt was migrating to the west (i.e. on the left side of Fig. 15). This interpretation is consistent with regional observations from the granites and surrounding greenstones that the gneissosity and parallel leucosomes were originally horizontal during the early stages of partial melting and softening of the crust. Softening of the crust facilitated greenstone sinking and associated development of the granite dome, which led to tilting of the layering to its current steep attitude (Pawley et al. 2004).

CAULIFLOWER STRUCTURES

Cauliflower structures form lobate structures at the upper margin of a layer-parallel leucosome (or intrusive sheet), whereas the lower margin of the leucosome is typically more planar (Fig. 29b). The cauliflower structures are often transgressive and can cut across the foliation in the overlying layer, or the cauliflowers can deflect the foliation to form a pinch and swell geometry. Cauliflower structures are interpreted to be the result of a gravitational instability, with the less dense, less viscous melt in the layer-parallel leucosome buoyantly ascending, and intruding, into the denser

overlying rock (Burg 1991; Burg and Vanderhaege 1993). The process can be considered as small-scale, incipient diapirism.

BRANCHING FRACTURES

Branching fractures are melt-filled veins that project from one side of layer-parallel leucosome into a more competent layer, with the veins interpreted to be the upward termination of the fracture network (Burg and Vanderhaege 1993). The fractures are considered to form when the accumulation of a buoyant melt below a competent layer causes the local fluid pressure to increase, eventually overcoming the tensile strength of the layer (Clemens and Mawer 1992). This is shown in Figure 29c, where the increasing fluid pressure causes the Mohr circle to move to the left until it intersects the failure envelope for the competent layer. Failure and cracking of the overlying layer creates a pressure gradient which draws the melt into the crack (Burg and Vanderhaege 1993).

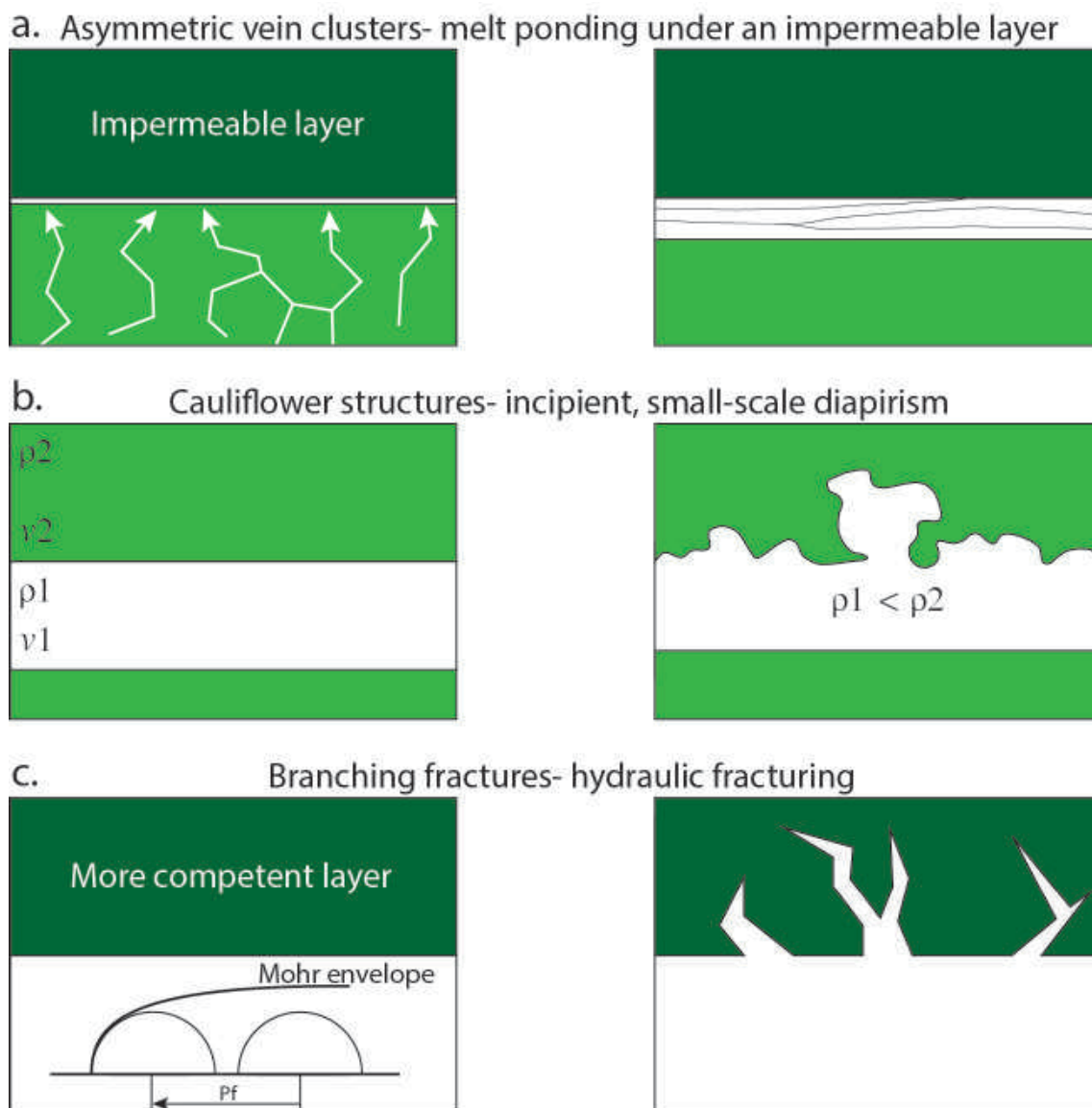


Figure 29. Diagram showing the different types of syn-anatectic way-up indicator.

a) Asymmetric vein clusters, where the percolating or migrating melt ponds underneath an impermeable layer. **b)** Cauliflower structures, with the white layer representing leucosome with a lower density and viscosity that ascends into the overlying layer. ρ and ν are density and viscosity, respectively. **c)** Branching fractures, where the melt ponding under a competent layer raises the fluid pressure and results in the hydraulic fracturing of the overlying layer. Figure modified from Burg and Vanderhaege (1993).

MIGMATITES AND MINERALISATION

Since migmatisation is a metamorphic process that produces a felsic partial melt, elements of economic interest can also be affected by this process and can be transported into partial melt. Thus, some migmatites can host mineralisation directly, such as at the Challenger Mine in the Gawler Craton (see below for more detail).

Furthermore, fluids generated during partial melting can be important sources of regional fluid flow events that can also concentrate mineralisation. The migration of hot, metamorphic fluids into upper crustal settings where they can interact with basin or surficial waters has been implicated in models for large mineral deposits, including iron oxide-copper-gold (IOCG) deposits such as occur in the eastern Gawler Craton (e.g. Bastrakov et al. 2007).

DEALING WITH MIGMATITES IN THE FIELD

An outcrop of migmatitic rocks should be viewed as a whole before detailed examination is attempted as some features are easier to see at the broad scale.

Is the rock dominated by leucosome, with disrupted and dispersed palaeosome, residuum, or melanosome (i.e. a diatexite)? Or is the melt less abundant, with coherent structures between the melt patches/layers (i.e. a metaxite)? There may also be features at the outcrop-scale such as broad compositional layering, which are not so obvious under close inspection. For example, there may be subtle differences in the colour of the palaeosome, or variation in the proportion of leucosome that could reflect differences in the composition of the protolith, such as bedding.

Colour can be important for distinguishing the various components. There is a good chance that the melt phase will be leucocratic, and the palaeosome and residuum will be darker (i.e. mesocratic to melanocratic). The resistor lithologies will range in colour from leucocratic for quartzite to melanocratic for mafic rocks. If the origin of each part of the migmatite is uncertain, they can still be described with reference to colour and texture, e.g. 'the thick, fine-grained, grey layer is boudinaged with medium-grained, massive, leucocratic material ponding in the boudin neck'. This still describes the features without using the jargon, which can be sorted out later.

The flow chart at the end of this report can be used to help distinguish between the various types of migmatites.

SOME GENERAL COMMENTS

- Descriptions should be systematic, starting with the large-scale (i.e. outcrop-scale) features, progressing to smaller features.
- Photographs and annotated sketches of key observations are very helpful.
- Observations should be separated from interpretations.

IF THE MIGMATITE IS A METATEXITE

The neosomes and the palaeosomes, and the relationships between them should be described. This could include the following observations:

- What are shapes of the leucosomes? Are they equant, elongate, sheet-like, planar, curvilinear, etc?
- What are the orientations of the leucosomes and how do they relate to the foliation or compositional layering in the host? For example, are the leucosomes parallel to the axial planes of folded palaeosome, or do they fill shear zones (extensional, compressional) or boudin necks? This is important as it will provide insights into the stresses acting on the migmatite during partial melting.

- If there are several sets of leucosomes in different orientations, how do the different sets relate to each other? Are they texturally continuous, suggesting they were contemporaneous, or do they cross-cut each other, suggesting progressive injection or even several events?
- What do the margins of the leucosomes look like? Are they sharp, diffuse, feathery, etc?

These observations are important as they allow classification of the metatexite, and an understanding of the processes that formed them (e.g. the degree of strain, fraction of partial melting, external strain).

IF THE MIGMATITE IS A DIATEXITE

- The proportion of rafts/layers/schleiren versus melt phase is estimated. This can be as a percentage or it can be qualitative, i.e. are the blocks common, scattered, rare, etc. However, the use of qualitative terms will require consistency.
- What are the rafts/layers/schlieren composed of? Are they composed of residuum or palaeosome? This is important as it may provide evidence about the original rock, such as composition, whether it was homogeneous, etc.
- What are the size, shape and aspect ratios of the rafts/layers/schlieren?
- Are the rafts/layers/schlieren aligned or randomly oriented? If aligned, are there truncations, folds, etc. Are the rafts tiled or imbricated? These observations can provide information about the flow regime and stresses during anatexis.
- Are the rafts/layers/schlieren evenly distributed or do they occur within zones? This may provide information about any original compositional layering.
- What does the melt phase look like?
 - Is it relatively homogenous or is heterogeneous?
 - How is it heterogeneous?
 - Is there evidence for flow, such as schlieren or mineral alignment?
 - Is there evidence for injected melt/magma? This could be syn-anatectic injection of external melt/magmas, which could have irregular diffuse margins and distinct compositions or textures. Or it could be late-stage pegmatite veins or injected magmas that have relatively sharp margins?

These observations are important as they allow classification of the diatexite and an understanding of the processes that formed them (e.g. the degree of strain, fraction of partial melting, external strain).

WHAT TO RECORD IN A MIGMATITE

The orientations of structural elements are measured as for any other outcrop. The type of structure measured, and what they are defined by (e.g. leucosome, schlieren, palaeosome, solid-state foliation, bedding, etc), should be recorded. This second point can be important as a melt-filled shear zone is likely to be contemporaneous with anatexis, whereas a mylonitic foliation (which results from recrystallisation of the minerals) would have occurred later. Some of the structural elements that can be measured include (see Fig. 30):

- Foliations and/or layering, making sure to note what the feature is defined by, e.g. solid-state foliations in the palaeosome, leucosomes, schlieren, etc.
- Fold axes and axial planes, recording whether it is melt-filled or not.
- Shears (measured as a plane), recording the apparent sense of shear. If possible, measure the lineation that would represent the transport direction. This may not be possible if the leucosome is massive and isotropic.

- If boudins are present, the orientation of the layer that is being boudinaged plus, if possible, the plunge of the boudin neck, are measured as these will give an indication of the principal stress directions during the anatectic event.

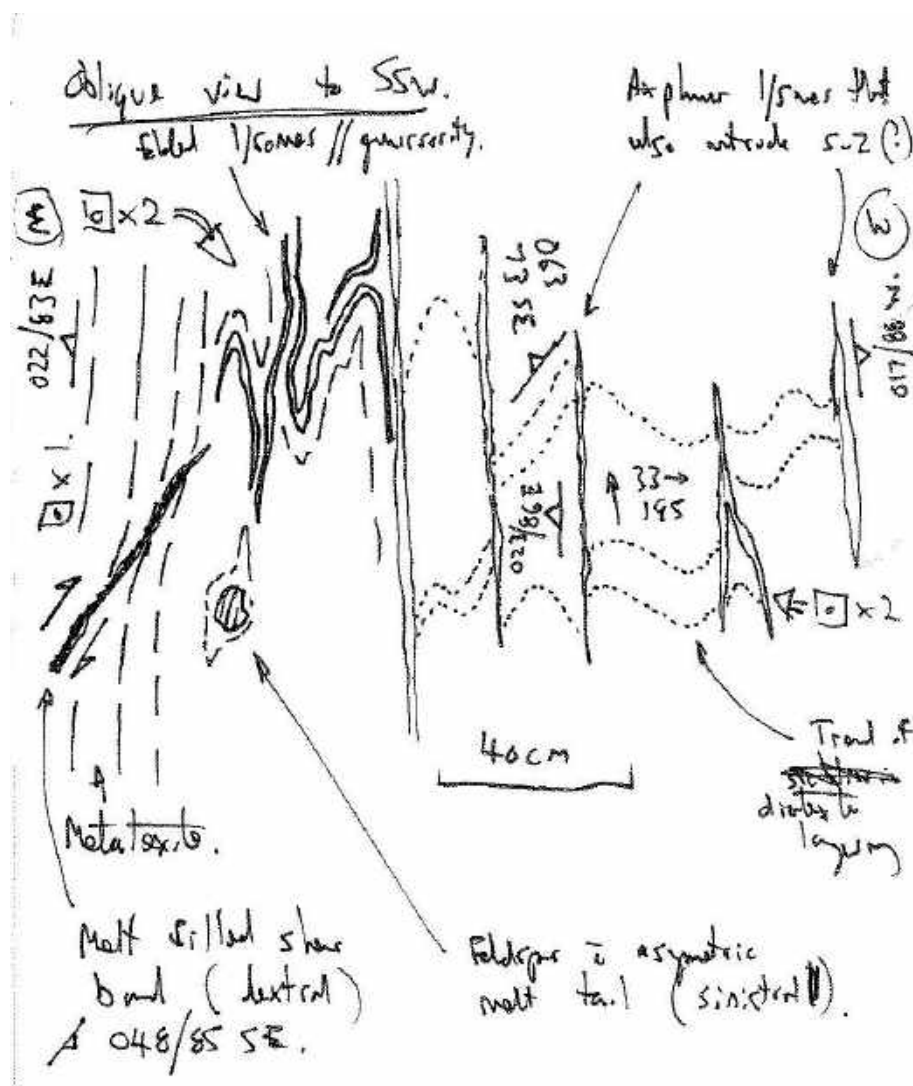


Figure 30. Example of a sketch from a field note book showing the information and measurements that can be recorded in the field. The outcrop is from the eastern Albany-Fraser Orogen and illustrates the transition from metatexite, with an extensional shear band, in the east, through disharmonically folded leucosomes, to diatexites to the west. The western diatexites contain schlieren that are folded into open, upright SSW-plunging structures which have ESE-trending form surfaces and NNW-trending axial planes that have been intruded by leucosomes.

It is worthwhile looking in the leucosomes for solid-state textures such as recrystallised quartz or feldspars, as these would indicate that the stress continued after cooling and crystallisation of the migmatite. Importantly, migmatitic and solid-state structural elements may not be in the same orientation, as the different rheology may cause the rock to deform differently, but they would be reconcilable with the same stress field.

SOME EXAMPLES OF MIGMATITIC ROCKS FROM SOUTH AUSTRALIA

CHRISTIE GNEISS, MULGATHING COMPLEX AROUND MOUNT CHRISTIE AND CHALLENGER MINE, GAWLER CRATON

The Mulgathing Complex is a Neoarchaeon to earliest Palaeoproterozoic (c. 2555–2420 Ma) belt of rocks located in the central Gawler Craton (Fig. 31). The Mulgathing Complex comprises a wide variety of lithologies from ultramafic intrusions and komatiite, basaltic and felsic volcanics, clastic and chemical metasediments together with a range of felsic to mafic intrusions that both predate and are synchronous with the early Palaeoproterozoic Sleafordian Orogeny (Daly and Fanning 1993; Reid et al. 2007; Jagodzinski et al. 2009). The Christie Gneiss is a unit that encompasses all of the metasedimentary lithologies of the Mulgathing Complex and was defined in the absence of significant zircon geochronology (Daly and Fanning 1993; Reid and Daly 2009), and may thus encompass a number of sedimentary successions of different ages within a broad age range (c. 2555–2485 Ma; Jagodzinski et al. 2009). The Christie Gneiss preserves an abundance of migmatitic lithologies. At the Mount Christie type-locality (Fig. 31) the outcropping meta-banded iron formation is interlayered at the scale of tens to hundreds of metres with stromatic metatexite migmatite that contains abundant poikiloblastic, coarse-grained garnet, cordierite, K-feldspar, biotite and quartz (Fig. 32a). Such mineral assemblages are common also at Challenger Gold Mine, where stromatic metatexite migmatites contain gold-bearing leucosomes (Fig. 32b). Peak metamorphic poikiloblastic garnets within the migmatite possess gold inclusions, supporting the notion that gold mineralisation also predates migmatite formation at Challenger, and that gold mobilisation during peak metamorphism played a role in localising the gold within the migmatite (Tomkins and Mavrogenes 2002).

At Challenger there is a greater concentration of partial melt in and around the orebody in comparison to adjacent barren gneiss (Fig. 32c; McFarlane et al. 2007; Tomkins 2007; McGee et al. 2010). This has been interpreted to be a function of pre-metamorphic hydrous alteration within the ore zone, possibly as part of an epithermal or mesothermal gold mineral system (McFarlane et al. 2007). For this reason, recognition of migmatite and the variable intensity of partial melt within a sequence of migmatites has direct exploration significance; high degrees of partial melt may indicate protolith heterogeneity possibly related to early or pre-metamorphic hydrous alteration.

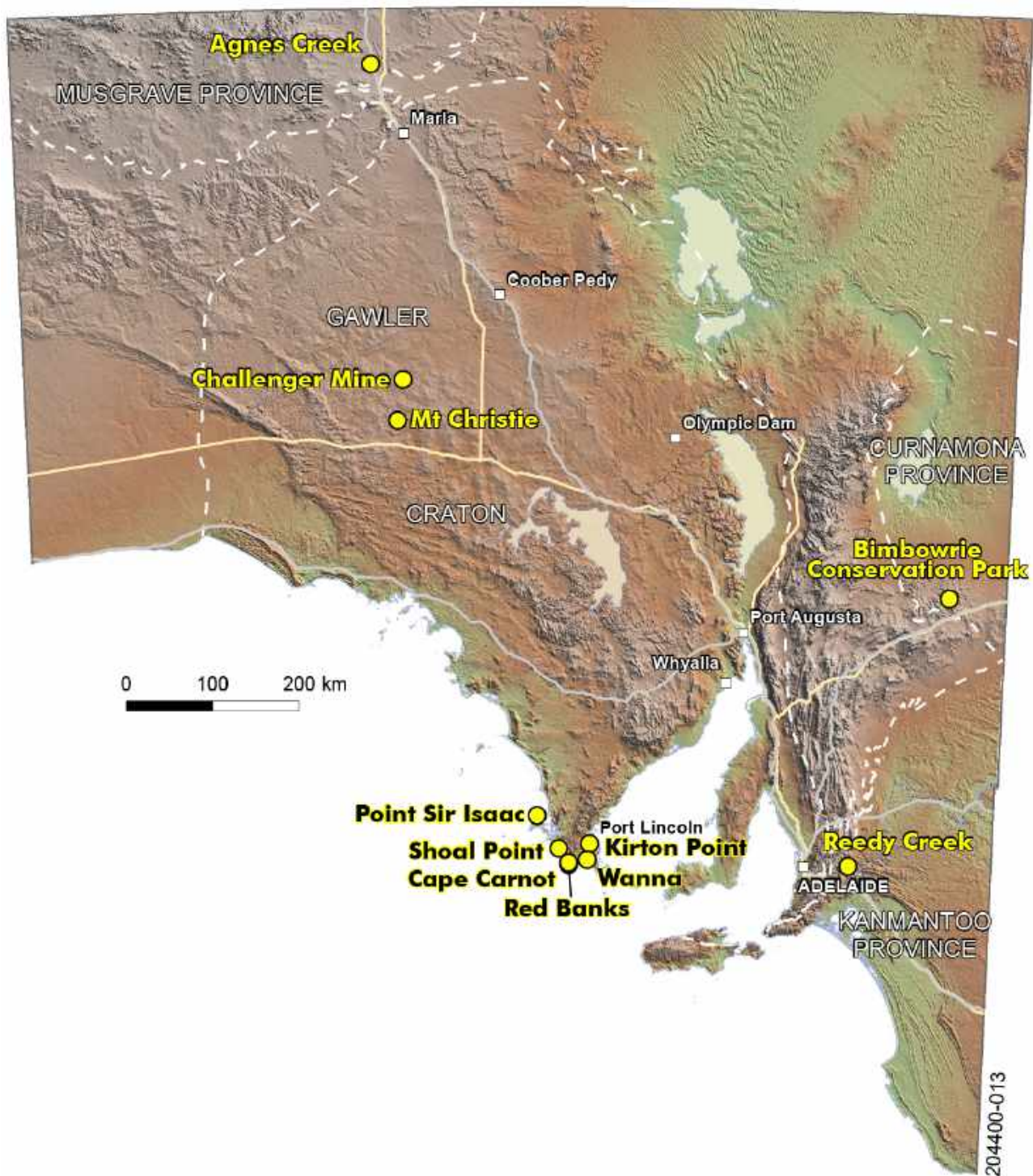


Figure 31. Location of the field localities that are described in this report book with reference to the major tectonic elements of South Australia.

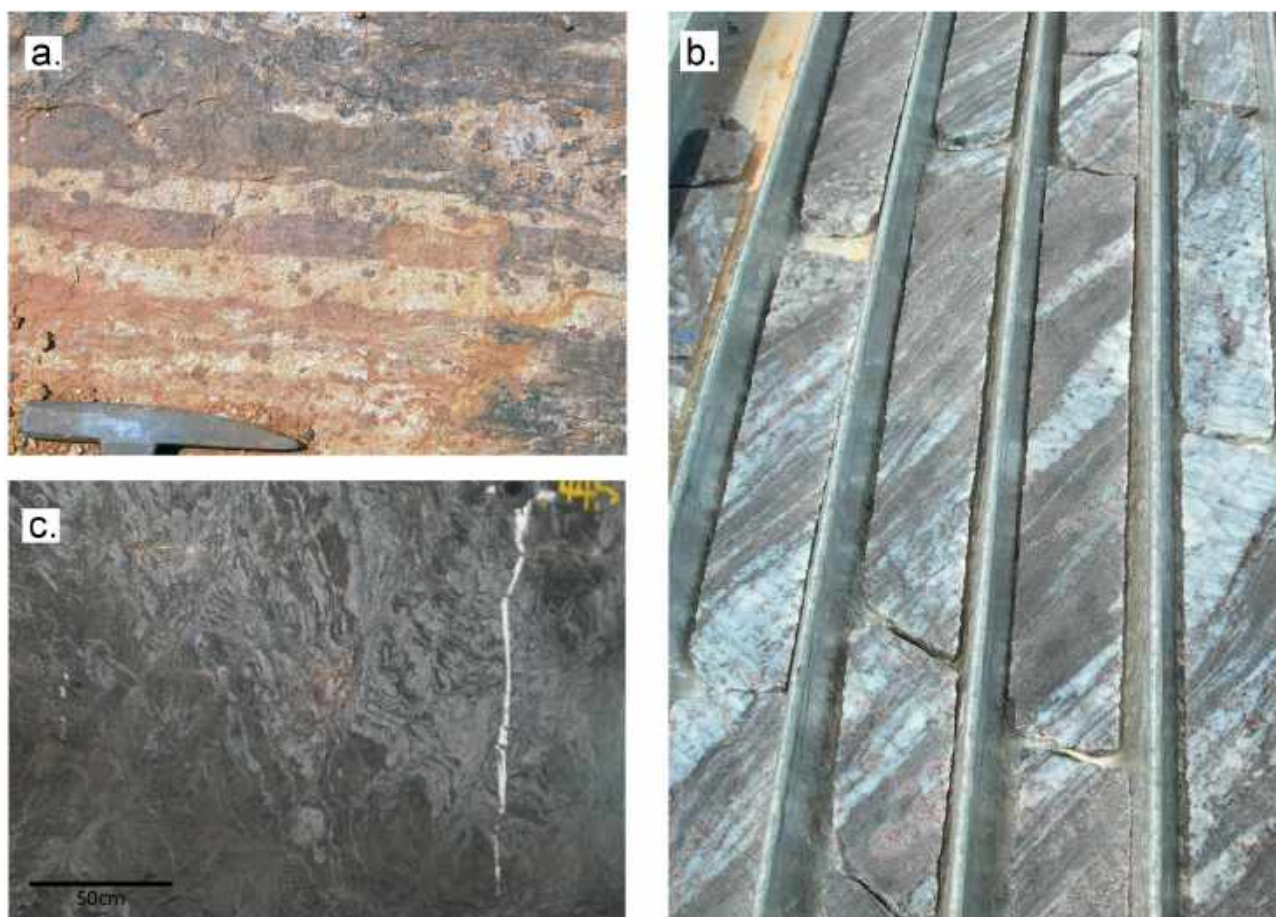


Figure 32. Examples of migmatite from the Mulgathing Complex, central Gawler Craton.

a) Stromatic metatexite migmatite with garnet-bearing, in-source leucosomes at an outcrop near Mount Christie. **b)** Typical stromatic metatexite migmatite that is host to gold mineralisation in diamond core from Challenger Mine. Visible gold is often present within the coarse blue-quartz rich leucosomes. **c)** Underground photograph from Challenger Mine near the M1 ore shoot. In this photograph, the upper right portion of the gneiss is clearly more leucocratic than the lower left portion. This differentiation into greater or lesser degrees of partial melt is interpreted to be in part related to the localisation of melt into a zone of enhanced water content by pre-metamorphic hydrous alteration (see McFarlane et al. 2007; McGee et al. 2010). (Photos 412911–412913)

MIGMATITES OF THE KIMBAN OROGENY (~1700 MA) WITHIN THE SLEAFORD COMPLEX ON SOUTHERN EYRE PENINSULA, GAWLER CRATON

The Sleaford Complex is the southern belt of Neoarchaeon to early Palaeoproterozoic rocks with similar rock types and ages to the Mulgathing Complex, of which it is considered a lateral equivalent (Daly and Fanning 1993; Daly et al. 1998; Swain et al. 2005). Like the Mulgathing Complex, the Sleaford Complex also underwent high temperature metamorphism during the Sleafordian Orogeny (Daly and Fanning 1993; Dutch et al. 2010; Jagodzinski et al. 2012). However, the Sleaford Complex also underwent a second phase of high temperature metamorphism and associated deformation during the c. 1730–1690 Ma Kimban Orogeny (Dutch et al. 2008; 2010). Therefore, large portions of the Sleaford Complex are poly-metamorphic and deciphering which minerals or structural elements formed during each event requires careful examination and most probably detailed geochronology. As a result of the Kimban Orogeny many spectacular examples of migmatite are developed along the southern coastal outcrops of Eyre Peninsula in particular those around Cape Carnot, Shoal Point and Point Sir Isaac (Fig. 33).

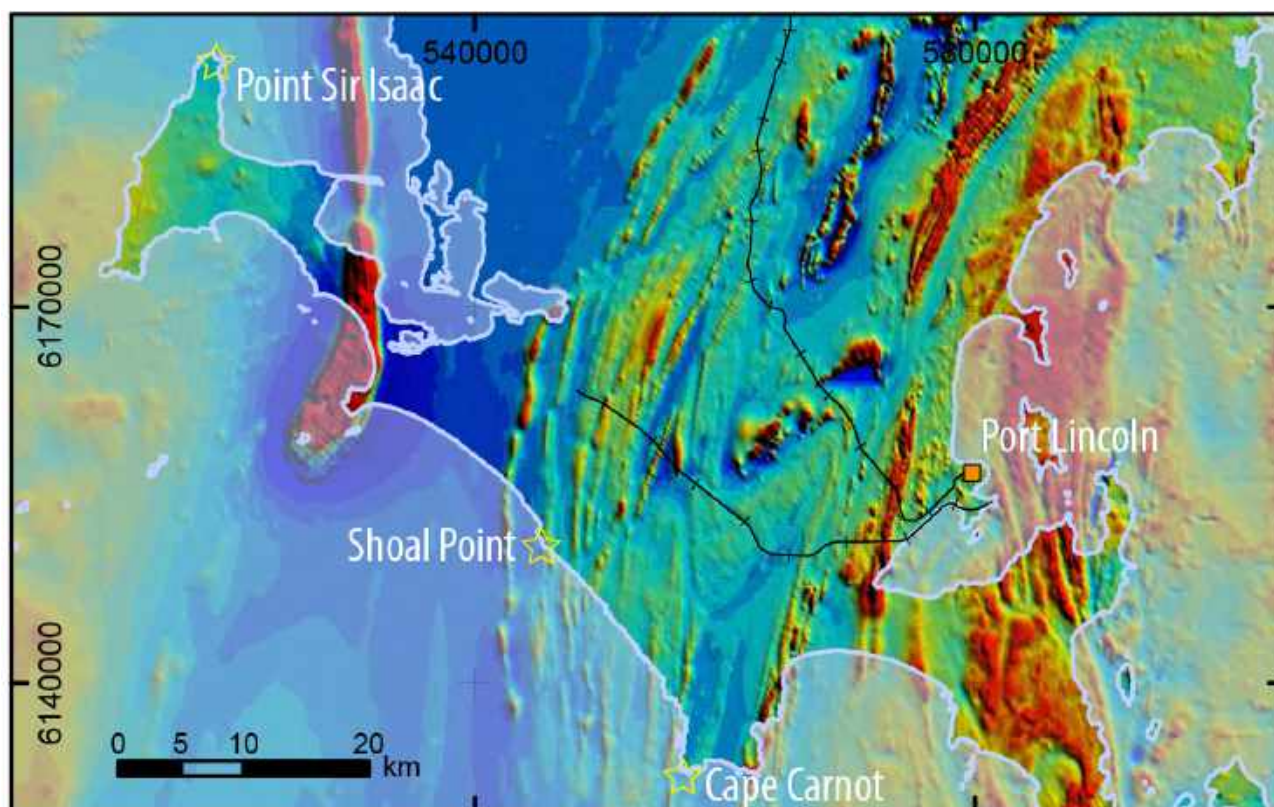


Figure 33. Migmatite localities described in this paper from the southern Eyre Peninsula, shown against regional TMI image.

At the western headland of the Cape Carnot locality, there are two broad lithologies, garnet + cordierite-bearing megacrystic granitic gneiss, and metapelitic gneiss. SHRIMP dating of the granitic gneiss suggests the granite was emplaced at 2431 ± 7 Ma, with metamorphic zircon growth at 1715 ± 6 Ma (Jagodzinski et al. 2012). The granitic gneiss preserves net-structured metatexite migmatites related to foliation boudinage (Figs 34a and b), and examples of garnet $\pm$ cordierite-bearing in-source leucosomes that become diatexite migmatites in places (Fig. 34c).

Shoal Point, on the central south coast of Eyre Peninsula (Fig. 33) contains spectacular examples of metatexite and diatexite in a variety of metasedimentary and igneous protoliths. These units have undergone two phases of high-T metamorphism, firstly during the c. 2450 Ma Sleafordian Orogeny, and then during the c. 1730–1690 Ma Kimban Orogeny (Dutch et al. 2010). Peak conditions during the Sleafordian reached 750°C at 5–6 kbar, while during the Kimban, conditions reached over 800°C at up to 10 kbar. The peak Sleafordian assemblages are only preserved within boudins in the high-strain Kimban fabrics, where they form net-structured metatexite migmatites with large garnet porphyroblasts in the leucosomes (Fig. 35a). Within the Kimban-aged fabrics, leucosomes formed parallel layers in stromatic metatexite migmatites, with some of the thicker layers forming transfer zones (Fig. 35b), as well as discordant dilational structures such as boudin necks (Fig. 35c) and shear bands (Fig. 35d) in dilation metatexite migmatites. At greater degrees of partial melt production, the rocks disaggregated to form schollen diatexite migmatites which have been folded (Fig. 35e). There is very little palaeosome preserved in this unit, with a large proportion of light coloured leucogranitic melt and only minor dark coloured, garnet-bearing melanosome and residuum.

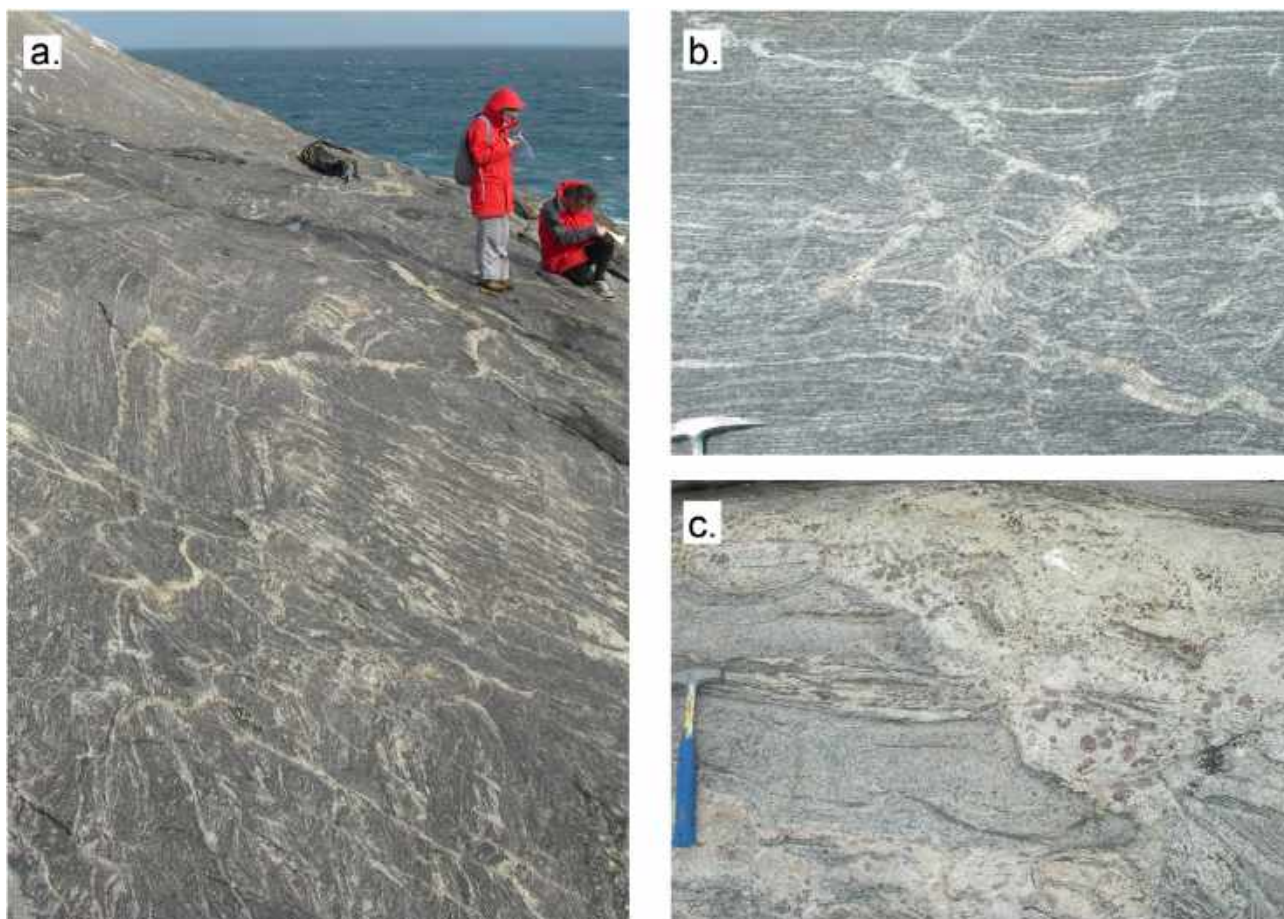


Figure 34. Examples of migmatite from Cape Carnot, southern Eyre Peninsula. a) Net-structured and stromatic metatexite migmatite with a K-feldspar megacrystic granite protolith. **b)** In situ and in-source leucosomes forming in dilational sites in a K-feldspar megacrystic granite protolith. **c)** Transgressive garnet-cordierite-bearing in-source leucosome that grades into diatexite migmatite to the right of the field of view. (Photos 412914–412916)

The migmatites developed on the Coffin Bay Peninsula have formed in both mafic and felsic igneous protoliths. The Point Sir Isaac coast consists of generally undeformed late Sleafordian-aged (2414 ± 6 Ma) garnet $\pm$ cordierite bearing S-type granite, locally intruded by a number of mafic dykes ranging from 5–50 m in width (Dutch et al. 2008). This area was subsequently metamorphosed during the Kimban Orogeny at conditions reaching 750°C and 10 kbar. Importantly, the majority of the granite, due to its relatively anhydrous assemblage, was unaffected by the later metamorphism. Deformation and migmatitisation was limited to discrete zones interpreted to be hydrated fracture zones or alteration zones, or the relatively hydrous hornblende-bearing mafic dykes. High grade melting within the felsic shear zones has produced net-structured metatexite migmatites with leucosomes occurring both concordant with, and cross-cutting the shear fabric, and within shear bands (Fig. 35f). Melting within the mafic lithologies resulted in small scale patch metatexite migmatites, which were probably produced by the reaction:



This can be seen in Figure 35g where small amounts of leucocratic melt contain garnet and clinopyroxene porphyroblasts. The fact that the melting within the granite was limited to hydrous zones, and that the hornblende-rich mafic units melted at all, reflects the strong role of H_2O in increasing melt fertility.

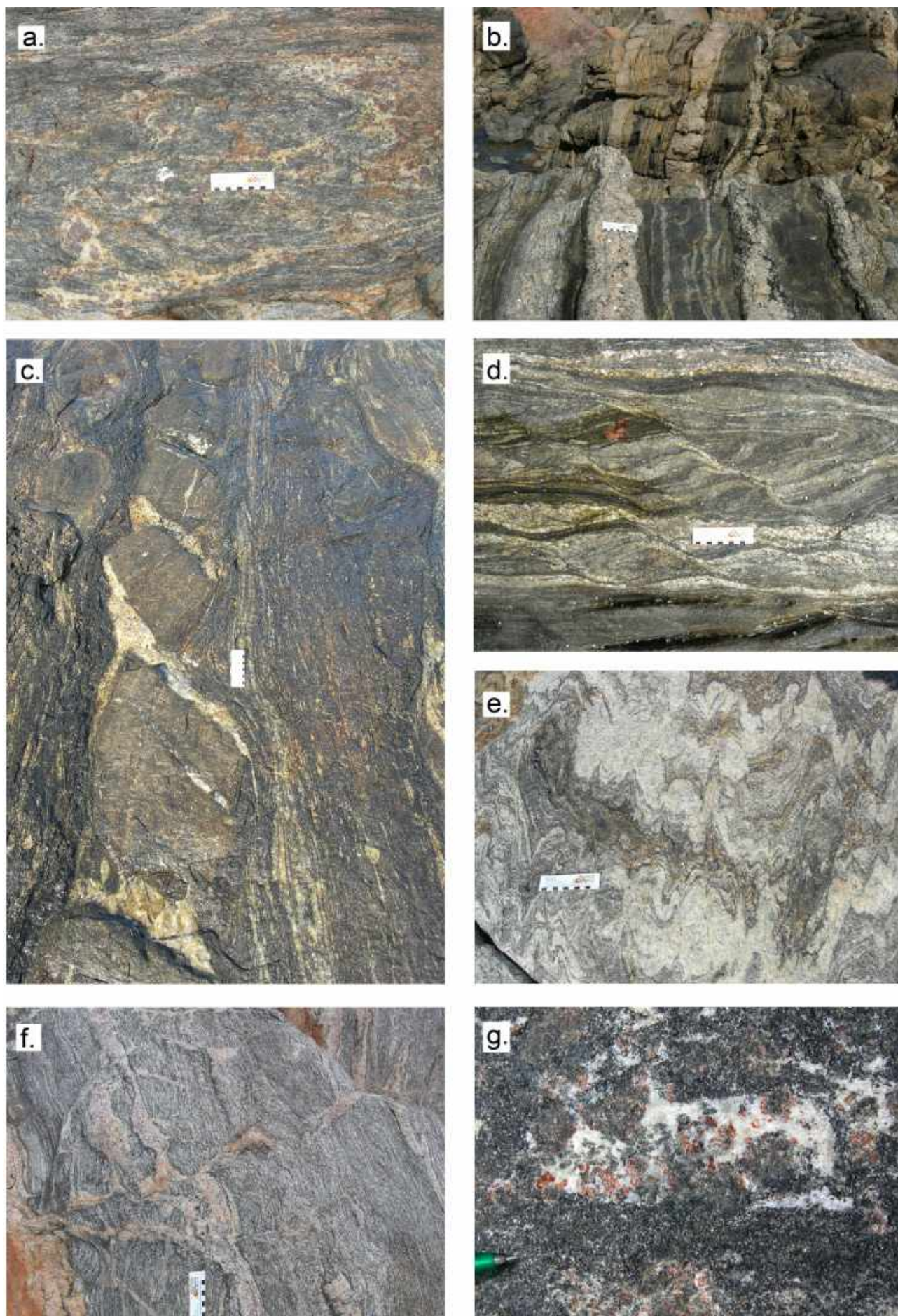


Figure 35. Examples of migmatite from Shoal Point and Point Sir Isaac, southern Eyre Peninsula. a) Net-structured metatexite migmatite from Shoal Point with large garnet

porphyroblasts forming within the leucosomes. These leucosomes formed during the Sleafordian metamorphism and are now only preserved in low strain boudins within the high-strain Kimban fabrics. **b)** Stromatic metatexite migmatite from Shoal Point with thick leucogranitic veins channelling melt migration parallel to the compositional layering within the migmatite. **c)** Dilation metatexite migmatite from Shoal Point with leucocratic melt localised into dilational sites, in this case within the neck zones of domino-type boudins of a mafic lithology, which can be considered the palaeosome. The asymmetry of these domino boudins indicates sinistral shear. **d)** Kimban-aged, ~1700 Ma leucosome-filled shear bands in a net-structured metatexite migmatite from Shoal Point. **e)** Folded schollen diatexite migmatite from Shoal Point. The rock has a high degree of neosome and only minor residuum is preserved. **f)** Net-structured metatexites migmatites within a sheared ~2415 Ma granitic protolith at Point Sir Isaac. **g)** In situ leucosome containing garnet and clinopyroxene porphyroblasts within a patch metatexite migmatite at Point Sir Isaac. The protolith was a mafic dyke. (Photos 412917–412923)

OLARIAN (~1600 MA) MIGMATITES OF THE CURNAMONA GROUP, OLARY DOMAIN, CURNAMONA PROVINCE

The southern Curnamona Province is divided into the Broken Hill Domain in the east (mostly in New South Wales) and Olary Domain in the west. The province comprises a late Palaeoproterozoic (c. 1720–1640 Ma) metasedimentary succession, the Willyama Supergroup, with lesser volcanic components, which was moderately to highly deformed and metamorphosed during the earliest Mesoproterozoic Olarian Orogeny, and intruded by late orogenic felsic intrusive of the Ninnerie Supersuite (Page et al. 2005; Fricke 2008). The metamorphic style of the Olarian Orogeny is broadly high temperature – low pressure, ranging from granulite facies metamorphic conditions (e.g. Willis et al. 1983; White et al. 2005) in the Broken Hill Domain to greenschist facies in the northern-central portion of the Curnamona Province. The region of granulite facies extends westward into South Australia, where metamorphic conditions of 700–800°C and 4.6–5.6 kbar have been estimated just over the border (Webb and Crooks 2005).

In the Olary Domain to the west and northwest, the metamorphic grade is somewhat lower, decreasing from upper to lower amphibolites facies toward the northwest. This is interpreted to reflect differential exhumation along late Olarian shear zones of tectonically stacked nappes of Willyama Supergroup metasediments. Migmatitic rocks are located in the regions with upper amphibolites facies or higher grade, which are mainly in the southeast (Clarke et al. 1987; Crooks 2001; Webb and Crooks 2005), although there is also local migmatitisation in the northwest that may be related to intrusion of the Crocker Well Suite granitoids. Shear-bounded areas of lower amphibolites facies metasediments, which are significantly less recrystallised and have andalusite as the dominant aluminosilicate, generally do not show evidence of migmatitisation.

In the upper amphibolites facies rocks, evidence of partial melting is found in lithologies of appropriate bulk composition, mainly in the lower part of the Willyama Supergroup stratigraphy (Curnamona Group). The Wiperaminga Subgroup (lower Curnamona Group) is the most intensely affected, especially in its oldest units, while migmatitisation in the overlying Ethiudna Subgroup is more incipient (Conor and Preiss 2008). There is little migmatite development in the upper Willyama Supergroup in the Olary Domain, although it is common in the Broken Hill Domain.

Many gold and copper deposits in the Curnamona Province are associated with pegmatitic and other leucocratic veins (Cooke 2003; Burt et al. 2004). Some occur in high-grade regions close to the source of anatexis (e.g. White Dam) while others were formed at much higher crustal levels in low-grade metasediments (e.g. Portia, Kalakaroo). Such veins are likely to be related, at least in part, to partial melting during the Olarian Orogeny (Skirrow 2003). High heat flow during this orogeny both partially melted Willyama Supergroup rocks and resulted in the remobilisation of metals during regional fluid flow and related structural events.

As an example of migmatite in the Curnamona Province, the following observations come from the Mulga Creek – Oonartna Creek area in Bimbowrie Conservation Park. Within Wiperaminga Subgroup rocks, partial melt generally constitutes less than 15% of the rock mass, and typically forms discrete, in situ and in-source leucosomes that are parallel or sub-parallel to the main compositional layering (i.e. stromatic metatexite migmatite), with minor leucosomes in oblique shear zones (Fig. 36a). Such leucosomes are commonly folded by second generation and younger folds (Fig. 36b). Locally, partial melting has proceeded to a greater extent and stromatic metatexite migmatite grades into schlieric diatexite migmatite (Fig. 36c), or stromatic migmatite is intruded by foliated, syn-tectonic leucogranite sheets (Fig. 36d). Where the parent metasediments are albite-rich, which is commonly the case in the Wiperaminga Subgroup, the leucosomes are also albitic.

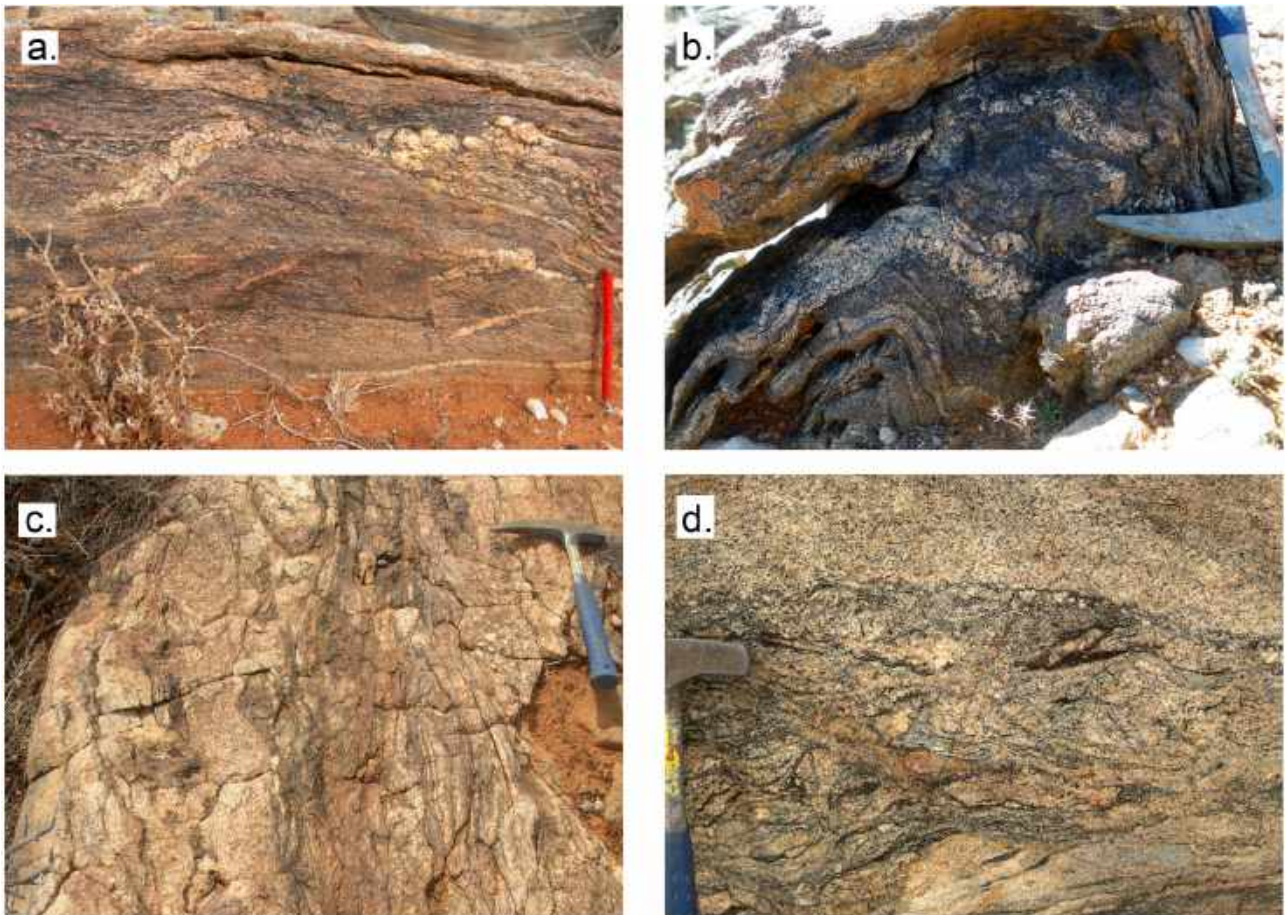


Figure 36. Olarian-aged (~1600 Ma) migmatites of the Wiperaminga Subgroup, Curnamona Province, Bimbowrie Conservation Park. **a)** Coarse-grained in-source leucosomes within a psammopelitic protolith. The leucosomes are generally parallel to the layering, but note that some leucosomes are also developed in en echelon dilational arrays that suggest sub-horizontal, top to the left shear (present-day reference frame). **b)** In-source leucosomes preserved within individual psammopelite layers, folded here by an open, probable third generation fold. **c)** Transitional metatexite to diatexite migmatite. Some portions of this migmatite consist entirely of medium grained leucosome that has engulfed the restite bands and thus preserves schollen bands. The region to the right of the photo has a greater degree of melanocratic layers and schlieren. **d)** Melt-rich metatexite migmatite (bottom) that is intruded by weakly foliated, syn-tectonic granite sheet (top). (Photos a–c, 412924–412926; Photo d, 413529)

By contrast the coarse-grained two-mica granites of the Bimbowrie Suite are S-type, mainly potassic granites, and are mostly undeformed except where they are cut by late, greenschist-facies shear zones. Some have intruded along bedding planes while others appear to cross-cut the regional structural trends, and they have very sharp intrusive contacts. Therefore they appear to have formed late in the orogenic process (Fricke 2008), whereas most migmatisation occurred

early under high heat flow conditions. At Bimbowrie therefore, we can make the following observations:

- There were compositional controls on the degree of partial melting, with greater partial melt formed within more psammopelitic lithologies.
- Partial melting is confined to the lower stratigraphic units and decreases up-section.
- The large plutons of mostly undeformed late Olarian, two-mica granites significantly post-date peak metamorphism, and may therefore have an unrelated origin.

The first observation can be explained simply as a function of the control of bulk rock composition on the timing and degree of partial melting. The second observation indicates that early heating during burial was a significant process in the Olarian Orogeny. Migmatite formation during burial metamorphism is likely to have been a major factor in the formation of migmatite in the lower stratigraphic units of the Curnamona Province (Clarke et al. 1987).

Large bodies of truly syn-tectonic granite have not been found in the Olary Domain, but migmatisation of supracrustal rocks occurred early in the deformation history, and granitic magmas thus generated show evidence of only incipient mobilisation and pooling on a limited scale.

While some of the late granite plutons in the Curnamona Province, e.g. the Bimbowrie Suite, have geochemical signatures suggesting derivation from partial melting of the Willyama Supergroup, others have formed via fractionation from mantle-derived melts (Barovich and Foden 2002; Fricke 2008). This suggests there may have been a second phase of melting of supracrustal rocks in tandem with mantle processes to produce late- to post-orogenic granites that were generated at a lower crustal level than is currently exposed and intrude a variety of structural levels within deformed Willyama Supergroup rocks.

MUSGRAVIAN OROGENY (~1200 -1160 MA) AND THE MIGMATITES OF THE EASTERN MUSGRAVE PROVINCE

The eastern Musgrave Province is interpreted to comprise c. 1600–1550 Ma magmatic arc rocks (Wade et al. 2006) that were deformed during the c. 1200–1160 Ma Musgravian Orogeny, which was accompanied by the c. 1200–1140 Ma, anhydrous, charnockite series Pitjantjatjara Supersuite (Camacho and Fanning 1995; Smithies et al. 2010). These rocks were subsequently intruded by c. 1080–1040 Ma rocks of the Giles Event (Glikson et al. 1996; Edgoose et al. 2004) before being reworked during the c. 570–530 Ma Petermann Orogeny (Scrimgeour and Close 1999). The Musgravian Orogeny was a regional amphibolite to granulite facies metamorphic event that resulted in partial melting of the protolith in the eastern Musgrave Province to form the gneisses of the Birksgate Complex (Major and Conon 1993). The tectonic setting of the Musgravian Orogeny is unclear. However, based on the long-lived, widespread nature of the event, and the high-temperature granites of the Pitjantjatjara Supersuite, it is considered to have been associated with extension and/or upwelling in an intracontinental setting (Smithies et al. 2010; 2011).

Recently, the GSSA recommenced 1:100 000 mapping in the easternmost part of the province. Although in the preliminary stages, mapping of the migmatitic Birksgate Complex on the AGNES CREEK 1:100 000 map sheet has revealed several structural observations that may be of regional significance:

- The Birksgate Complex rocks have a layering that is generally defined by parallel leucosomes, indicating the rock is a stromatic metatexite migmatite, although there are also locally developed dilation metatexite migmatites, characterised by melt-filled shear bands and boudins (Fig. 37a).
- On the regional scale, the gneissosity and parallel leucosomes are north-northeast-striking with a steep dip (Fig. 38), although there is local variation that can be attributed to outcrop-scale folding and the apparent realignment of the layering adjacent to large faults (Fig. 38).

- Mafic selvages to the leucosomes are rare, and their relatively sharp boundaries (see below) suggest that they are mostly in-source leucosomes that have segregated and migrated from the site of partial melting. Some leucosomes have mafic selvages however, indicating that at least some partial melting occurred at the current exposure level.

Based on their textures and contact relations, the layer parallel leucosomes can be subdivided into two types (Fig. 37b): there are medium-grained leucosomes with relatively sharp, straight margins; and coarser-grained leucosomes with less sharp, but still straight margins. The margins of the later type are often stepped, following the grain boundaries of the individual crystals in the host, suggesting that the residuum contained a film of melt that allowed the grains to separate along their boundaries, rather than cracking. In contrast, the relatively sharp, straight margins of the medium-grained, gneiss-parallel leucosome suggests that they may have been earlier and seen more strain (i.e. the margins have been transposed), relative to the parallel, coarse-grained leucosomes with stepped 'unmodified' margins. While the possibility exists that these two leucosome generations formed in different melt-producing events, it is proposed that they developed progressively during the same event. Precise geochronology however, would be required to distinguish between these two possibilities.

In addition to the layer parallel leucosomes, there is also a series of oblique, coarse-grained leucosomes that have irregular margins and which cut the gneissosity at low to moderate angles (Figs 37a and b). The medium-grained leucosomes are truncated and deflected by the oblique leucosomes. The coarse-grained, gneiss-parallel leucosomes also appear to be deflected by the oblique leucosomes, but closer examination reveals that they are also texturally continuous with them. The oblique leucosomes are interpreted to be syn-anatectic, melt-filled shear bands that have been observed to occur in three orientations; steep northeast-striking dextral, steep south-southeast-striking sinistral, and north-northeast-striking reverse shears that dip moderately to the northwest (Figs 38b and c). The deflection of the leucosomes suggests they are overprinted by the melt-filled shear bands, although the textural continuity between the coarse-grained layer-parallel, and oblique leucosomes, and the absence of cross-cutting relations, indicates they formed at the same time with the melt from the layer-parallel leucosomes likely flowing into a lower pressure (i.e. dilatant) site represented by the shear band. At one locality the gneissic fabric is cut by a conjugate pair of melt-filled sinistral and dextral shear bands.

These observations suggest the 1600–1550 Ma protolith underwent approximately east-southeast to west-northwest-directed shortening (based on present orientations) during the Musgravian Orogeny, thereby producing the predominantly north-northeast-striking gneissosity and layer parallel leucosomes. The orientations of contemporaneous, melt-filled shear bands described above (Fig. 38c), are consistent with this shortening direction and can be interpreted as a set of conjugate structures. The relationship between the various structures also suggests that locally at least, the rocks were subjected to pure shear, and not simple shear during the 1200–1160 Ma Musgravian Orogeny. However these conclusions, which are based on limited mapping in the easternmost Musgrave Province, are at odds with the interpretation, based on petrology, that the orogeny is associated with extension and/or upwelling in an intracontinental setting (Smithies et al. 2010; 2011). Further work is required to test what these field-based observations mean and if they are regionally relevant.

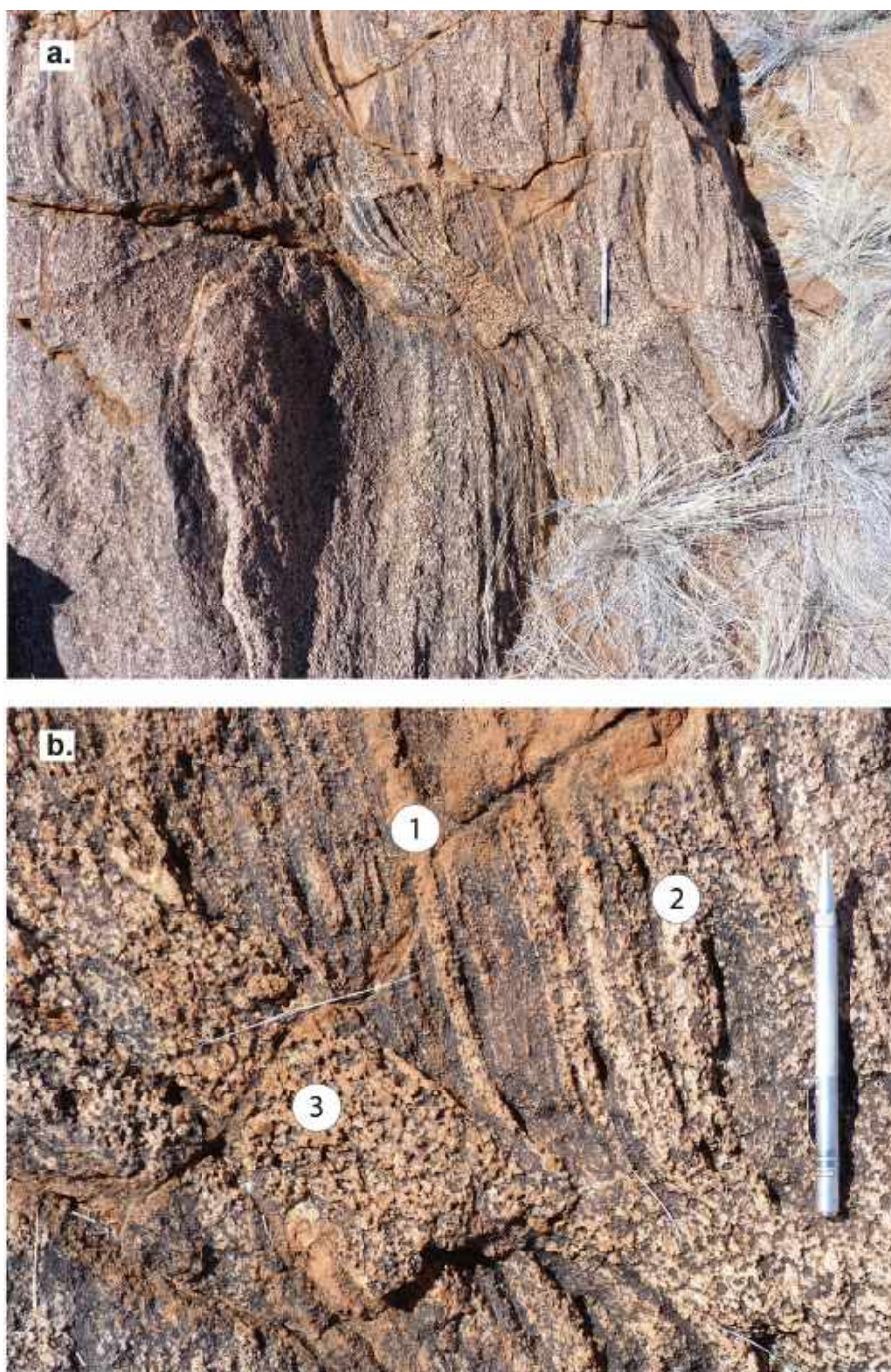


Figure 37. Outcrop of the Birksgate Complex, eastern Musgrave Province. a) Reverse, melt-filled shear band. **b)** Close-up illustrating the difference between early, straight-edged leucosomes (labelled 1), and parallel, later, coarser grained leucosomes that have sharp stepped margins that follow grain boundaries (labelled 2). The straight-edged leucosome is deflected and cut by the oblique shear band (labelled 3), which is filled with leucosome that is texturally continuous with the coarser grained leucosome, indicating that they are the same generation. (Photos 412928 and 412929)

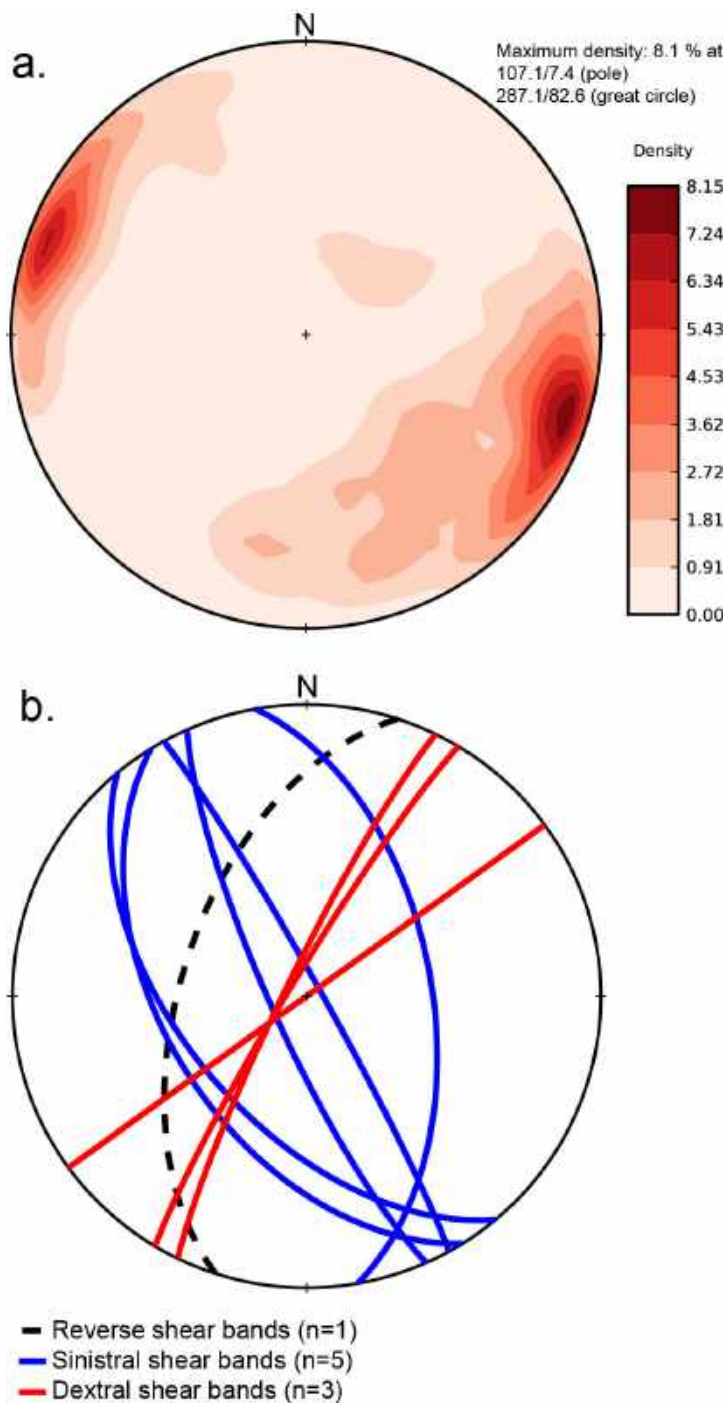


Figure 38. Equal area stereonet for a) the gneissosity (contoured poles to the planes), and b) the melt-filled shear bands on the central part of the AGNES CREEK 1:100 000 map sheet (as great circles). c) summary stereonet that shows the relationship between the average orientations of the various shear zones and the average gneissosity (thick black line), with the proposed shortening direction indicated by the large black arrows.

DELAMERIAN (~510–490 MA) MIGMATITES IN THE KANMANTOO GROUP, EASTERN MOUNT LOFTY RANGES

The Kanmantoo Group is an extremely thick succession of shallow and deep-water mainly clastic sediments deposited rapidly in an early Cambrian extensional basin near the eastern margin of Gondwana after the Neoproterozoic breakup of Rodinia (Flottnann et al. 1998). Deep burial by sedimentation was immediately followed by onset of the Delamerian Orogeny (~510–490 Ma), involving overall northwest-directed tectonic transport (Preiss 1995; Foden et al. 2006).

Metamorphism above greenschist facies is found only in the eastern and southern Mount Lofty Ranges and Kangaroo Island. The highest grade (sillimanite grade, locally accompanied by migmatisation) is restricted to a narrow zone of high T-low P metamorphism trending north-northwestward from the Glenelg River in western Victoria to the Barossa Ranges in South Australia. Within this zone, Neoproterozoic and early Cambrian metasediments include psammopelitic and lesser pelitic schist, metasandstone, quartzite, marble and calc-silicate, but evidence of partial melting is restricted to the stratigraphically lowest unit of the Kanmantoo Group (Carrickalinga Head Formation). In its type area on the west coast of Fleurieu Peninsula, this formation is an essentially unmetamorphosed dirty sandstone-siltstone alternation, but in the eastern Mount Lofty Ranges it is strongly migmatised. Partial melts were generated early in the deformation history and largely follow a strong layer-parallel foliation (S1), which is related to northwest-directed thrusting to form a stromatic metatexite migmatite (Fig. 39a). This foliation and accompanying neosomes were folded by upright north-south-trending F2 folds of probable transpressional origin (Fig. 39b) and later northwest-trending F3 folds comparable to structures seen in the low-grade areas of the Delamerian Orogen. The migmatites are cut by shallow-dipping sheets of undeformed post-tectonic granite (Fig. 39c).

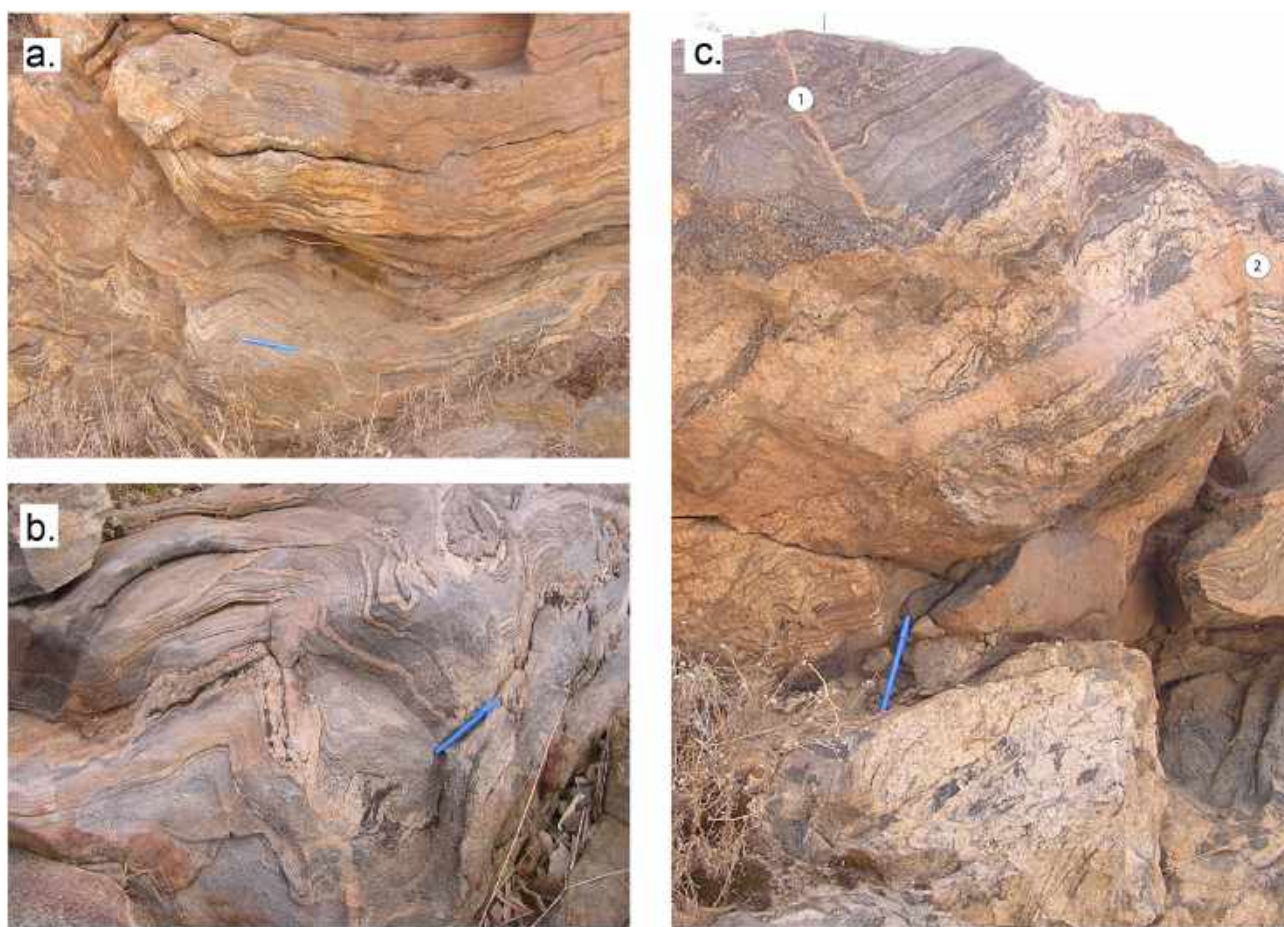


Figure 39. Examples of migmatitic Kanmantoo Group metasediments near Reedy Creek.

a) Stromatic metatexite migmatite with layer parallel partial melt focussed within certain sedimentary layers. **b)** Coarse-grained stromatic metatexite migmatite with layer parallel in-source leucosomes in a biotite-rich residuum, which was folded by upright probable F₂ folds. **c)** Some zones of this migmatite have undergone significant partial

melting and can be considered transitional diatexite migmatite in the layers in the centre of the field of view. A narrow leucosome vein projects sub-vertically from these melt-rich zones (labelled 1) and the entire migmatite is cut by shallow dipping granite dyke (labelled 2). (Photos 412930–412932)

The fact that partial melting is recorded only in the Kanmantoo Group, and then only in its lowest formation, may reflect a combination of factors:

- Depth of burial – likely to be at least 10 km, possibly up to 15 km, for the Carrickalinga Head Formation. The geothermal gradient may still have been high as a result of syn-depositional rifting of the Kanmantoo Trough.
- Water content – these sediments were extremely rapidly deposited only a short time before the onset of metamorphism and may therefore still have contained significant pore fluids. As shown above, the presence of free water is significant for lowering the solidus for metasedimentary rocks. By contrast, Neoproterozoic sediments that underlie the Kanmantoo Group and are not migmatitic were already up to 300 m.y. old at the time of the Delamerian Orogeny. These were thoroughly dewatered and hence possessed lower melt fertility.
- Lithology – these relatively immature, clay-rich sandy sediments with much detrital feldspar and mica, were of the right bulk composition to undergo partial melting at relatively low temperature.

ACKNOWLEDGEMENTS

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APPENDIX

Flow-chart for distinguishing between the different types of migmatites

