THE UNIVERSITY OF ADELAIDE

THE PALMER GRANITE:
GEOCHRONOLOGY, GEOCHEMISTRY AND GENESIS

by D. Pluckhahn

1993

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The Palmer Granite:
Geochronology, Geochemistry and Genesis

By
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This Thesis is submitted as partial fulfillment for the
Honours degree of Bachelor of Science

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University of Adelaide
November 1993

National Grid Reference (SI-54).6728-III 1:50 000

Abstract

Various igneous bodies have intruded into the Palmer area throughout the Delamerian Orogeny. The earliest, the Rathgen Gneiss, intruded either before or during D1 which gave it the prominent foliation. D1 was also responsible for crenulations in migmatite veins throughout the area. These crenulated migmatite veins are in areas folded by D2 mesoscale folds. Some pegmatite veins are also folded by the D2 folds. The Palmer Granite intruded during D2 as is seen by shearing in a semi-crystalline state and a tectonic foliation that has been folded. The ballooning of the granite during emplacement deforms the surrounding sediments and the pre-granite folds hence their axis lie parallel to the contact of the granite. The effect of the granite intruding during the deformation has lead to the axis of the D2 folds forming after the granite to have a degree of randomness about their axis. Migmatite grade was reached again after the intrusion of the granite causing melt veins to develop that disrupt the foliation. D3 formed a regional syncline of the area combined with some small scale folding within the granite, however a foliation did not form.

The emplacement of the granite and other igneous bodies throughout the area has been controlled by using the bedding plane of the Kanmantoo.

The geochemical trends throughout the Palmer granite is formed by two different groups fractionally crystallising zircon, amphibole, and biotite. This results in a decrease of normally ? incompatible elements. The two groups form by one group from a homogeneous source and the other a heterogeneous source. G The xenoliths crystallised from a mafic magma. The amphibolites form two groups according to their differentiation and genetic relationship. They both form by fractional crystallisation however U and Pb are decreasing cannot be explained by this. G Another possible mechanism is liquid un-mixing. why not magma?

mafic + intermediate To tie all of the groups together a model of a mafic pluton that crystallises the xenoliths as a chilled margin. The mafic magma evolves some of the Palmer Granite whilst turbulently convecting hence homogenising the magma. A magma recharge forms the more evolved mafic what and this forms more Palmer Granite which convects in a laminar fashion forming heterogeneities. Part of the mafics evolve enough to be caught up in the Palmer Granite and as it does not crystallise zircons all the fractional crystallisation of the Palmer Granite must have occurred in the ~~mafic pluton~~. magma chamber

G: Grammar / style / wording — rephrase

"mafic" is an adjective, not a noun.

ACKNOWLEDGEMENTS

> *"You must be careful each time you step out of your door , because your front walk is really a road, and the road leads ever onward. If you aren't careful you're apt to find yourself.....well .....simply swept away, a stranger in a strange land with no clue as to how you got there.*
>
> J.R.R.Tolkien

For those who I have met upon this road in this strange world that we try to understand. From strangers whose acquaintances I have made fleetingly and then passed in the night, to people with whom I have discussed matters deep and profound. From those people never met who wrote work that is inspiring to those who I have engaged in idle talk. In this year many new, exciting, challenging discoveries have been made about the Earth we walk on, the people in the street we see and the friends we meet every day. From some corner of the world some day in the distant future I will remember the howl of the wind in this ancient land on the roots of the mountains we now climb free, for this is a time I will not forget.

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Chapter 1 - Introduction

1.1 Introduction

The Palmer Granite is an example of a granite that was emplaced into an area which already has had a perturbed geotherm. The Palmer area was retained at migmatite temperatures for most of the Delamerian Orogeny (Fleming and White, 1984) which provides a unique view of the effect of the deformations that affected the area. The migmatite veins and folds retain this evidence with overprinting relationships. In few places are is the three deformations clearly seen plus the effect of 16 melting in between these deformations. The mechanisms of emplacement of an igneous body is seen in the exposure and as all of the magmatic types in the area show the same type of emplacement the structural control of the host rock is inferred to be the most important factor.

only?

Igneous rocks provide the only direct sampling of the lower crust. By unravelling the effects on elements from magmatic processes, constraints can be placed on the thermal and compositional zoning within the lithosphere. Nd isotopes can be used to determine when new additions to the 16? crust from the asthenoshere. The effects of advected heat from crustal stretching and convective heat from isothermal rebound during lithospheric compression (Sandiford et al. 1992) means a large amount of mass movement through melting allows sampling from many various ? unexposed terrains.

??

The Palmer Granite is an I-type granite implying that no weathering has affected it. In this ? thesis it will be shown that the history can be unravelled from a granite using the different behaviour of elements under different conditions to determine from what the granite formed, by which what mechanisms, and approximately where.

1.2 Previous Investigations

Investigations within the area of the Palmer Granite have been associated with the granite, the Palmer migmatites and mineralisation within the granite. The Kitticoola mine is within the granite and has been in operation from 1845 to 1938 and 1969 to 1971 producing gold and copper. In 1969 a polarisation and resistivity survey was conducted by McPhar Geophysics (Fidler 1971) and resulted in four surface diamond-drill holes to be undertaken by Westgate Drilling in 1970. McPhar also directed five underground diamond drill holes which was done by Kitticoola Mining Co. Pty. Ltd. in 1970. In 1972 Barrett and Nixon conducted surface and underground mapping of the area.

The first workers studying the granite (Rattigan & Wegener, 1951) thought the granite was of ? anatectic origin. White did a PhD project on the Palmer Granite in 1956, studied the formation of migmatites in the Palmer area in 1966 and with Compston and Kleeman showed that the Palmer Granite is not of anatectic origin in 1967. The regional geology with respect to the

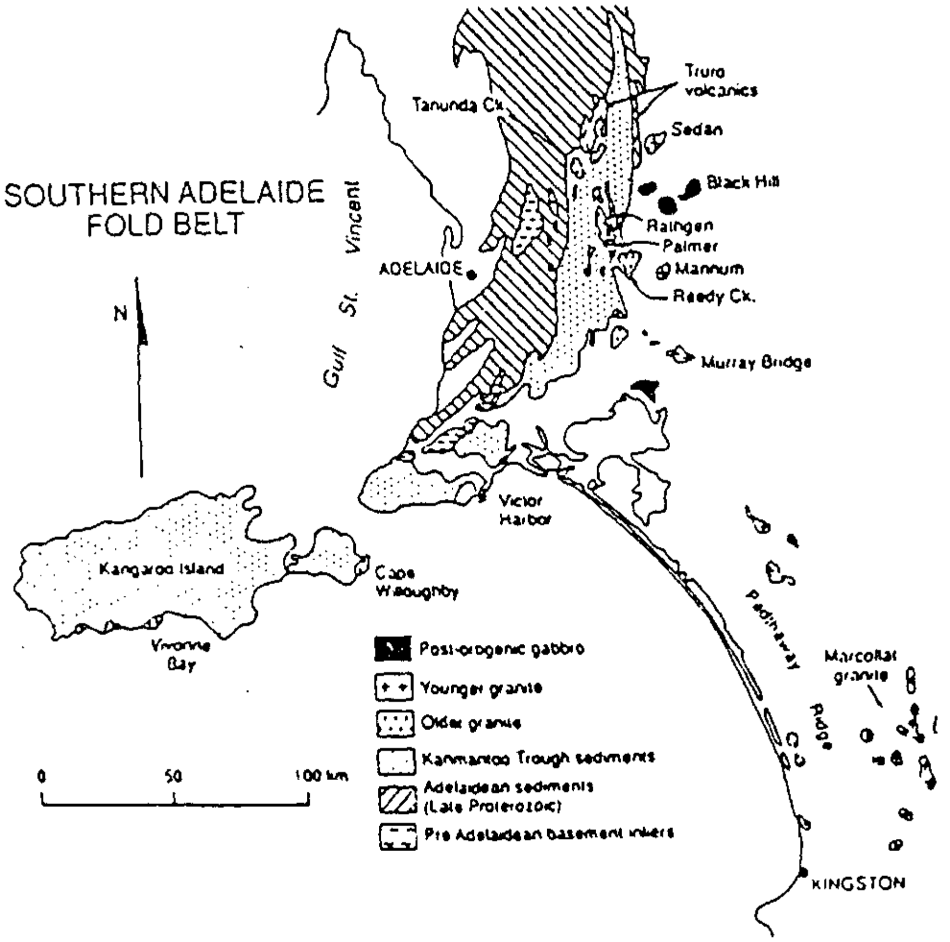


Figure 1:exposed igneous rocks of the SAFB and Padthaway ridge. Position of Palmer Granite is shown. (Foden et al 1992)

Unclear

timing and form of metamorphism and folding in the region is given by Offler and Fleming in 1968 with a detailed study of the timing of folding in the Palmer migmatites by Fleming and
84 or 85? White in 1985.

Chapter 2 - Regional Geology

2.1 Regional Geology

Palmer is situated on the eastern margin of the exposed Southern Adelaide Fold Belt (SAFB) on the Palmer fault zone. Tertiary faulting along this zone exposes the Proterozoic to early Palaeozoic rocks of the SAFB. To the east the Cainozoic sediments of the Murray Basin cover the SAFB except for topographic basement highs of the Kanmantoo group and Summerfield
? Intrusive Suite around the Reedy Creek area of Mannum, and the sub-cropping Black Hill Norite north of Mannum. The Murray River also exposes the post Delamerian Mannum Granite (figure 1)

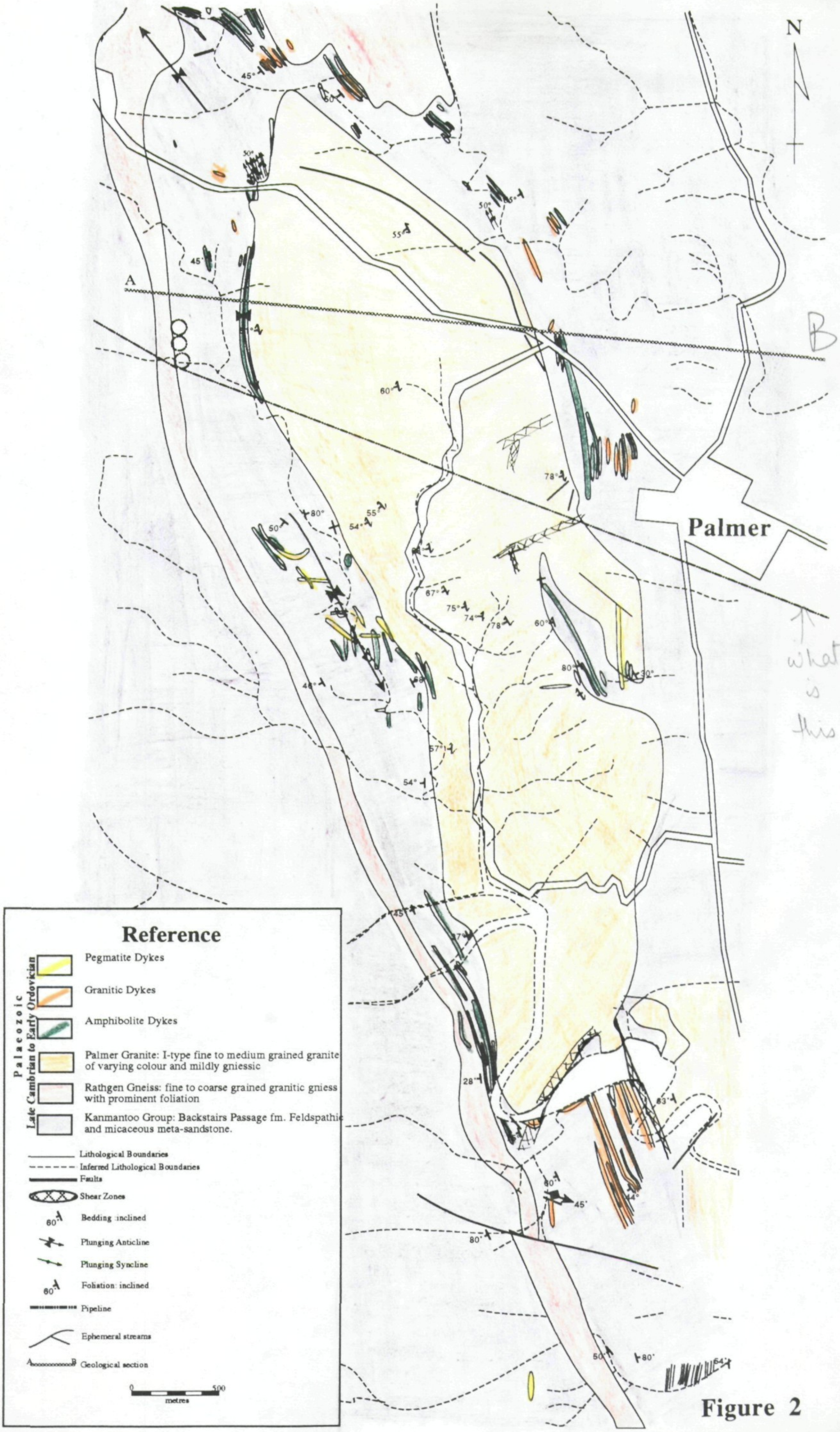
and the P G

The eastern margin of the Palmer Granite occurs 100 metres to the west of Palmer and outcrops as a broad north-south trending lenticular body. The outcrop of the granite is characterised by rolling hills which are higher in the tor covered landscape of the north, and brecciated and altered on the western side, and are lower in the unaltered south-eastern area. The migmatised sediments of the Kanmantoo Group form high relief to the west with gorges cross-cutting the strata, and becomes lowers as the proportion of melt veins decreases towards the granite to the east. The proximity of the contact is exploited by creeks which to the north form a low between the ? Palmer Granite and the steep terrain of the Rathgen Gneiss.

The Palmer granite intrudes the Kanmantoo Group metasediments along the bedding plane which appears to have been the dominant structural control for all of the magmatic rocks except for the late stage pegmatites and some local migmatite veins. The first appearance of magmatism in the area is the Rathgen Gneiss which is either pre- or syn-D1, (using the notation of Offler & Fleming (1968)) for three folding deformations in the SAFB during the Delamerian, D1, D2, and D3). This is a gneissic granite body that obtained its schistosity via D1 (Fleming
84 or 85? & White, 1984). The other intrusions throughout the area are amphibolite dykes, granite veins of uncertain origin, an undifferentiated granite located approximately 500 metres east of the most south-eastern portion of the Palmer Granite, and pegmatite veins. The map (figure 2) shows the various granite, amphibolite and pegmatite dykes to occur in scattered outcrops. This is partly a function of the lack of exposure and partly because they are discontinuous around the Palmer Granite, although no reason for this is apparent.

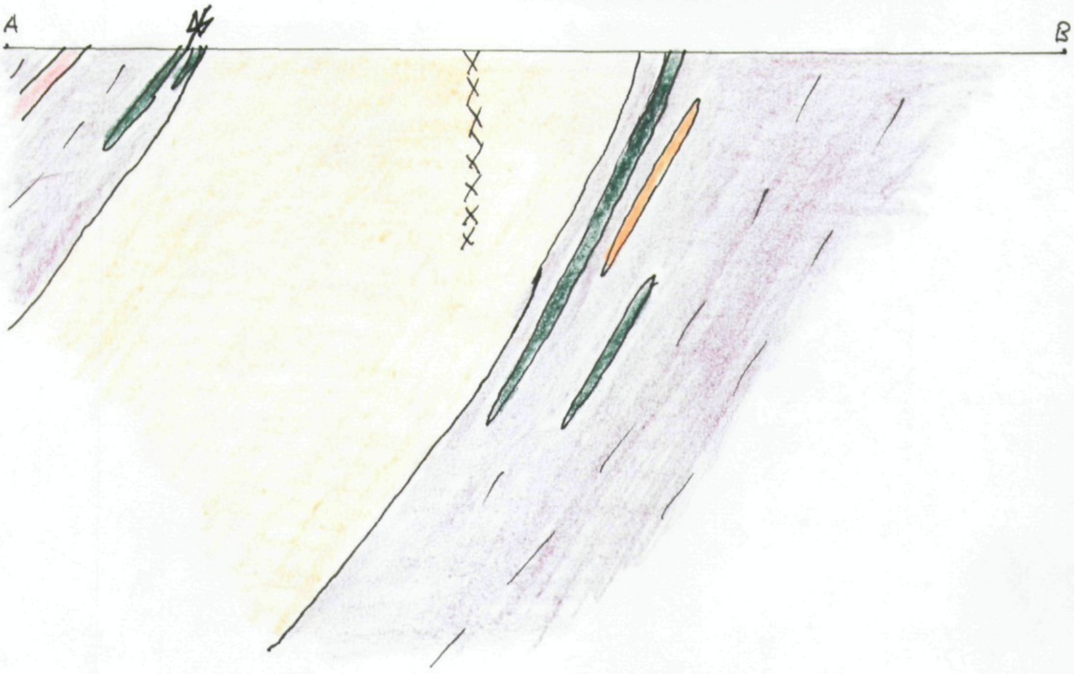
only one of the lithologies albiet dominant

The Kanmantoo group was deposited as a greywacke in a tectonic trough during the late PreCambrian to early Cambrian. It has subsequently undergone a compression during the



what is this?

Figure 2



Legend

Scale

?

Delamerian Orogeny, which manifests itself in the eastern part of the SAFB with a combination of folding and thrusting. The Delamerian has also been associated with regional metamorphism which centres on a belt of igneous intrusions that extend from Pewsey Vale in the north through to Murray Bridge and under the Cainozoic cover sequence in the Padthaway ridge through to Victoria. This metamorphism grades from migmatites which are locally present adjacent to igneous intrusions. The maximum regional scale metamorphism is sillimanite grade which goes through andalusite-staurolite, then chlorite grade (Fleming & White 1984) away ? from the belt of intrusions. Structural evidence shows that migmatisation has been maintained for a large portion of the Delamerian (Fleming and White 1984) and hence is not likely to be ? related to individual intrusions.

2.2 Palmer Granite

sample location map? App 4

The Palmer Granite is a heterogeneous intrusion with respect to colour and grainsize. These can vary from outcrop to outcrop ~~or~~ and even on less than metre scale. This variation is most evident in the road cutting (location 2) where a fine grained grey granite is intruding a fine grained pink granite with very sharp boundaries (figure 5). Such intrusive relationships can be expected when a granite is emplaced in an actively deforming area as a partially crystallised magma ~~in~~ is extremely weak with respect to shearing (Miller et al 1988) (figure 6), so any fracture will 87 ? propagate readily and will drain fluid from between crystals to form a vein. The mineralogy is similar between the different coloured rocks with the most variation in the feldspars with microcline varying between 40% and 25%, and plagioclase varying between 5% and 15%. While the grainsize appears different in hand specimen, in reality the average size of most minerals is 0.3 millimetres and variation is due to aggregates of minerals and large quartz and plagioclase grains. Biotite is present but is less than 5% in all cases. All other minerals occur in minor amounts with some magnetite, hornblende, sphene, apatite and some rare zircons. The grain boundaries vary but most of the quartz, microcline and plagioclase have rounded boundaries but do not show crystal faces. The Palmer Granite is mildly gneissic overall with intermittent melt veins and small scale folding within the fabric as evidence that the granite is partially migmatised.

The Palmer Granite samples were taken from outcrops in the field. Tors dominate the exposure in the north whereas the freshest samples in the south occurred in cliffs, creek beds and road too cuttings. The eastern side of the granite was (to) altered for meaningful geochemical data so no samples were taken there, however it also must be noted that even the freshest looking samples in thin section showed some signs of alteration to clay minerals. The contact relationship G1 || between the granite and? is usually able to be discerned within a few metres, however only two actual contacts can be observed. One, approximately 400 metres north of the pipeline on the western side, was observed by White et al (1967) but was not found in this study, and a second → ?

didn't look or ?

? intermittent melt veins and small scale folding within the fabric as evidence that the granite is partially migmatised.

2.3 Xenoliths

The xenoliths in the Palmer Granite appear as fine grained medium grey inclusions with well defined boundaries and rounded outlines, except at locality 3 where diffusion with the granite has occurred. A similar mineralogy to the Palmer Granite is present, except for a larger proportion of hornblende and biotite. The fabric within the xenoliths cross-cuts their boundaries and is aligned with the fabric of the rest of the granite. The orientation of the xenoliths ~~is~~ was controlled by the flow of the granite when it was in a molten state. The occurrence of xenoliths in any abundance is restricted to the mid northern area, although they sporadically occur throughout the granite body.

2.4 Amphibolites

The amphibolites are sheet-like structures that are mainly hosted by the Kanmantoo but also occur within the Rathgen Gneiss and the Palmer Granite. They intrude parallel to the bedding in the Kanmantoo and the schistosity in the granite and gneiss. They vary in width but are generally less than ten metres across. The mineralogy is dominated by hornblende which occurs as round grains 0.2 millimetres in size and plagioclase with minor amounts of biotite present. The present mineralogy is not the original as recrystallisation has occurred during gneissification. Hence the CIPW normative mineral assemblage is the best approximation to the assemblage at crystallisation of the magma. (Appendix) ?

Chapter 3 - Structural Geochronology

3.1 Introduction

The following chapter aims to show the relative timing of events that have affected the Palmer area. This is done by the relationships between various folding and schistosities without any more than a surficial account of the structural geometries and mechanisms involved.

The silica content of the amphibolite dykes separates them into mafic and intermediate groups. For the purpose of this chapter they will all be called amphibolites as their behaviour in the field is the same and they are indistinguishable without the aid of major element analysis or thin sections.

3.2 D1

The effect of the first deformation can be seen in the development of a foliation within the Rathgen Gneiss and the crenulation of melt veins in the Kanmantoo (figure 7). The direction of shortening is broadly perpendicular to the boundary of the Palmer Granite indicating that the

Figure 4: Exposure of the contact between the Palmer Granite and the Kanmantoo group. The granite cross cuts folds contained within the Kanmantoo that are of early D2 origin. (Locality 1)

Figure 9: Pre D2 amphibolite and genetically associated granite are folded by an early D2 are cut by the amphibolite vein A1. The sample is folded by a series of D2 folds parrallel to the fold F2. Amhibolite vein A2 cuts across the D2 folds. The sample contains the D2 foliation shown as S2 which may or may not affect the vein A2. The sample shows that the mafic magmatism in the area occurred over a large time span.

Why fig 9 after fig 4?

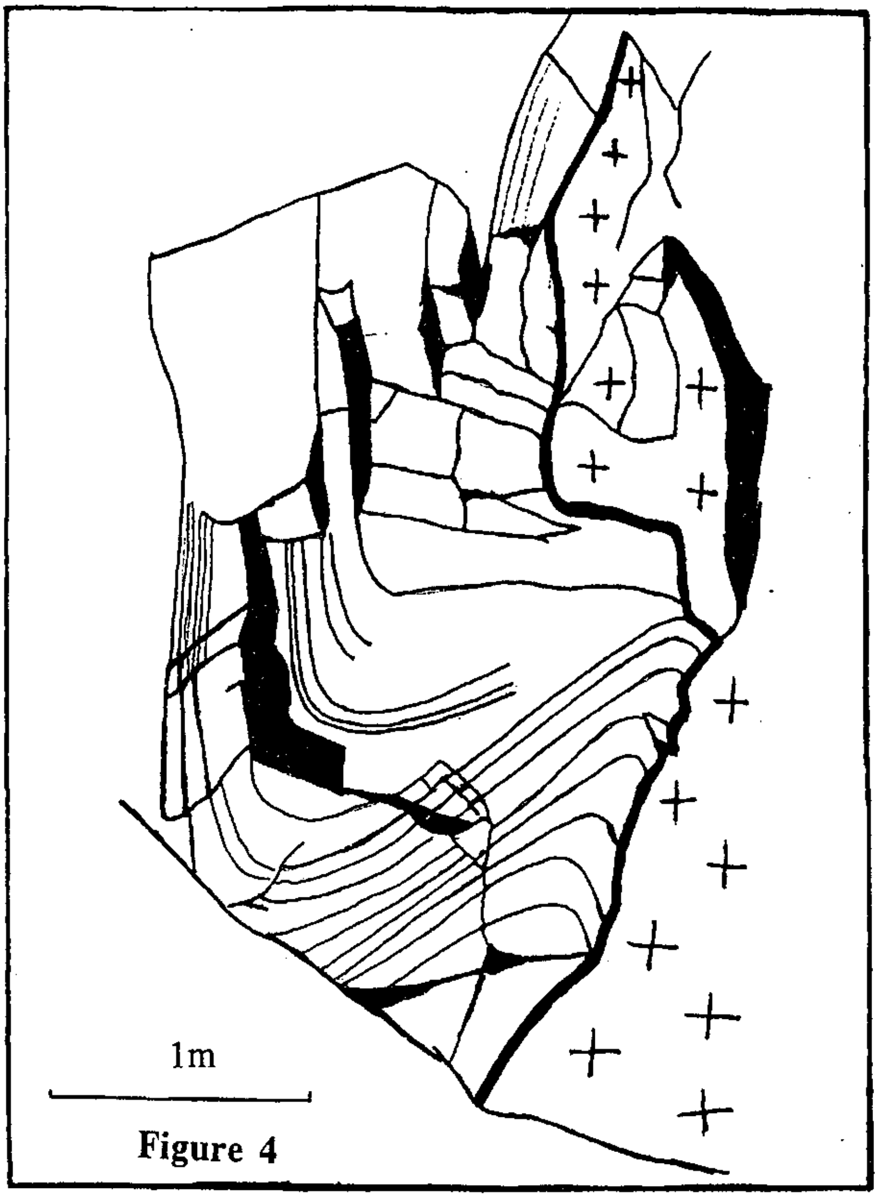


Figure 4

Figure 9

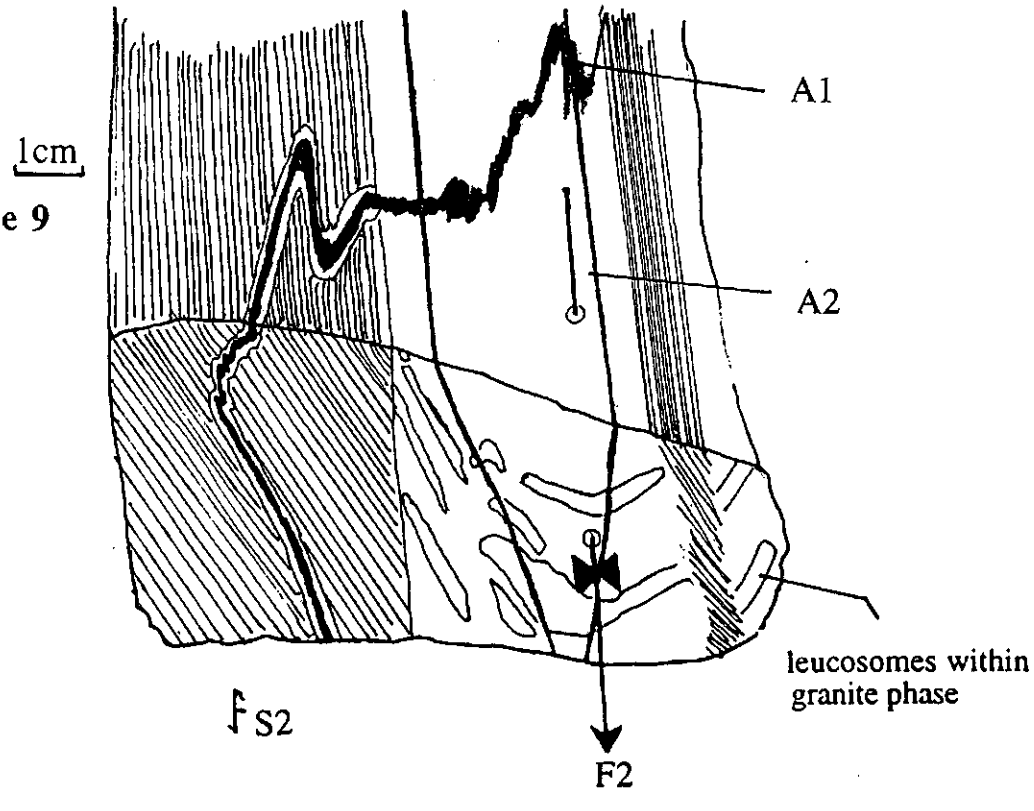


Figure 6: The effects of a partially crystallised liquid with different stress regimes as is described by Miller et al (1988). Fig. a shows the effect of compression, which is taken up through the lattice hence the system behaves rigidly. Fig. b shows a shear stress being applied. The contiguity of the lattice is broken and the fluid between the crystals fills the gap lubricating the shear and resulting in a catastrophic failure.

Figure 5: Fine grained white Pamer Granite is intruded by fine grained grey Palmer Granite. The relationship is typical of faulting in a partially crystalline state where the granite acts partially ductile and partially brittle. At the planes of shearing liquid has filled the shear plane and crystallised to form a coarser grained white granite which is marked by crosses. (Locality2)

fig 5 after fig 6?

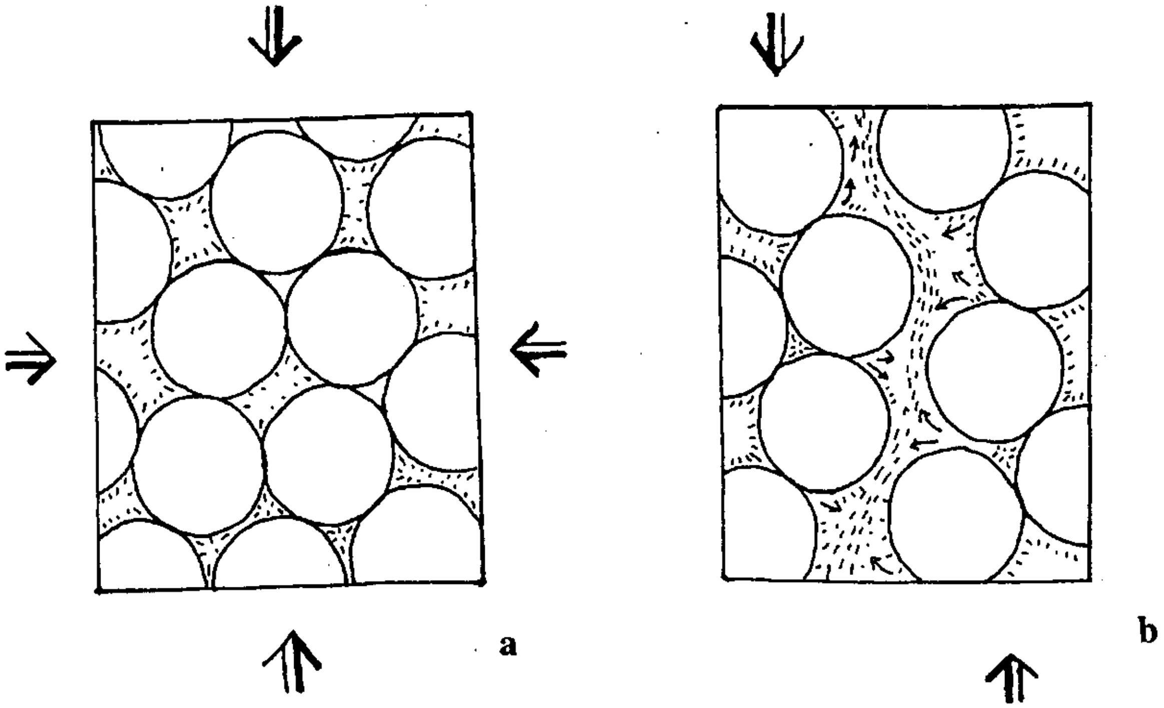


Figure 6

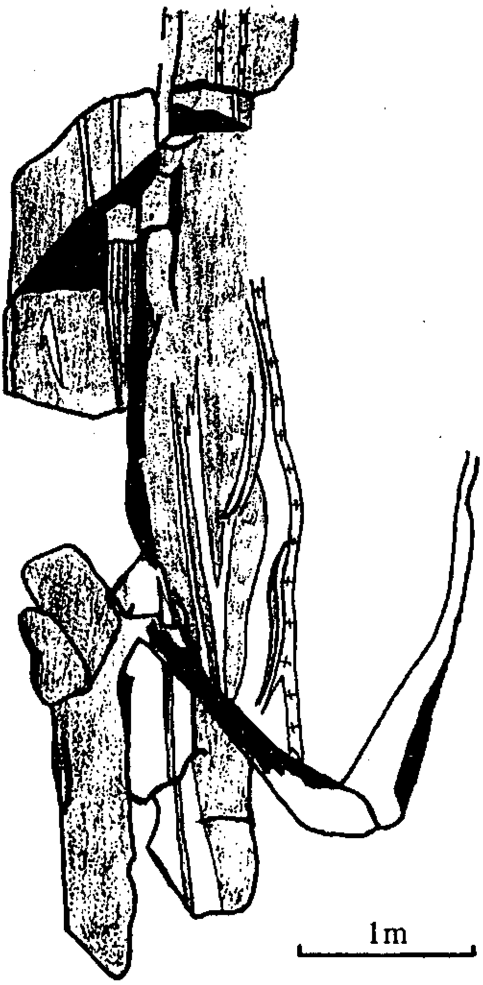


Figure 5

shortening had occurred before the arrival of the granite. The arrival of the granite distorted the original crenulation so that it wraps around the body, except in the southern most area where the relationship is unclear but the sediments appear to interfinger with the granite (figure 8).

3.3 Amphibolite Dykes

where

The mafic dykes were emplaced over a large span of time. This can be seen in figure 9 were mafic veins cross-cut other deformed veins. As a vein that is folded by D2 cross-cuts another vein the intrusions must have started before D2. An amphibolite vein cross-cuts the Palmer Granite therefore the latest intrusions of amphibolite dykes must be late or post D2. Therefore the structural evidence shows that the amphibolites intruded the area over a long period of time,possibly initially post Rathgen Gneiss as this is not observed to cross-cut them. As the amphibolites are all affected by D3 (see later in chapter for effects of D3), this constrains the last intrusions of amphibolites.

Space

3.4 D2

The onset of ~~the~~ D2 is seen in mesoscale folds (see figure 7) which had a north-south axis (Fleming and White 1984) and, as with the D1 crenulations were wrapped around the granite when it was emplaced. The granite cooled during the deformation and gained a foliation which is seen in the biotite grains. Xenoliths represent flow features of the magma at the time of crystallisation. As the foliation in the biotite grains cross-cuts the boundaries of the xenoliths the foliation must be of tectonic origin not magmatic. Compression continued after the foliation was formed as the xenoliths and foliation also show folding on a less than ten centimetre scale (figure 10). These post emplacement folds also manifest themselves in the surrounding Kanmantoo group as ten metre scale folds which dip steeply to the north-west.

through?

Melting in the Kanmantoo continues before, during and after the intrusion of the Palmer granite. Pegmatite veins are folded around the axis of pre-intrusion D2 folds at locality 4, showing that melting did not stop after D1. At the same locality a pegmatite cuts across the same fold showing continued melting, and the post-intrusion D2 folds at locality 5 fold pegmatites around their axis. This points to melting during or after the granite intruded. The evidence for post D2 melting is given by melt veins within the Palmer granite that disrupt the foliation present and the folding of that foliation (figure 10). Within the melt veins there is a random orientation of biotite grains implying that no deformation was going on at the time.

3.5 D3

The current exposure of the Palmer Granite is a cross-section across the side of the intrusion. The method of bringing this from the original sill type intrusion is that the area of study forms part of the eastern limb of a broad syncline (figure 3). Hence the western side of the granite is the original up direction. This syncline was formed by D3 and gives the entire field

can this be proved?

Figure 7: Syn or pre D1 migmatite vein is ptygmatically folded by D1. Undeformed post D1 pre D2 migmatites and the ptygmatically folded D1 migmatites are all folded by an early D2 fold whose axis is parrallel to the boundary of the Palmer Granite. (Locality 3)

Figure 8: Cartoon showing relationship of Palmer Granite and Rathgen Gneiss with the Kanmantoo metasediments. The southern area is speculative as the actual contact is not observed and faults cut across where the contact is exposed. The granite dykes are of undifferentiated origin however, geochemistry shows that some, if not all are <u>not</u> related to the Palmer Granite.

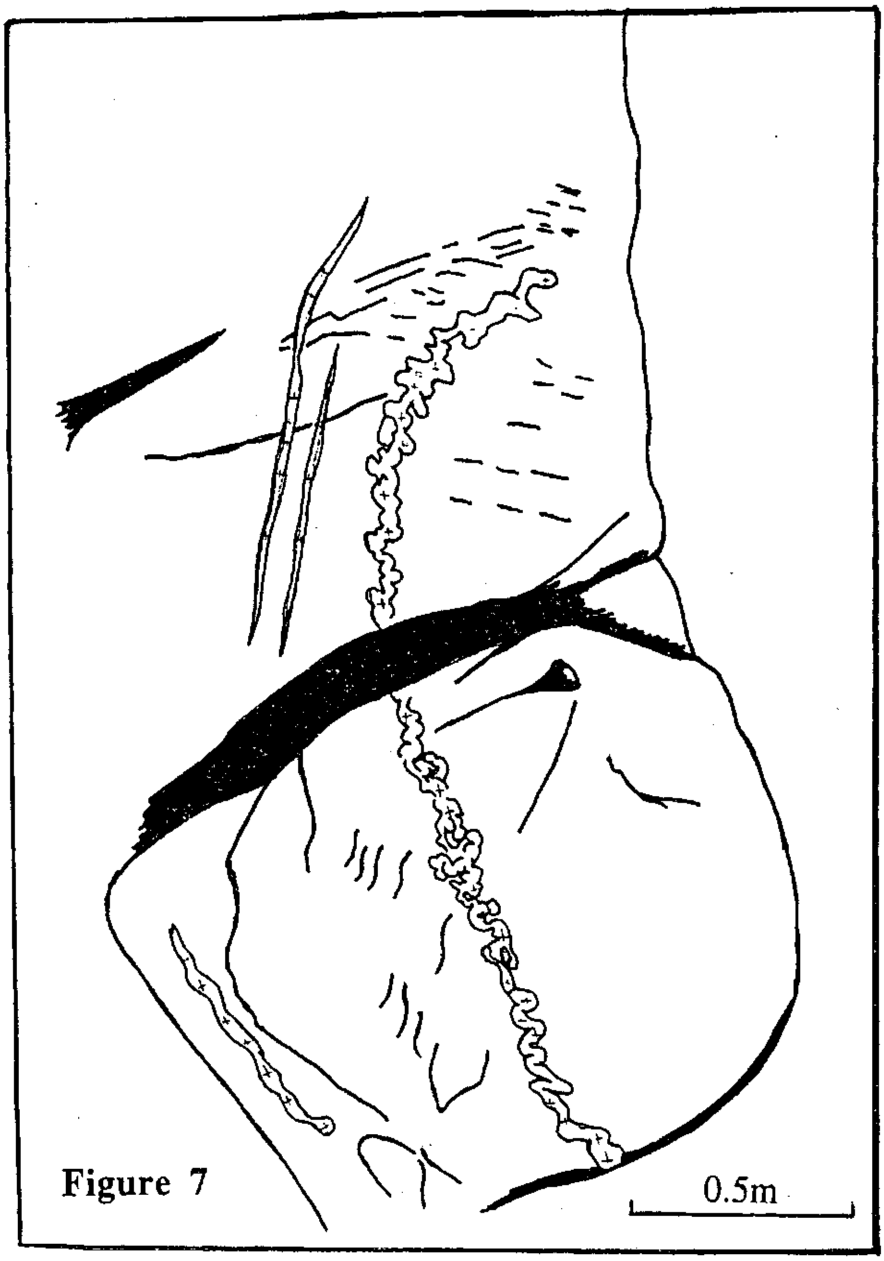


Figure 7

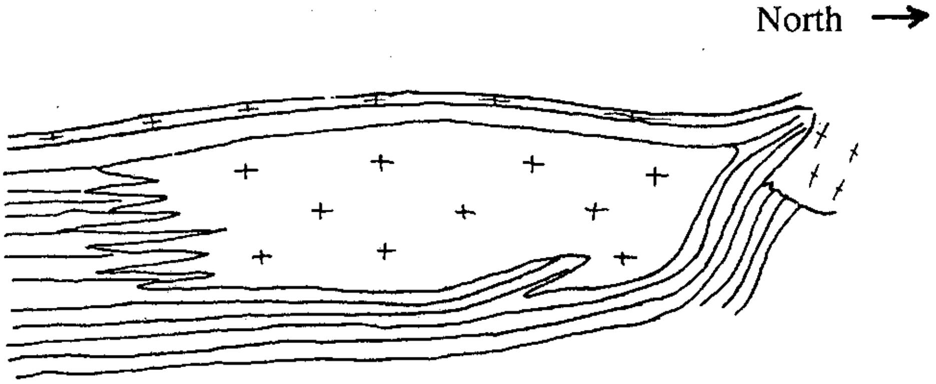


Figure 8

Figure 10: The foliation within the Palmer Granite formed during D2. The foliation cuts across the xenoliths at and angle implying a tectonic origin. The xenoliths show that folding occured after the granite crystallised. The inset shows a close up of a melt vein that runs through the granite. This implies that the area was brought up to migmatite grade metamorphism after the granite intruded. The melt veins do not show any alignment of biotite grains, which were disrupted during melting, hence D3 did not cause a foliation to develop in the area. (Locality5)

Figure 11: D3 fold folding D2 foliation and folds. (Locality6)

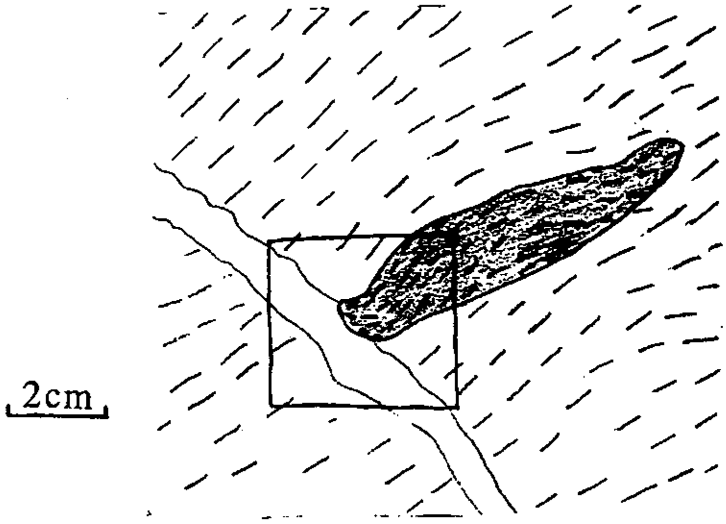


Figure 10

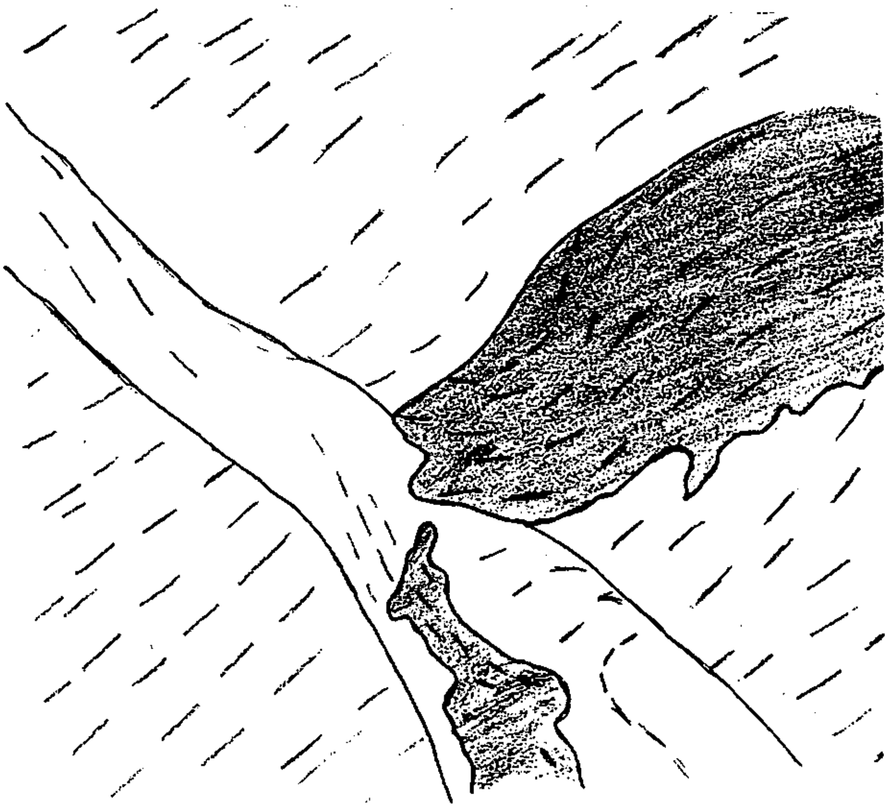


Figure 10 (inset)

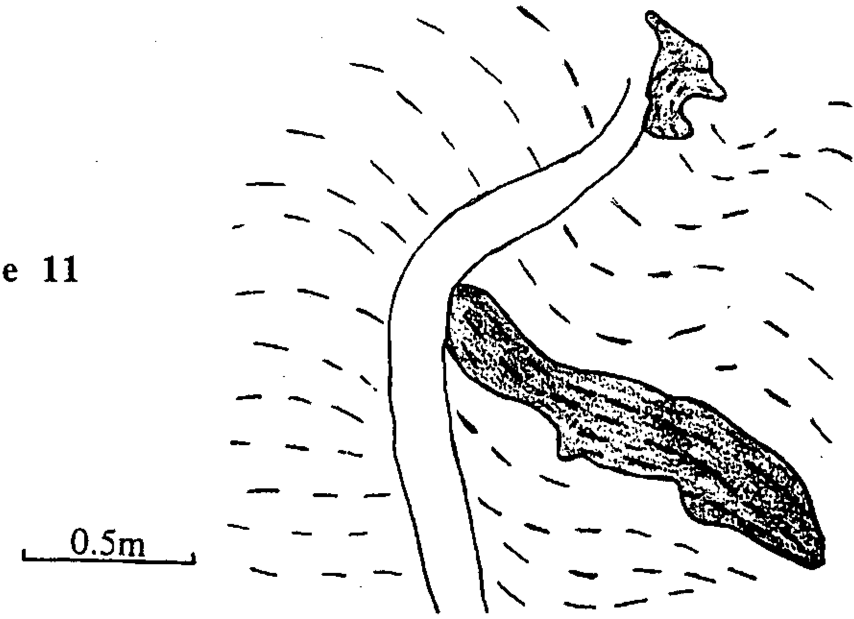


Figure 11

area a generally westerly trending dip of foliations as well as bedding. D3 has also had some small scale folding within the Palmer Granite by folding some of the melt veins (figure 11), which also lends support to the veins being migmatised in a post-D2, pre-D3 time interval.

3.6 Faulting

Faulting throughout the Palmer Granite occurs as a result of the Palmer Fault zone. A series of trend? faults run through the granite and has caused brecciation ~~in~~ on the eastern side. The zones of faulting have acted as a conduit for fluid movement as is highlightedby haematite crystallising along the shear planes and resulted in major chloritization and sericitization (White et al 1967). This results in the interpretation of the faults being difficult at a surface level. The faults are of an uncertain age however they are possible Delamerian in origin and have been re-activated to form the current exposure of the SAFB.

Chapter 4 - Emplacement

4.1 Regional

The emplacement processes of magmas are recorded in the outcrop of an intrusion. On a large scale the bedding surface of the Kanmantoo formed a plane of weakness which the Palmer Granite utilised to create space. On a metre scale however the granite shows a cross-cutting relationship (figure 7). The bedding plane is used as a weakness throughout the area by also controlling the strike of the offshoot sill of Rathgen Gneiss that runs south from the main body (see map, figure 2), the numerous granite veins, and the amphibolite sills. The migmatites have also used the bedding plane but the lateral migration of the magma in the migmatites is unlikely Gl. why? to be great as this will result in ponding. Hence the migmatite veins show compositional ? variation in the original rock and in situ melting. The southern ~~portion~~ part of the Palmer Granite has little clear exposure however it appears to differ from the northern end in that instead of exploiting one plane of weakness it exploits many planes as the strike of the sediments has an overall impression of trending into the granite body. The utilisation of the bedding could be interpreted as the progressive filling of a space via a progression of sills. A series of sills opening up the cavity can explain why the granite interfingers at one end. A problem with the interpretation infilling through sills is that the geochemistry should have a systematic variation across the body, and have low variation along strike with the body. The across strike coherent variation is not seen which either means the sills were very thin or staggered (figure 12), and combine with a heterogeneous source. It is likely that the emplacement of a magma does not give many clues to the ascent mechanism, because if diapiric ascent is the mechanism then it must have stopped and spread laterally along the bedding plane. Alternatively if dyke transport were the mechanism the vertical fracture must have changed direction and become horizontal.

A correlation with the structural style of the Anabama Granite is evident as McDonald (1992) showed it to be sheet-like in overall dimensions and ~~is~~ structurally concordant with the surrounding sediments, with a local cross-cutting contact. Following the suggestion of Blisset ? and Reed (1973) McDonald suggested that fracture propagation was the method of ascent through the crust and emplacement of the granite suite. On the eastern margin of the Palmer Granite at locality 6, the strike of the sediments veers away from the contact on a twenty metre scale (figure13). This could indicate a pre-intrusion fault that formed at a low angle (at the time of intrusion). This is by no means conclusive and may be a feature of the effect of emplacement, however it should be taken into consideration.

4.2 Granitic Dykes

The origin of the granitic veins that occur throughout the area are of uncertain origin. They may ~~be~~ either represent a large scale ~~of~~ partial melting of the Kanmantoo sediments. This would explain the uneven distribution around the Palmer Granite as partial melting throughout the area is limited by the amount of water available through the break down of muscovite (Fleming and 85? White 1984). They may represent offshoot dykes from the Rathgen Gneiss. The Rathgen gneiss as well as the sediments have been wrapped around the Palmer Granite. This is evident at the north-western extremity of the Palmer Granite where the 'hinge point' (figure 8) at which 6 the bedding plane is split apart to admit the granite. As the Rathgen Gneiss came before the Palmer Granite it too was deformed with the bedding. On the eastern side of the Rathgen Gneiss it grades into the Kanmantoo with finger like protrusions which, if they also formed sills, would wrap around the Palmer Granite in the style that is seen today.

A final explanation for the granitic sills is that they are from another granite body that intruded into the area, possibly under the Palmer Granite after it had been tilted by D3 and followed the bedding along many planes. The contact is obscured in the southern part of the Palmer Granite so ~~any~~ the relationship cannot be confirmed. However a likely candidate for this later intrusion is an undifferentiated granite that lies approximately 500 metres to the east of the Palmer Granite within the Murray Basin. The geochemical data shows that these granitic sills are not related to the Palmer Granite however an insufficient data set means that in this study their relationship with any of the above possibilities cannot be concluded (Figure 14).

Chapter 5 - Geochemistry and the Formation of Granites

5.1 Introduction

The study of trace elements can place some fundamental constraints on the generation of granites. The major element variation is generally insensitive to many magmatic processes. The similarity in the major element chemistry between similar rock types means that while an influx of a major element will alter the composition of a magma slightly, the crystallising assemblage

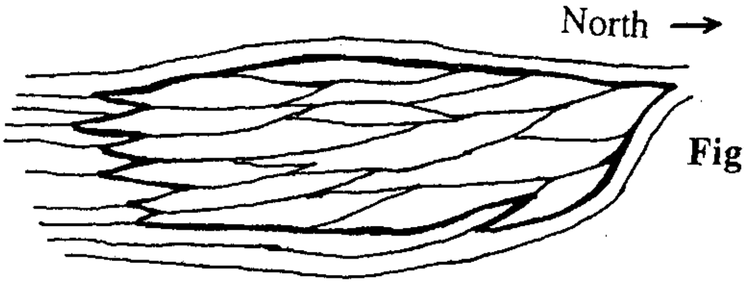


Figure 12

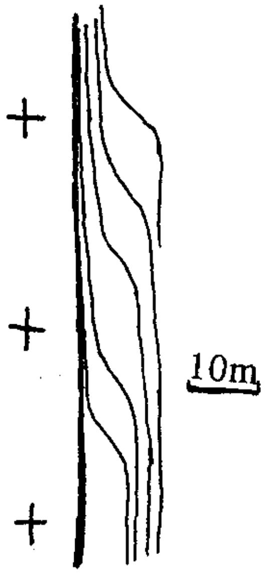
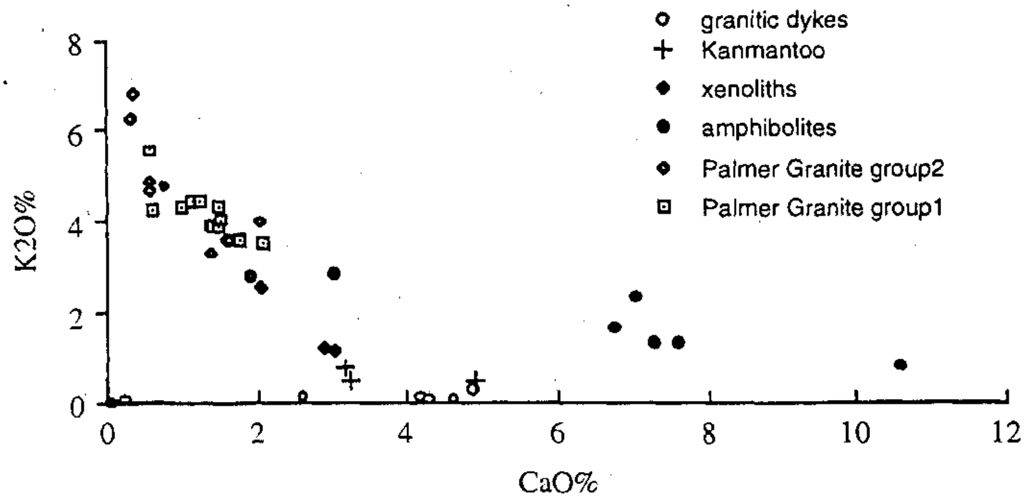


Figure 13



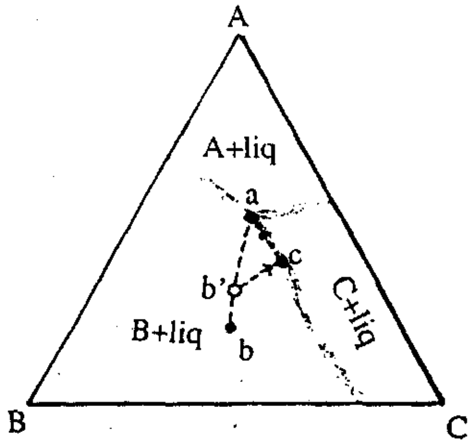


Figure 15

Figure 12: Cartoon showing a possible layout that explains the form and geochemical variation within the granite if the intrusion is comprised of multiple sill intrusion. A staggering of the sills can be used to explain the lack of a trend in the chemistry across the intrusion.

Figure 13: Variation in the strike of the Kanmantoo away from the contact ~~th~~Wat could indicate a fault that occurred previous to the intrusion of the Palmer Granite and controlled its emplacement and possibly even ascent. This evidence is not conclusive.

Figure 14: Major element variation shows that the Kanmantoo metasediments and the granitic sills have lower potassium than the Palmer Granite and amphibolites. The samples taken are therefore not related to the Palmer Granite hence a different origin for the granitic sills must be sort.

Figure 15: The effect of changing major element magma concentration on crystallising assemblage. For a magma crystallising in the hypothetical ternary system of minerals A, B, & C. If the magma has a bulk composition at a, the eutectic or minimum temperature at | G which melt and crystals will coexist. The magma will crystallise minerals A, B, & C. If an addition of fresh magma occurs of composition b, then with mixing the total magma composition will lie at b'. Mineral B will crystallise pushing the concentration towards c. At this point minerals A and B will crystallise pushing the concentration back towards a where A, B, and C will crystallise again. This means that the final assemblage is controlled by the position of the eutectic which is controlled more by physical parameters than the bulk chemistry.

will evolve to the same end point (figure 15). However small changes in the proportions of the crystallising assemblage will cause noticeable changes in the trace element concentrations. The reason for this is that trace elements do not form an integral part of the major lattice structure and hence do not have much control of the stability of minerals, except for zirconium and phosphorous which form their own minerals. Therefore, in order to be included into a crystal lattice a trace element must replace a major element within a site. When considering whether a trace element will be preferentially accepted over the major element, admitted, or accepted with adjustment to the crystal lattice, the difference in radius and charge must be taken into account. The size variation of sites in different minerals means that different elements will be preferentially taken up according to the radius of that particular ion. The charge of the trace element requires balancing if it is different to the element it is replacing. This requires the addition of another element or different ratios of other elements in another site. The variation of radius and charge means that for each mineral crystallising different preferences for elements occur (Mason & Moore 1982). For a crystallising assemblage an empirical way of describing the preferences for an element is the bulk distribution coefficient, D. For an element that is preferentially taken up in the crystallising assemblage D is greater than 1, and if it is preferentially retained in the liquid D is less than 1. G

An element will usually only substitute for one or two major elements, and the major elements are usually contained in only a few minerals. Therefore from the progression in the concentrations of different trace elements, the crystallising phases can be inferred. The similarity of the behaviour of elements has lead to their being modelled for magmatic systems using equations that simplify various processes. The use of D values is fundamental to the modelling process, however the mentioned criteria for the selection of D values means that changes in the crystallising assemblage, the pressure, temperature and oxygen fugacity will alter the D values so the results obtained can at best only be used as a guide.

The amphibolites and Palmer Granite appear~~s~~ to originate from the same deep seated pluton. The evidence for this statement will be discussed throughout this section, as will the implications to magmatic processes deep within the crust. The various igneous rocks seen are a suite of mafic, and intermediate rocks, which are the amphibolite dykes that have been mentioned previously. The Palmer Granite can be divided via its geochemicistry into mafic and intermediate suites. This classification is based on their silica content. They also appear to not be directly genetically related, and this ~~which~~ will be discussed later. The Palmer Granite is broken up into two groups, group one and two which have elemental variations shown ~~shoon~~ in fig 16. Group two shows more variation than group one. The xenoliths are the final group and are of an intermediate igneous origin. ?

How?

5.2 Trends and Relationships in Geochemical Data

For this study the relationship between the rock types is often inferred from geochemical evidence. For sorting the data that gives the two granite groups linear relationships must be divided into genetic and mechanical groupings. Linear trends in the data can be for a genetic relationship where a process acts on one rock to form another, or a mechanical relationship where the same mechanism has operated on rocks of different origin to produce a similar end-member. The data ~~is~~ also consists ~~comprised~~ of real trends, which show the effect of a process, and apparent trends, which appear to show a process but in fact only show the scatter of the data (figure 17). The Palmer Granite plots on an elemental variation diagram in a linear fashion that forms a coherent group. A generalisation can therefore be made that the same processes have operated on the granite to maintain this coherence. However for any trend to represent a magmatic process the individual samples must occur in the same order with all elements. For example if in order to explain Zirconium concentrations some samples are put in the order A, B then C for increasing differentiation. And if the order for Cesium is A, C then B, then the model must be wrong as the criteria for accepting any theory is that the relative order of differentiation must remain the same for different elements as it is a constant factor. Therefore the combined Palmer Granite data shows an apparent trend. Another example of an apparent trend is the increase in silica with differentiation.

Apparent trends can sometimes be used to show where a process is leading even if the initial products are not the same. For example the intermediate rocks show where the mafics will go with increasing differentiation even though they are not related, as the same process is affecting them. A real trend is one in which a rock of an initial composition can be shown to produce a product via a magmatic process. These rocks are genetically related as the more differentiated rocks can be shown to be related to the less differentiated ones. The important criteria in selecting or rejecting a mechanism is that an order of differentiation occurs and is maintained. For this purpose, wherever relevant, the sample number will be placed next to the sample to show where anomalous samples occur, and to show the variation where samples are said to be genetically related.

To change the order a sample occurs in post-crystallisation alteration is required. Wherever possible the elements used will be chosen for their insolubility in fluids, or evidence as to why alteration has not occurred will be given. Where the absolute values are taken as indicators of processes ~~is~~ involved, it is assumed that a source with anomalous values of trace elements is not present within the crust. Figure 18 is included to show the variation of possible sources that might have interacted in the origin of the Palmer Granite.

5.3 Xenoliths

The description of the geochemistry will start with the xenoliths as they crystallised before the granite and formed a solid part of the wallrock of the initial mafic pluton. The xenoliths are of

? magma chamber

Figure 16: elemental variation diagrams for the Palmer Granite. The anomalous line is a highly fractionated sample. 16a shows group 1. 16b shows group 2. Note the greater scatter in group 2.

For Basis of division into groups

Figure 17: A hypothetical variation diagram for a cluster of data series for which the thick line shows the line of best fit. However by comparing other variation diagrams for the data the thick line may by wrong. A multiple source such as shown by the thin lines could explain the data best. Care must be taken when modelling to try and not fit a model to the wrong trend.

Figure 18: The possible sources of the xenoliths or for contamination of the magma other than how the rocks those exposed in the area. A point to note is the concentrations of incompatible elements such as Zr, Nb, Y, and Ba (expand wrt mafic liquids) which should increase with partial melting. This Which does not relate to the low values seen in the Palmer Granite.
(Foden pers. com.)

Figure 16

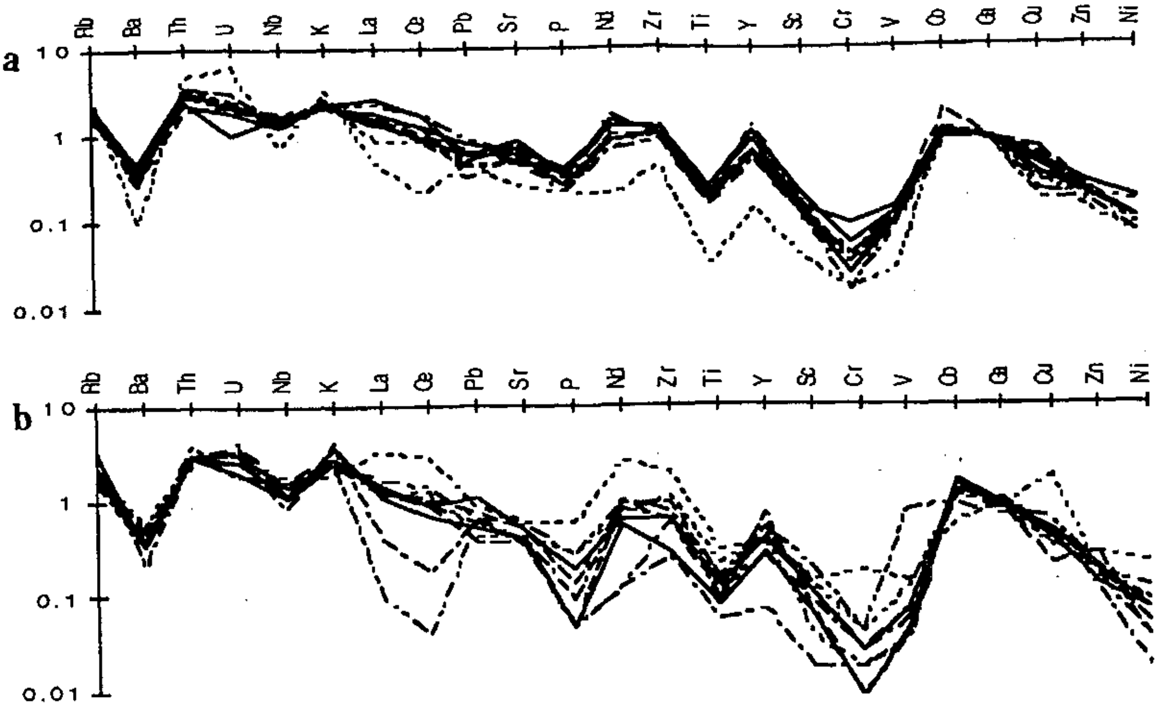
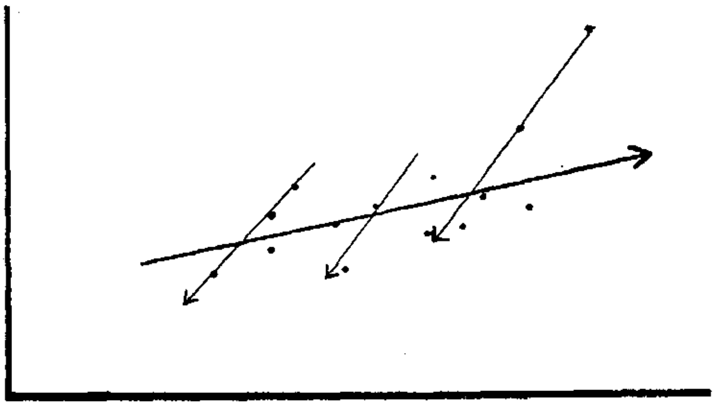


Figure 17



7?

Element	Archean	±	E.-Middle	±	Adelaiden	±
	E. Proterozoic		Proterozic		basalts	
Nd	27	11	53	39	12	2
Sm	5	2	10	69	3	0.5
EpsNd	-19	5	-17.8	6	1.5	1.1
ModelAge DM	2.89	0.4	2.37	0.29	1.7	0.2
Rb	90	72	220	81	27	22
Sr	145	93	176	150	153	25
K2O	3	2	4	2	1	1
Na2O	3	1	3	1	3	1
CaO	4	4	4	4	7	3
Al index	1.04	0.36	1.04	0.39	0.74	0.13
Ba	610	350	1045	516	116	96
Zr	184	73	268	143	91	14
Nb	11	4	16	10	6	1
Y	28	15	42	22	25	3
V	141	130	101	88	325	25
Sc	19	14	19	11	41	5
Ni	42	35	28	58	106	13
#samples	12		25		8	

weight
%?

Figure 18

an intermediate mafic igneous type and hence could represent either an early crystallising phase of the Palmer Granite, the wallrock that the pluton was intruded into or a chilled margin that formed before the granite magma. No geochemical trend can be put through the xenoliths. This is possibly due to the ~~lack~~ paucity of samples, the existence of a complex relationship, or the lack of any common origin. To overcome the lack of coherence in the trace element data, a comparison with major elements, and absolute abundances of trace elements is used.

The absolute abundances show that the xenoliths appear to be related genetically (figure19). This is important as no trend of differentiation is apparent, so now some constraint of their evolution can be placed. The second important observation is that they have a low concentration of Barium. Barium acts as an incompatible element in mafic rocks and as a compatible element in silicic rocks. Therefore if the xenoliths represent an early or cumulate phase of the Palmer Granite, then the Barium concentration should be higher than the granite. This is not the case therefore the two are not related in this manner. Similarly if the xenoliths represent an intermediate liquid that was caught up in the granite then due to the incompatible nature the Barium concentration should be high, hence it must have been a solid phase in the mafic pluton. The remaining possibility is that the xenoliths are a fractionating phase from a mafic liquid. The incompatibility of Barium will give a low concentration in the cumulate, which is seen, and hence it can be said that this is the origin of the xenoliths.

As a crystallisation product from a mafic magma the xenoliths may represent either wallrock or a chilled margin to the pluton. If it is the wallrock then this probably represents a previous magmatic chamber that has solidified and is now acting as a host to this pluton. If it is a chilled margin then the mafic magma must have cooled, possibly due to intrusion into cold country rock, at an early stage, and then separated into mafic and granitic components. The xenoliths do not necessarily have to be related to the sampled mafics, or if they do then their crystallisation does not control the distribution of trace elements within the magma. If the magma composition was controlled by the crystallisation of the xenoliths then the trace element composition in many cases would be driven to relatively opposite values to ~~that~~ those seen (figure 20).

A suggested source for the observed mafics is a magma reflux into the pluton. This is the probable origin of the intermediate samples as will be seen later. The implications of a chilled margin is that a barrier ~~is~~ formed between the magma and the wallrock. This means that for assimilation to occur the chilled margin must be remelted to expose the wallrock to the magma. The variation in Nd isotopes for the Palmer Granite show that there must be one source is not i t/s responsible for it's formation, but if the wallrocks are covered then assimilation is ruled out and G either a heterogeneous source or magma recharging must be used. Assimilation of a wallrock of the same composition as the xenoliths appears unlikely as the incompatible elements such as

Figure 19: Elemental variation of xenoliths. Coherentness of data suggests one source was involved.

Figure 20: Crystallisation of the xenoliths from a mafic melt should remove K and Ca from the liquid. This is not the case hence the xenoliths are not a cumulate of the observed mafics.

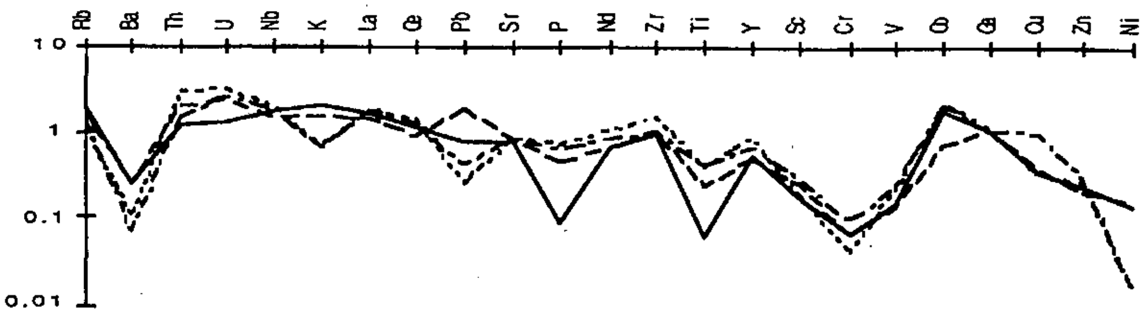


Figure 19

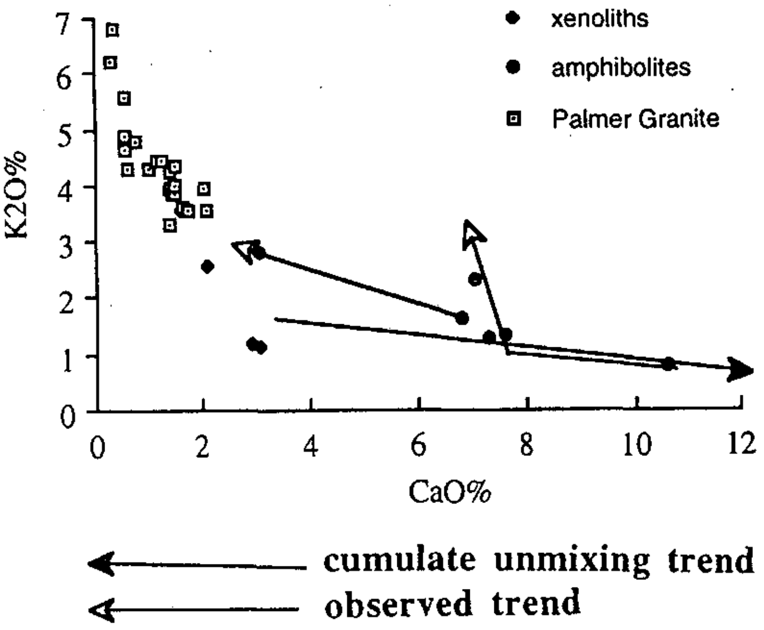


Figure 20

zirconium, thorium, yttrium should go to very high levels with significant amounts of partial melting. The general amounts of incompatible elements are not very high for a granite hence assimilation is not very likely. The xenoliths representing a chilled margin is therefore the most probable origin. G

5.4 Mafics — Amphibolites

The mafic suite follows a normal fractional crystallisation path for most elements except Uranium, Lead, and Iron (figure 21,22). Uranium and Lead should be highly incompatible in any liquid with fractionation however their values decrease with increasing differentiation. Caution should be used when using Uranium and Lead as they are both very susceptible to fluid movement. Evidence that fluids have not affected the values in the mafics are the lack of alteration products within the amphibolites, and the [illegible] that the values decrease in a linear fashion with differentiation. It would be unusual for fluids to change the values in a regular fashion as the samples are separated spatially, hence fluids should increase the disorder in the system, not the order.

The other anomalous element is Iron, which increases with increasing differentiation. This is despite the fact that some of the major crystallising elements in a mafic system ie. olivine, pyroxene, and amphibole, all contain Iron. By comparing Iron with Magnesium it can be seen that the overall behaviour for most of the rock types is the same except for the mafics, where the concentration of Iron decreases when Magnesium increases. The similarity between the two elements would suggest that the same minerals are controlling the concentration. The anomalous behaviour of these elements would suggest that fractional crystallisation has not been the major controlling factor for iron. A possible alternative is magma unmixing in which liquid-liquid separation occurs to give two layers; a lower denser layer of a mafic liquid, and a higher, lighter layer of more silicic liquid. The distribution of elements between mafic and silicic melts is controlled by the occurrence of complexes (Hildreth 1981) and hence will vary from the distribution expected from the crystallisation of solids.

The lack of any other explanation for the decrease in uranium and lead is a strong argument for magma unmixing. For any model it must explain all of the elements and a decrease in uranium and lead cannot be explained by straight fractional crystallisation or assimilation. The adherence of the other elements to the expected pattern for fractional crystallisation would suggest that this was occurring simultaneously and that the effect of liquid-liquid unmixing is only seen where the resulting difference is greater. Some evidence for a combined effect can be seen in thorium where were the value remains almost constant for the mafics. This would suggest that the trend of liquid separation for decreasing thorium is counterbalanced by the trend for increasing thorium with fractional crystallisation.

G1: U $\cong$ 5 ppm Zr $\cong$ 150 ~~200~~ ppm U $\neq f(\mathrm{Zr})$

G2: U [5 – 10] Zr [50 – 400] U $\neq f(\mathrm{Zr})$

Figure 21: Variation of a, uranium and b, lead with zirconium. Decreases in the mafics and intermediates cannot be explained by fractional crystallisation.

Figure 22: Variation of iron and magnesium against zirconium. Both are taken out by similar crystallising phases yet iron is increasing while magnesium is decreasing.

Figure 21

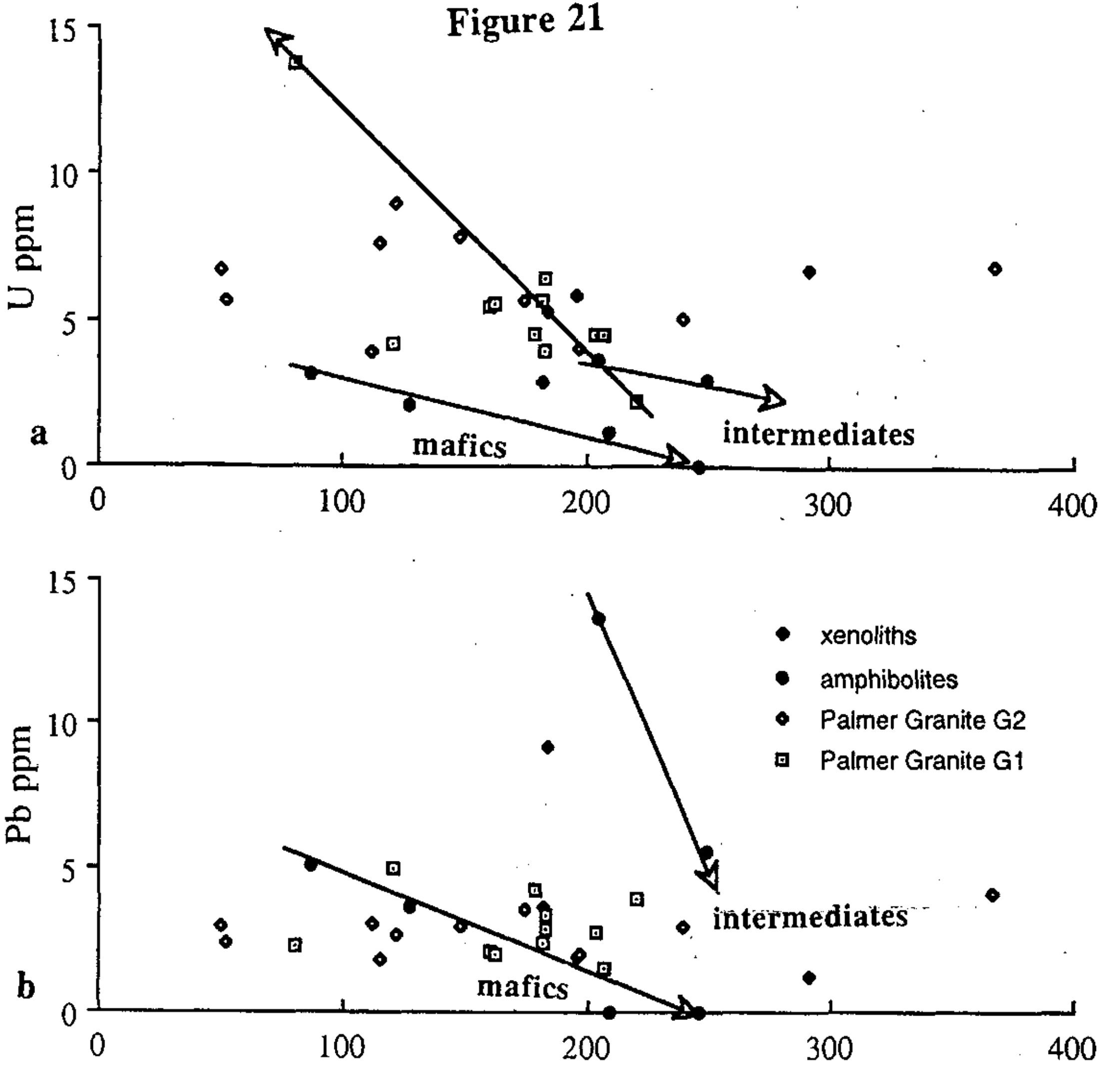
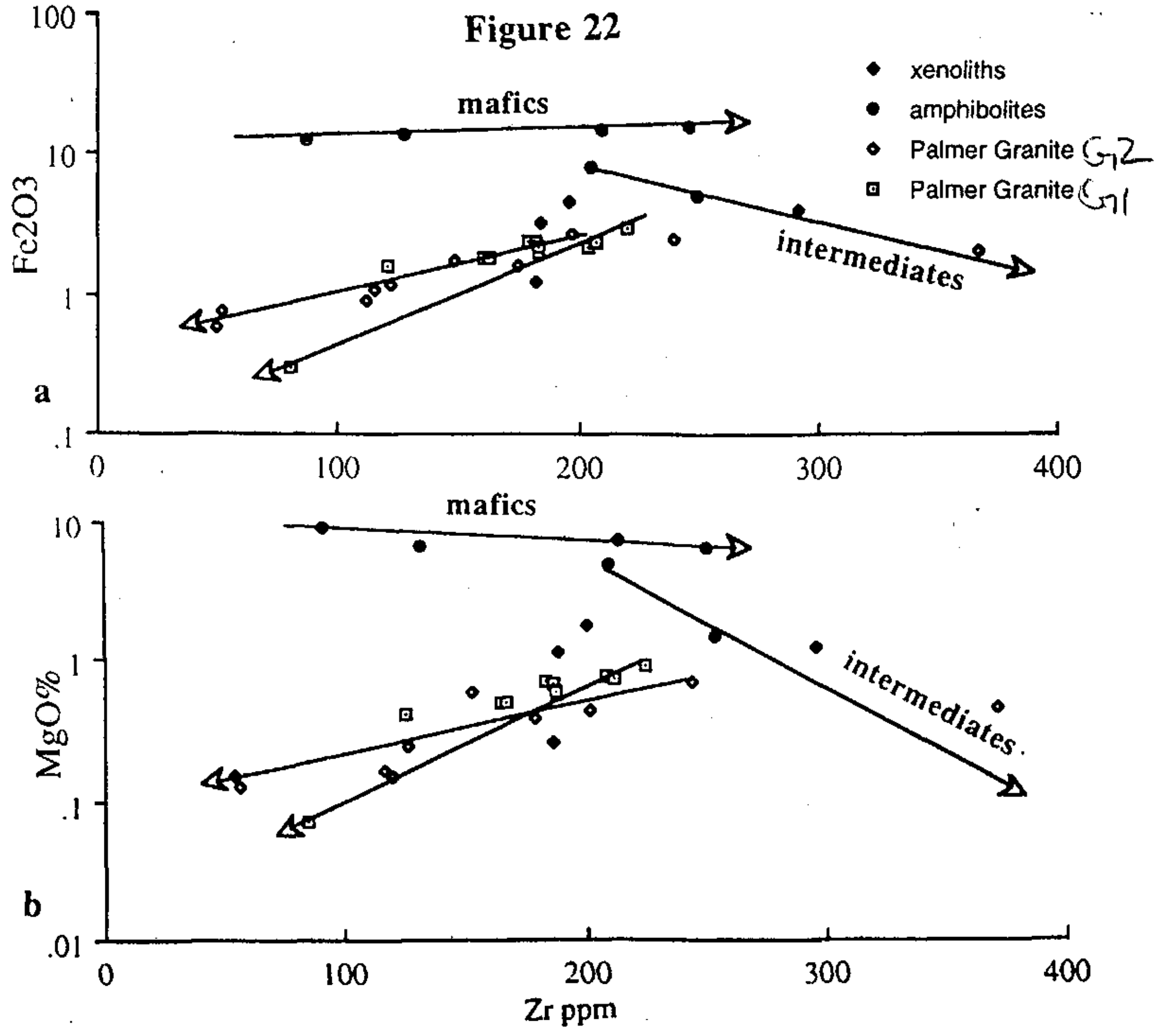


Figure 22



The mafics are the only suite present that are not crystallising apatite (figure 23), as is evident by the highly incompatible nature that phosphorous is showing. Zircons are also not crystallising as the concentration of zirconium is increasing. The CIPW normative compositions show that olivine is a possible crystallising phase in the most mafic endmember. The suggested fractionally crystallising assemblage from this is clinopyroxene.

5.5 Intermediates — Amphibolites

The origin of the intermediate mafics follows along the same lines of evidence as for the mafics. The uranium and lead concentrations are still decreasing however the iron content is now also decreasing. This suggests that diffusion controlled processes are still operating and that the decreasing iron content reflects fractional crystallisation ~~having~~ playing a more dominant role. If laminar flow in the silicic cells forms then the ~~a~~ concentration gradient within the layer will develop with the highest concentrations in the outer part of a convective cell causing the gradient between the silicic and mafic magma to lessen hence retarding diffusion (figure24).

The crystallisation in the intermediates is different to the mafics as shown by the elemental distribution. The crystallisation of apatite leads to a reduction in the amount of phosphorous and in the yttrium content. Zircon is not a crystallising phase leading to enrichment in zirconium. Plagioclase is increasingly becoming more prevalent lessening the increase in cesium and barium and leading to a decrease in titanium. Niobium is becoming more incompatible, which is possibly due to lower amounts of amphibole crystallising. A point to note is that if the trend of fractionation for the intermediates is followed with allowance for the behaviour in silicic melts then the end result will be similar to sample number 15. This sample appears to have formed without zircon saturation, unless it evolved from a liquid of high zirconium concentration. If a totally separate source is inferred then it does not explain why the other major and minor chemistry is so similar to the rest of the Palmer Granite. This sample also contains more phosphorous than the other samples indicating that it has evolved from a liquid that has had less fractionation of apatite than the rest of the other granite which also correlates with an origin directly from the intermediate liquid.

5.6 Group 1 Palmer Granite

The evolution of the first group of the Palmer Granite occurred from a homogeneous source. The trends shown throughout the Palmer Granite ~~is~~ are the ~~reverse~~ opposite to those seen in most igneous suites due to the decrease in many incompatible elements with increasing differentiation. In order to explain the compatibility of some of the incompatible elements the behaviour in a fractionally crystallising system was modelled. The behaviour of yttrium, zirconium, niobium, and titanium ~~were~~ was used due to their resistance to fluid flow and because of the work of Pearce and Norry (1979) which gives an estimation for the values of D for yttrium, zirconium, niobium and titanium, from a large data base and applied examples for different volcanic suites. For the

HOW?

Figure 23: Variation of phosphorous with calcium. Phosphorous is only removed by crystallisation of apatite which indicates that the mafics are the only ones not fractionally crystallising apatite. It must be noted that the amount of apatite crystallised is not significant enough to control the distribution coefficient of Y.

Figure 24: The effect of turbulent versus laminar convection. With turbulent convection efficient mixing within a layer will occur. The concentration is represented by the darkness. In a turbulently mixing magma the difference between layers is enhanced which will increase diffusion across a layer as the rate of diffusion is a product of the concentration gradient. For laminar flow equilibration over the boundary layer tends to occur which in the turbulent case would be destroyed by mixing. This equilibration retards diffusion. The turbulent and laminar flow also affects bulk differences in composition as a new influx of granitic magma to a laminar flow regime will act with convection like a multi-coloured piece of plasticine as the flow will stretch the plasticine but the lack of mixing makes the coloured layers thinner hence increasing the heterogeneity. With turbulent flow the layer still becomes thinner, but a thin layer is more susceptible to being destroyed with turbulent mixing.

Figure 23

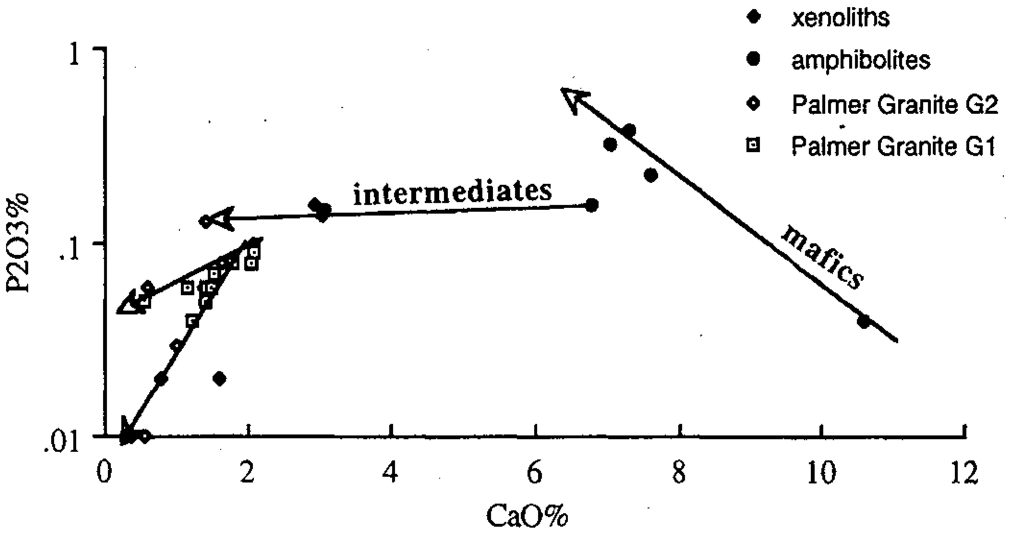
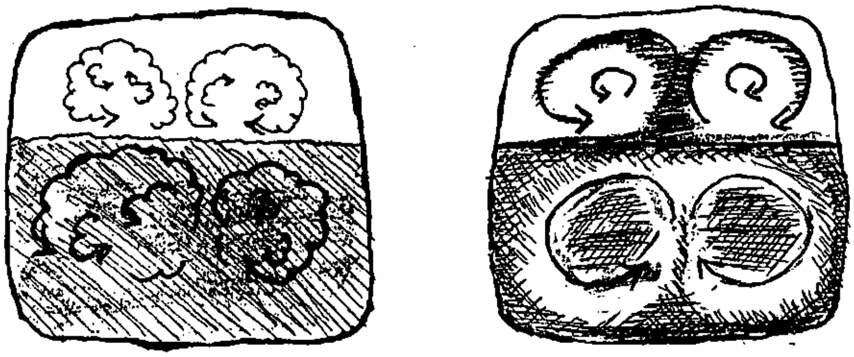


Figure 24



turbulent **laminar**

suites studied it was shown that a decrease in these elements occurred when amphibole, zircon, and biotite occur in the crystallising assemblage. Their (Pearce & Norry, 1979) work had amphibole, zircon, and biotite as the dominant phase only in some Andean-type arcs. However they will also be expected to occur as part of the crystallising assemblage for I-type granites due to their peraluminous nature which enhances zirconium saturation (Watson, 1979).

By varying the assemblage of Pearce and Norry (1979) of K-feldspar + plagioclase = 60%, biotite + zircon = 15%, hornblende = 20% and magnetite = 5% a crystallisation model for the Palmer Granite was obtained. In order to see the behaviour of the elements chosen the Rayleigh fractionation equation (Cox et al, 1979) which models perfect fractional crystallisation was used:

$$C_L = C_L^0 . F^{(D-1)}$$

where:

C_L= concentration of element in liquid
C_{L0}=original concentration of element in liquid
F=fraction of liquid remaining

The results of the best fit are seen in figure 25 for a starting composition equivalent to the most primitive sample, number 5, and a change in the distribution coefficients part way through which represents the changing proportions of minerals with differentiation. As a further test to see if fractional crystallisation is feasible the elements cesium, barium, and thorium were also modelled. The behaviour of these elements covers a wide spectrum of possible replacements. Yttrium replaces Ca^{2+}, which is present in the minerals clinopyroxene, hornblende and very strongly into apatite. Zirconium has a large radius and a +4 charge, therefore it cannot replace any other element and will remain incompatible until the mineral zircon appears, in which zirconium is a major constituent. Cesium has a similar radius to potassium which it replaces however it is preferentially taken into biotite relative to K-feldspar due to the larger site in biotite. Titanium can replace Al in six-coordination therefore it appears in pyroxene, hornblende, and biotite. Barium will replace potassium and therefore behaves similarly to cesium however it is also taken up in hornblende. Niobium and thorium both have high charges (+5 and +4 respectively) however niobium has a small radius and can be taken up in hornblende, biotite and zircon. Due to the large radius of Th it is not taken up by any mineral and therefore is incompatible. (The information above was taken from Mason and Moore, 1982). Monazite ?

5.7 Group 2 Palmer Granite

Given that the first group of granites comes from a homogeneous source and evolved by fractional crystallisation to give the variation, the second group must be due to mixing with a different source. The second group do not show the same contiguity that group one show and

Figure 25: Fractional crystallisation models for elements versus Zr. The parameters in each equation are;

Zr F=1 to .6 D_1=1.5
F=1 to .6 D_2=2.75

25a: Nb D_1=1.7
D_2=2

25b: Y D_1=4.2
D_2=2

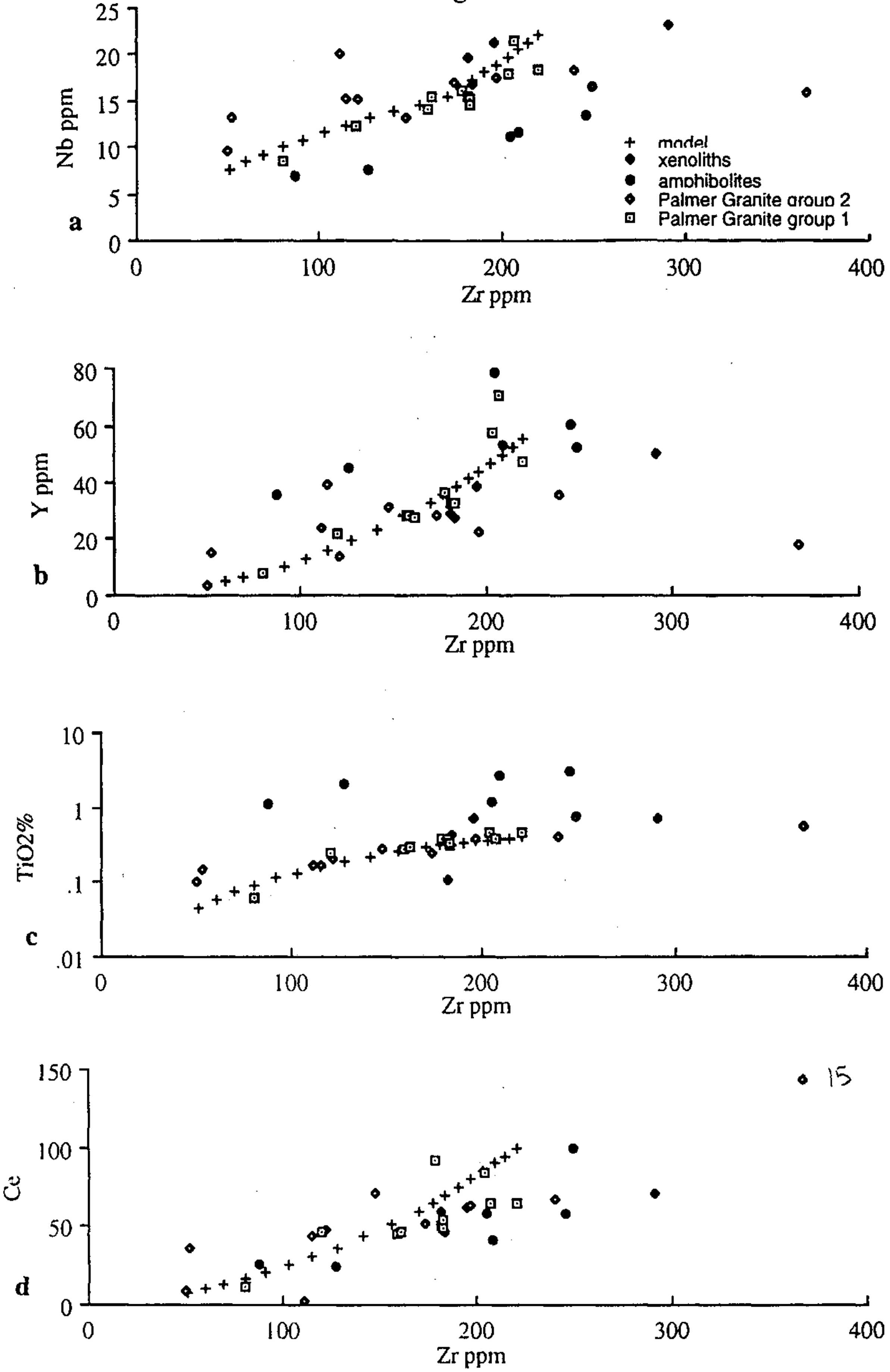
25c:TiO% D_1=3.7
D_2=1.6

25d: Ce D_1=4
D_2=2

25e:Ba D_1=1
D_2=2.9

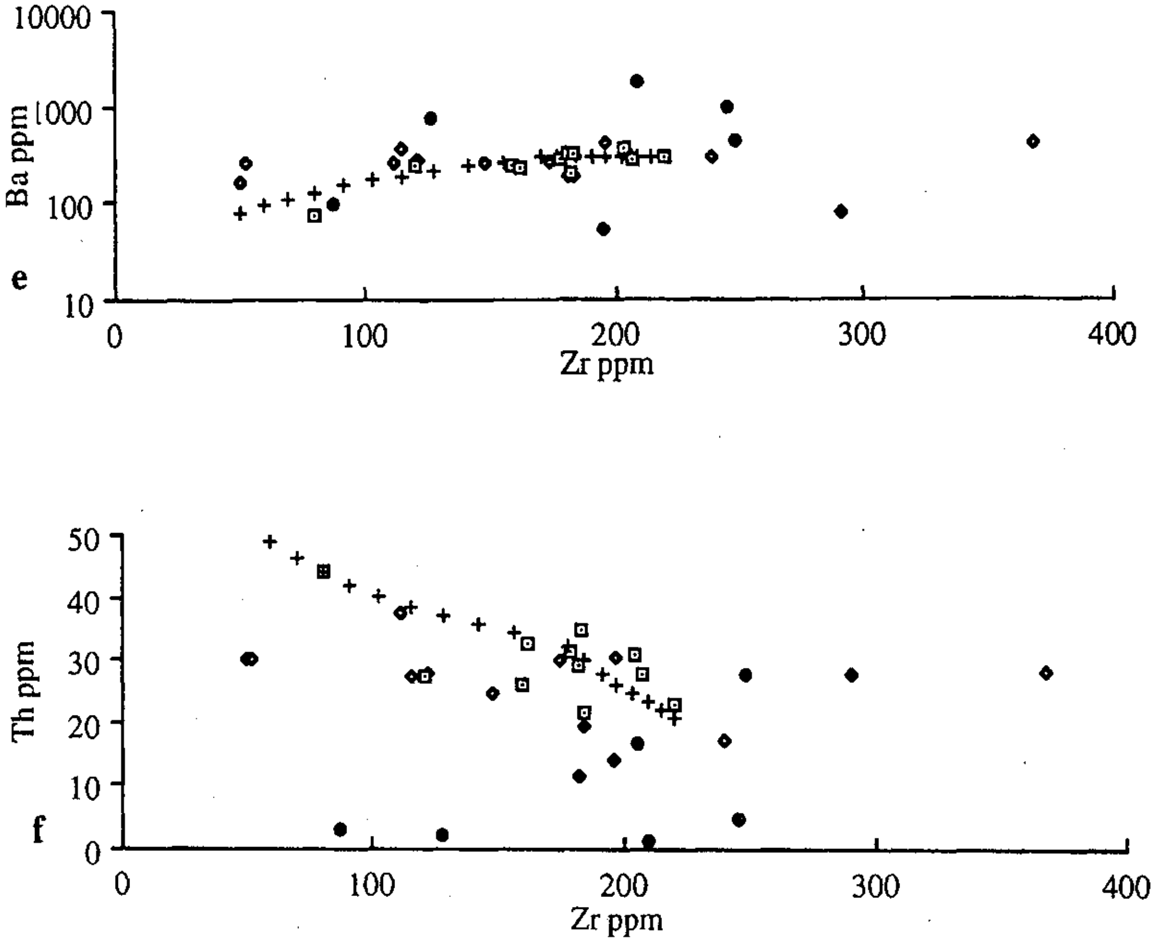
25f: Th D_1=.05
D_2=.4

Figure 25



o unclear

o Which sample is which?



e
Ba ppm
10000
1000
100
10
0
100
200
300
400
Zr ppm
f
Th ppm
50
40
30
20
10
0
0
100
200
300
400
Zr ppm

from this it can be inferred that the granitic magma is not convecting in a turbulent fashion. This is also required to maintain the homogeneity of group one as it would otherwise mix with group two. If the second group were added to a convecting cell with laminar flow then due to the viscous nature of silicic magmas ~~means~~ mixing will be by diffusion only and convection and any heterogeneity will be enhanced (see figure 24).

The second group ~~as a~~ does not show a simple relationship that is characteristic of group one. A trend cannot be derived from one single starting composition and the elemental variation diagrams show a larger scatter than for group one implying that the source was not homogeneous. The decrease in zirconium and the incompatible elements is the same indicating that the same fractional crystallisation processes were involved but that other processes also influenced the final composition. The dominant variation within the samples is the lesser extent of depletion of cesium, titanium, niobium, yttrium, iron, and magnesium. A generally higher concentration of aluminium, calcium and silica, and lower phosphorous. Although all appear to start from a similar starting point as group one. Normative differentiation indexes that show a similar overlap as aluminium, calcium and silica, and phosphorous, however go to higher values of differentiation. The higher aluminium to alkalis means that the stability of zircon is reduced. The reduction in the amount of zircons means that for lower concentrations of zirconium more fractionation must have occurred than for the equivalent concentration in group one. This is reflected in the normative differentiation indices. The higher aluminium also has suppressed the crystallisation of amphiboles to a certain extent which explains the lessening of the depletion of titanium, barium and cesium. The proportions in the crystallising assemblage also explains the variation in the major assemblage when compared with group one. Apatite is more prevalent and should increase the compatibility of yttrium, however it is not enough to push the values below that of group one. This indicates that in both groups apatite is not significant enough to be the controlling phase for yttrium (Mason and Moore 1982).

Gr

What order do you get? No evidence given.

5.8 Isotopic Evidence

The isotopes of neodymium do not show a straight forward path as would be expected for fractional crystallisation. The only two samples that have similar values are samples 7 and 88 from group 2 (figure 26). The intermediate has the most mantle-like εNd values with the group 1 granite sample 5 having the most evolved εNd value. Isotopic ratios of Nd do not change through crystallisation processes hence they imply that more than one source material formed the granite. This is generally taken as being the assimilation of crustal material with a primitive mafic magma whilst the magma is fractionally crystallising. The simplest explanation along this line of reasoning would be a liquid that is equivalent to the intermediate sample 25 assimilates an isotopically evolved crustal material with increasing amounts of assimilation giving a progression in the granites of sample 88 to 7 to 5. There are several reasons why this is impossible. The first is that all indices of differentation such as silica, calcium, normative

Gr

D.I.(differentiation index) put sample 5 as the most undifferentiated sample not the least (figure 27). If the groups are still adhered to the progression from 88 to 7 agrees with the amount of differentation, however the similar isotopic values would imply similar amounts of differentation. Trace elements put sample 88 at the most halfway between the least and most differentiated sample. Given the evidence for fractionation and the variation between the mafic and intermediate rock types, the possibility of magma recharging of the mafic intrusion arises.

?

Chapter 6 - Pluton Model

6.1 Introduction

The aim of this chapter is to tie in all of the geochemical evidence of the previous chapter into a feasible model showing the processes in a mafic pluton. The assumption is made that all of the rocks are related.

Which?

6.2 Xenoliths

The first definite crystallising phase ~~is~~ represents the xenoliths. The xenoliths crystallised onto the roof or walls of the pluton from a mafic magma as is shown by the geochemical evidence. The xenoliths have to get into the silicic magma by some mechanism. The calculated normative densities of the solid xenoliths are less than those for the liquid mafics so they would float if contained within the mafics which means they could fall from the walls ~~of~~ or be scoured from the floor of the pluton but they have to get ~~passed~~ past the boundary ~~of~~ between mafic to silicic liquid. Hence it is more likely that they fell from the walls or roof of the pluton and as they are more dense than the liquid granite be held in suspension by convection within the magma (figure 29a).

Why not brought up by "recharge"

The xenoliths crystallised from a cooling magma which does not appear to be the cumulate of the observed mafic. Therefore it is likely that the magma was recharged to give the mafic rocks that are seen currently exposed. The mafic rocks have undergone fractional crystallisation and liquid unmixing, therefore a separate silicic layer must float on top of this. A temperature gradient exists between the layers and within the layers so the mafic layer will either start to, or already be convecting within it's own convective cell. This convection is required to maintain a diffusion gradient so that magma unmixing can occur. Crystallisation within a discrete zone, such as the walls or floor of the pluton allows a continuous input of evolved liquid to the silicic layer, until it grows in vertical dimension to such an extent that it can convect (figure 29b).

which?

its

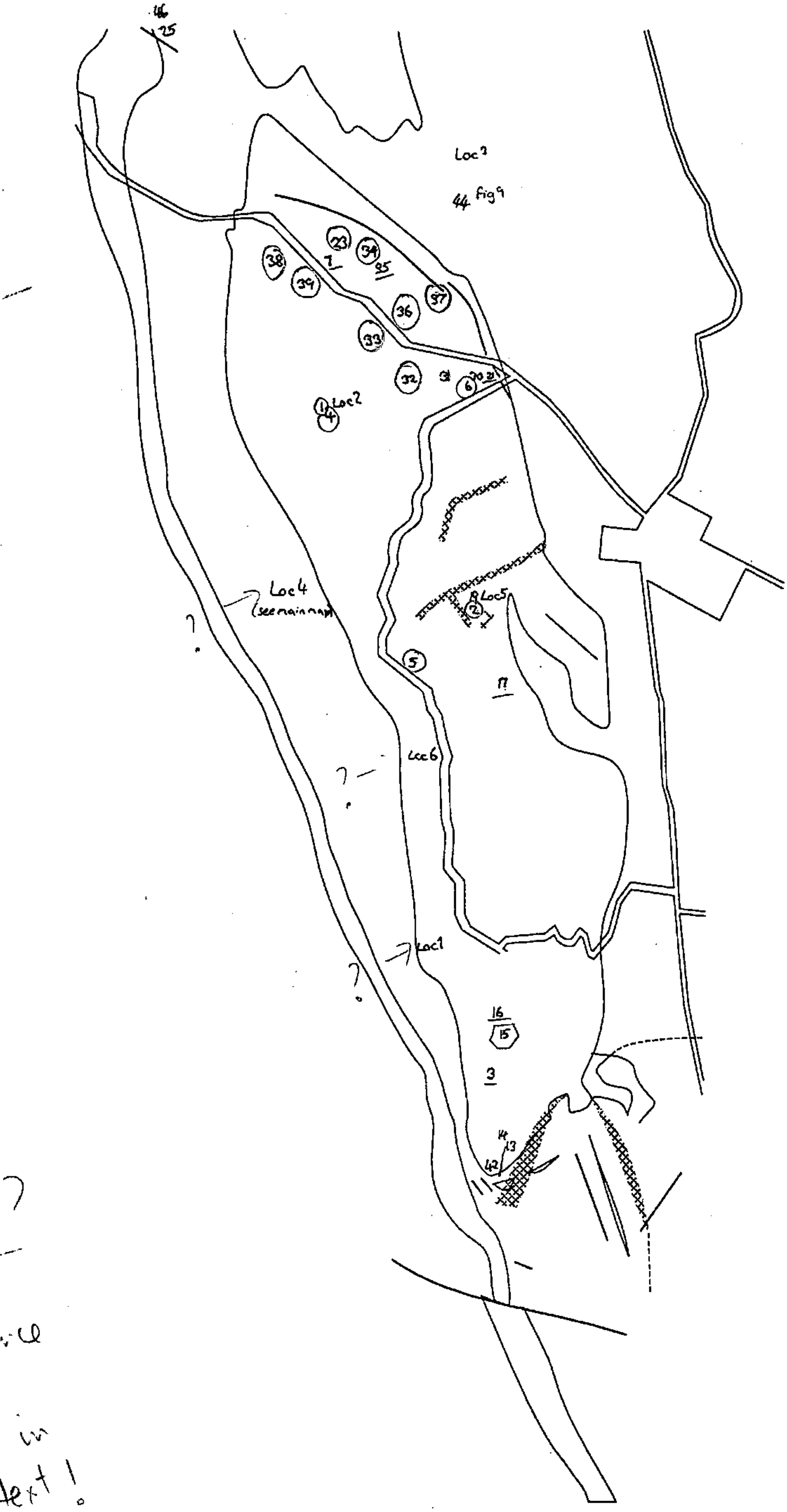
6.3 Turbulent Pluton Flow in Silicic Chamber

An assumption that the group 1 Palmer Granite samples ~~is~~ formed from the liquid derived from the mafics will give the constraint that the silicic magma must at some stage convect turbulently. This is because the entire heterogeneity in this group is due to fractional crystallisation. Therefore the starting point must be homogeneous which will not be seen from a continuously evolving mafic magma. For thorough mixing in a viscous silicic melt, the convection must be

Figure 26: Isotopic variation of samples. Isotopes remain the same through fractional crystallisation processes.

Figure 27: The variation of samples 5,7 and 88 with the amount of fractionation.

not shown



LOC 2 }??
and 2

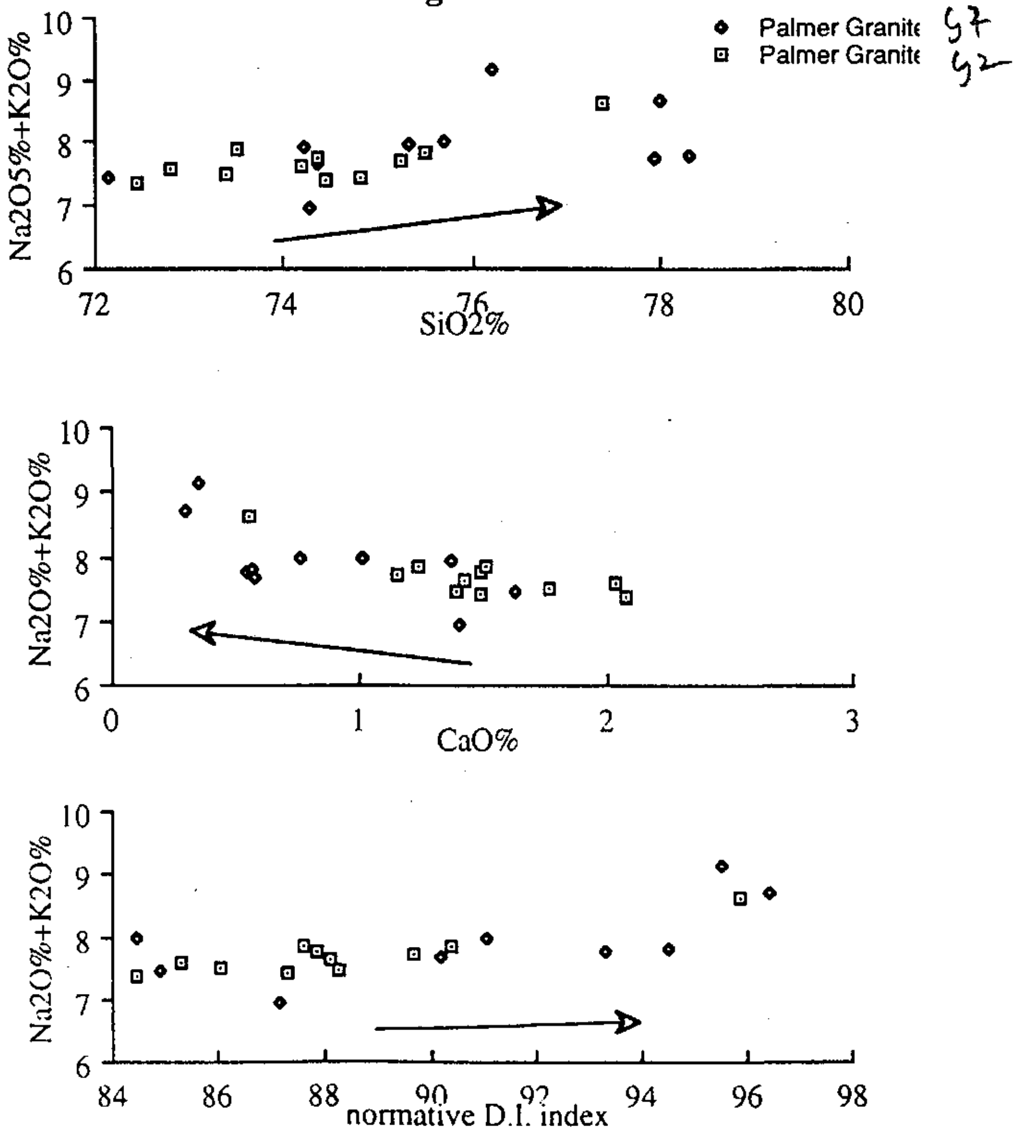
Fig 7

Reference this in the text!

Figure 26

sample no.	1004-5	1004-7	1004-25	88
rock	granite G1	granite G2	intermediate	granite G2
Nd ppm	21.53	2.34434	27.0168	24.35
Sm ppm	4.515575	0.3665255	6.324118	4.89
143/144 Nd	0.512236	0.512156	0.512369	0.512255
147Sm/144Nd	0.1269	0.0946	0.1416	0.1215
143/144Nd ch	0.512638	0.512638	0.512638	0.512638
T mod:dep	1.49	1.20	1.52	1.38
eps Nd (0)	-7.841790893	-9.402346295	-5.247367538	-7.471158985
eps Nd ch(500)	-3.38	-2.88	-1.73	-2.67

Figure 27



Sample 157?

turbulent. If turbulent convection is occurring in a viscous silicic melt then in a mafic melt which is likely to have a larger vertical dimension, turbulent convection is almost certainly occurring. The result of turbulent convection is to increase the gradient between the two magmas hence enhancing diffusion in the form of liquid unmixing.

6.4 Laminar Pluton

? flow in ~~silicic~~ felsic chamber

G For the formation of the group 2 Palmer Granite samples a new magma influx of more isotopically primitive magma must recharge the magma. The variation in isotopes and in the elemental variation diagram requires some mixing of the two magmas. If a plume of hot magma is expelled into the chamber and is less dense than the existing magma it will form a turbulent plume. Combine this with an already turbulently convecting magma and efficient mixing will occur. The effect of the rate of input of the recharge and the time it takes to mix will cause a heterogeneous source that is seen in the granite samples. To maintain the heterogeneity of the group 2 samples and the homogeneity of the group 1 samples, the convection in the silicic layer must be laminar. Turbulent flow can still occur in the intermediate liquid due to it's lower its viscosity. The change to laminar flow will reduce the ability of diffusion to operate due to the poor mixing of an element from the outside of a convective cell to the inner areas, which in turn reduces the gradient between the two magma types. This is a possible reason that iron is decreasing in the intermediate samples were it was increasing in the mafics, as fractional crystallisation becomes more dominant when compared to liquid unmixing (figure 29c).

6.5 Fractional Crystallisation. Where?

As both groups 1 and 2 have both undergone fractional crystallisation the question as to where this has happened arises. Fractional crystallisation can happen at the time of crystallisation if the interstitial liquid from the early crystallising grains is removed, or it can be a result of crystallisation at the pluton and the resulting decrease in density combined with the latent heat of crystallisation can be the trigger for ascent. The only constraint able to be placed is that sample 15 is a direct product of the intermediates. This means that the intermediates kept on fractionating to such an extent that the two layers ended with similar compositions, and part of the intermediate layer got into the silicic layer. The fact that sample 46 of the intermediates is highly silicic is testament to the fact that the intermediates did evolve significantly. Sample 15 shows that the Palmer Granite magma stayed in the pluton during this time. If the fractionation had occurred at the site of intrusion then sample 15 should also have fractionated. However the sample does not show a great deviation from the amount of differentation required to form a silicic magma, and does not show the expected zircon, amphibole and biotite fractionation expected from fractional crystallisation in a silicic system. Therefore this sample represents a direct descendant from the which ? intermediates, with no post separation alteration from fractional crystallisation. This also implies that the fractional crystallisation in the rest of the magma has

Figure 28

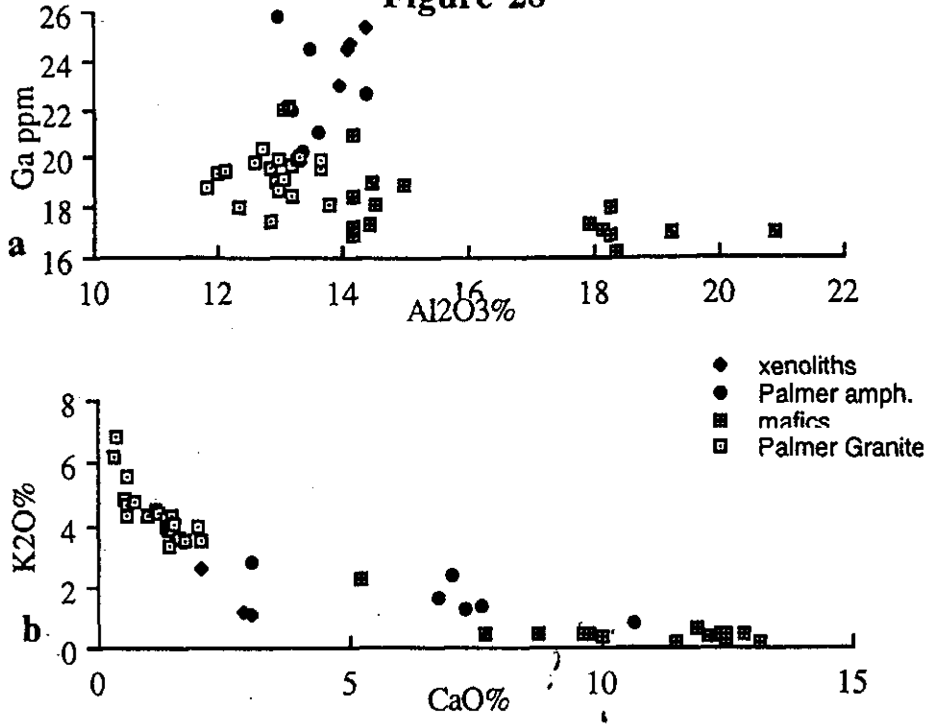


Figure 29

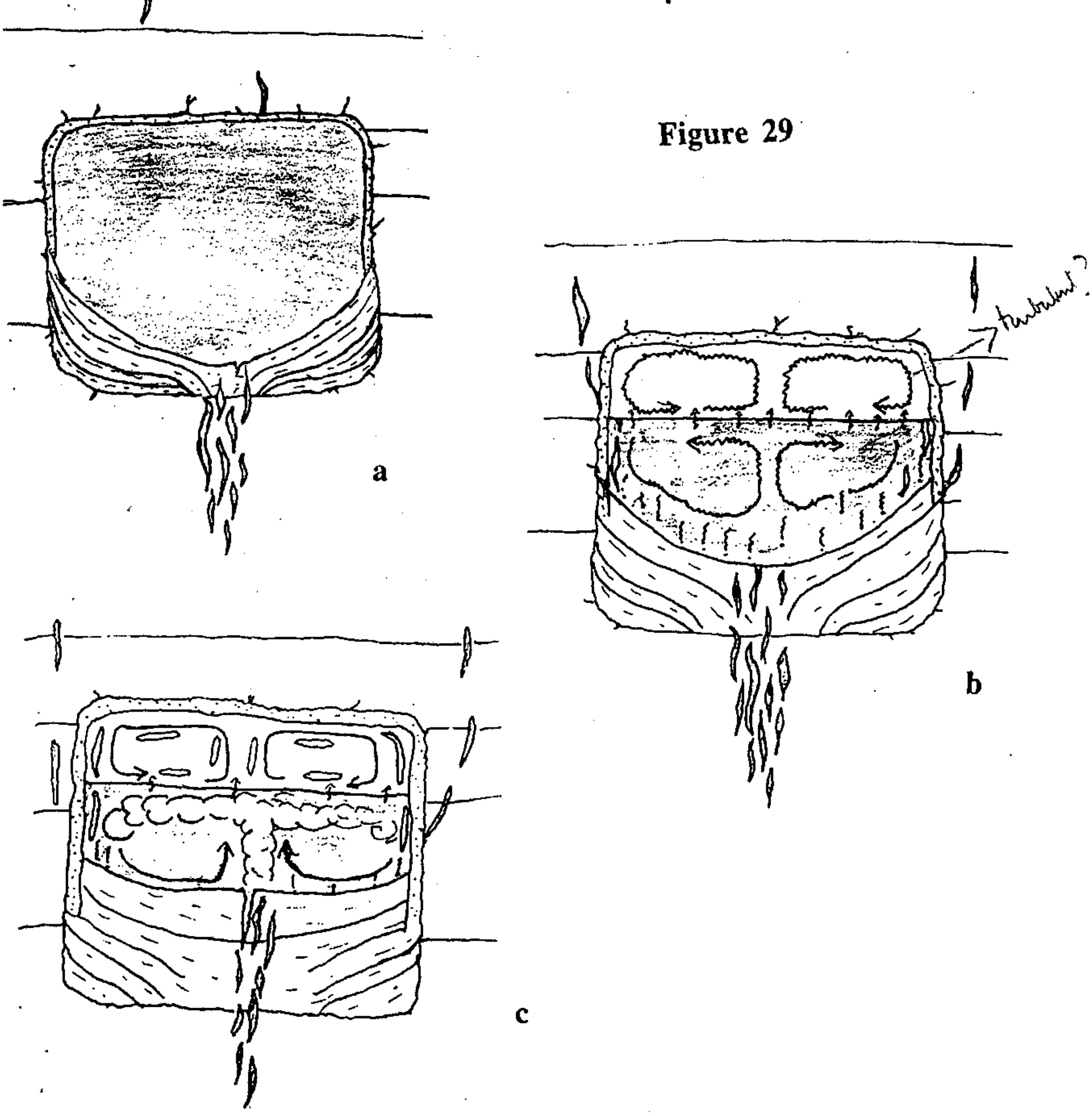


Figure 28: Elemental variation comparison of mafic samples from Palmer, north of the Marne river, and Mt Pleasant. The variation in the elements shoes a way in which the mafics, intermediates, Palmer Granite and xenoliths can be related. However some independent verification is needed to show if this assumption can be made. In order to do this the comparison of the Palmer area mafics with other totally unrelated mafics in the area is made to see if these have a similar amount of correlation to the Palmer granite as the Palmer Granite mafics.

Fig 28(a)shows variation of gallium with aluminium. Within the Palmer Granite a trend of decreasing gallium with respect to aluminium was observed. This agrees with the Palmer mafics being related to the granite. The xenoliths also have a high gallium content which is consistent with the mafics.

Fig 28(b)shows the higher amounts of potassium in the Palmer area mafics where the others appear to stay at relatively low values.

with what

The Palmer area amphibolites show more correlation than the other mafics therefore it is reasonable to infer some relationship. what is that?

(Foden pers. com.)

Figure 29a: Cartoon of the mafic pluton which is crystallising the xenoliths onto the wallrock. This original mafic magma is probably not represented in the sampled outcrops. Magma replenishment may be occurring.

Figure 29b: The pluton separates into two layers. Input of granitic magma to the silicic layer is probably occurring through fractional crystallisation at the walls and floor creating blobs of silicic melt. Diffusion is occurring at the boundary layer. Due to the homogenous source of group 1 turbulent convection is occurring, mixing the layer. Hence turbulent convection is also mixing the mafic layer. The magma is seen at the surface so offshoot dykes from the sides of the chamber must occur. A cumulate from the crystallising mafics is building up on the floor of the chamber.

Figure 29c: An injection of magma is required to change the isotopic composition. The silicic layer is now convecting in a laminar fashion hence any heterogeneities are preserved. Diffusion is still occurring across the layer and fractional crystallisation in the mafic layer means an input of silicic magma to the top layer is still happening. The silicic layer is simultaneously fractionally crystallising and hence producing its own heterogeneities. The mafic layer evolves to such an extent that some of it can be caught up in the silicic layer, as is represented by sample 15. Not much is caught up and as the mafic layer must be evolving more samples similar to 15 the silicic magma must depart for the surface around this time.

been essentially completed by the time the two mixed and therefore the fractional crystallisation must have been in the mafic pluton (figure 29c).

Conclusions

The generation of a magma implies an anomalous geotherm. The Palmer area has been maintained at a migmatite grade of metamorphism for most, if not all of the Delamerian orogeny. No single exposed igneous body can be used to explain this. ~~Which~~ This implies considerable amounts of igneous activity has occurred throughout the Delamerian that is not seen at the current erosional surface today. It is notable that melting in the area is constrained by the break down of hydrous minerals. If any external fluids had been present during the Delamerian the entire area would have melted. The protracted high grade metamorphism preserves an excellent record of the folding deformational events. This is the probably reason that evidence ~~fo~~ of three folding deformations is seen more clearly on the eastern side of the SAFB.

The emplacement of the Palmer Granite is controlled by the bedding plane of the Kanmantoo. The fact that virtually all of the igneous rocks in the area are controlled by the bedding plane sp implies that acsent mechanism has little control over emplacement. The Palmer Granite shows why similarity in emplacement style ~~as~~ to the Anabama Granite suite despite the fact that the Anabama Granite is emplaced into Adelaidean sediments. The possibility that emplacement and possibly ascent is controlled by shearing can be postulated, however at present no substantial evidence can be put forward supporting this.

The effects of the deformations seen in the area trend towards an increase in scale of folding. D1 gives a foliation in the Rathgen Gneiss and crenulation in the migmatite veins. Whilst its effects do not appear to have large scale effects, the large amount of shortening parrallel to sp bedding apparent in figure 7 shows that substantial thickening must have occurred. The sp prescence of D2 is felt most strongly in the area which is not surprising when it is considered that the Palmer Granite intruded at this time. A crystallising igneous body will generate a large amount of heat through the latent heat of crystallisation which will substantially weaken the sp sediments and make them ameniable to plastic deformation. Numerous mesoscale folds occur with the pre-granite folds having axial traces similar to the D1 crenulations and parrallel to the sp contact with the Palmer Granite. The syn-deformational nature of the intrusion of the Palmer Granite is evident by the effect of faulting in a semi-crystalline structure, a biotite fabric and subsequent folding of this fabric. Effect of the intrusion is seen in the orientation of the post intrusional D2 folds which have little correlation of axial traces over the area, which is to be expected when a rheologically different body is emplaced.

A broad genetic relationship can be made between the Palmer Granite, the amphibolites and the xenoliths. By careful subdivision of the samples on the basis of their trace element geochemistry and by describing the processes that can achieve the trends observed a model of the crystallisation history can be determined. And by fitting the crystallisation histories together in a feasable order and applying physical constraints to the processes a model of the differentiation of the Palmer Granite can be inferred. The isotopic variation within the granite implies a variable source. Assimilation is ruled out as the incompatible elements are too low so magma recharging of a mafic pluton is used. The xenoliths are not a restite phase of the Palmer Granite as they crystallised from a mafic melt. The most probable explaination is that they are a chilled margin, although a wallrock is not completely ruled out. The identification of two geochemically distinct groups in the Palmer Granite gives important clues as to the physical processes that formed the Palmer Granite. Both groups differentiated by fractional crystallisation of zircon, amphibole and biotite which gives a distinctive reverse trend in the incompatable elements. The recognition that one group formed from a homogeneous source and the other from a heterogenious source gives an insight into turbulent and laminar fluid flow sp within the chamber. The prescence of a sample that is best interpreted as a direct fractional Gr phase from a mafic melt without zicon, amphibole and biotite fractionation. The mixture of this with the granite melt implies that fractional crystallisation occured in the mafic pluton and not at the site of emplacement.

The final say on whether this model is correct must be through further isotope work. If samples from the mafics have ~~the~~ ~~same or~~ similar average isotopic composition ~~as~~ to group one, and if the other intermediate sample defines a trend away from 25 and towards the isotopic composition of the granite number 15, then the model given is correct. However on the information available this q is the best optionand even if wrong still shows the behaviour of the separate magmatic systems, which is an important part in the understanding of igneous rocks.

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Appendix 1

Concentration of major and minor elements from XRF analysis for the Palmer Granite, mafics, intermediates and xenoliths

Appendix 2
CIPW normative mineral assemblages for the Palmer Granite mafics, intermediates and xenoliths

→ legend?

?

	1004-32 PG g2	1004-3 PG g1	1004-7 PG g1	1014 PG g1	1004-17 PG g1	1004-16 PG g1	1004-21 PG g1	1004-35 PG g1	1004-15 PG	1004-34 PG g2	1004-36 PG g2	1004-37 PG g2	1004-23 PG g2	1004-1 PG g2
	75.5	78.31	76.2	74.22	77.93	74.37	77.99	75.33	74.27	74.83	74.2	74.45	77.38	72.81
	13.07	11.99	12.35	13.46	11.85	12.93	12.11	13.17	12.59	12.99	13.26	12.98	12.72	13.2
	1.57	0.9	0.58	1.71	1.06	2.69	0.77	1.62	2.1	2.02	1.8	2.39	0.3	2.17
	0.01	0.01	0		0	0.01	0	0.01	0.03	0.01	0.01	0.01	0	0.02
	0.36	0.14	0.13	0.51	0.13	0.37	0.11	0.32	0.38	0.47	0.43	0.59	0.06	0.65
	1.24	0.57	0.36	1.13	0.55	0.58	0.3	1.01	1.4	1.39	1.42	1.48	0.56	2.03
	3.44	3.17	2.35	3.66	2.91	3.4	2.46	3.69	3.65	3.55	3.78	3.56	3.06	3.63
	4.42	4.63	6.8	4.26	4.86	4.27	6.23	4.3	3.31	3.92	3.86	3.85	5.56	3.95
	0.24	0.17	0.1	0.28	0.17	0.39	0.15	0.25	0.55	0.31	0.28	0.37	0.06	0.45
	0.04	0.01	0.01	0.06	0.01	0.06	0.01	0.03	0.13	0.06	0.05	0.06	0.05	0.08
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0.24	0.32	0.24		0.35	0.67	0.3	0.29	1.93	0.25	0.23	0.25	0.3	0.19
	100.14	100.22	99.11		99.82	100.09	100.43	100.01	100.33	99.79	99.33	99.99	100.05	99.2
Y	21.5	24.1	3.8	31	39	22.7	~~15.4~~	28.6	~~18.3~~	32.7	28.1	36	7.7	57.7
Sr	61.6	45.2	42.6	72	48	56.6	~~51.2~~	62.3	~~73.4~~	64.9	65.1	78.6	32.8	112.5
Rb	144.6	147.1	238	155	160.6	158	~~222.8~~	162.1	~~144.5~~	149.9	147.2	163.2	211.8	118.8
Nb	12.3	20	9.7	13.2	15.2	17.4	~~13.2~~	16.9	~~15.9~~	15.2	14	16.1	8.4	17.9
Zr	120.7	111.6	49.6	148	115.3	196.6	~~52.5~~	173.7	~~367.8~~	182.7	159.4	178.4	80.5	203.8
Th	27.5	37.5	30	25	27.3	30.7	~~30.2~~	29.9	~~28.5~~	34.9	25.9	31.2	44.3	30.9
Pb	5	3.1	3	3	1.8	2	~~2.4~~	3.5	~~4.1~~	3.3	2.1	4.2	2.3	2.8
U	4.2	3.9	6.7	7.8	7.6	4	~~5.6~~	5.6	~~6.9~~	6.4	5.4	4.5	13.8	4.5
Ga	19.1	19.4	18	16	188	19	~~19.5~~	22.1	~~19.8~~	19.9	19.9	18.7	20.4	18.5
Cu	13	17	12		6	50	~~11~~	12	~~9~~	16	5	6	9	12
Zn	11	10	7		17	9	~~8~~	12	~~17~~	10	11	12	8	13
Ni	4	5	1	2	2	5	~~4~~	3	~~13~~	0	4	6	4	6
Ba	243	253	159	266	351	419	~~255~~	264	~~411~~	195	239	275	72	355
Sc	3.8	1.3	0.6	6.5	2.3	4.5	~~2.1~~	3.8	~~5.1~~	4.8	4.3	5.1	1.4	6.8
V	21	11.1	10.1	247	11.2	34.3	~~13.5~~	22	~~41.5~~	30.3	26.2	31	8.6	38.6
Co	130.2	108.8	125.5		110.8	95.3	~~136.6~~	93.9	~~50.6~~	159.3	75.8	80.1	98.4	89.3
Ce	46	2	9	71	44	63	~~36~~	52	~~143~~	54	45	92	11	84
Nd	15	3	3	27	23	18	~~13~~	23	~~65~~	24	17	41	5	37
La	29	2	8	33	25	23	~~22~~	27	~~70~~	33	30	47	10	54
Cr	3	2	2	2	1	5	~~1~~	3	~~21~~	3	2	5	2	7

	1004-19	1004-30	1004-31	1004-41	1004-25	1004-44	1004-13	1004-27	1004-42	1004-14	1004-46	1004-4
	x	x	x	x	inter	inter	mafic	mafic	mafic	mafic	mafic	PG g2
SiO2	69.09	74.87	71.92	70.13	60.3	49.11	49.01	72.02	49.18	48.57	69.8	75.69
Al2O3	14.11	13.94	14.07	14.39	13.63	14.39	13.49	14.05	12.96	13.2	13.38	12.84
Fe2O3	4.63	1.21	3.29	4.1	8.13	12.72	15.05	3.09	16.08	13.86	4.94	1.15
MnO	0.04	0.01	0.02	0.03	0.14	0.2	0.27	0.02	0.23	0.14	0.06	0.01
MgO	1.52	0.22	0.99	1.05	4.09	7.72	6.27	0.93	5.5	5.74	1.24	0.21
CaO	3.05	1.58	2.06	2.91	6.78	10.61	7.03	1.91	7.3	7.59	3.06	0.76
Na2O	4.98	3.97	4.69	5.11	3.51	2.83	1.02	4.59	1.84	1.95	3.41	3.21
K2O	1.12	3.57	2.58	1.17	1.64	0.8	2.34	2.8	1.29	1.33	2.82	4.79
TiO2	0.73	0.11	0.44	0.71	1.15	1.12	2.64	0.48	3.05	2.12	0.77	0.21
P2O5	0.14	0.02	0.1	0.16	0.16	0.04	0.33	0.11	0.39	0.23	0.15	0.02
SO3	0	0	0	0	0	0	0.03	0	0	0.02	0	0
LOI	0.38	0.39	0.2	0.33	0.48	0.66	2.19	0.24	1.63	5.02	0.46	0.44
Total	99.79	99.88	100.38	100.09	100.01	100.21	99.68	100.23	99.46	99.78	100.08	99.32
Y	38.5	29.4	28	50	78.5	35.9	53	6.4	60.6	45.1	52	13.9
Sr	111.1	102.4	105.6	111.9	113.5	112.7	137.4	143.3	162	136.4	101.5	49.6
Rb	92.7	130.7	121.1	74.8	47.2	15.5	118.8	107.7	56.6	59.6	120	146.1
Nb	21.3	19.7	16.7	23.2	11.1	7	11.6	3.1	13.3	7.5	16.5	15.2
Zr	195.3	181.5	183.6	291.1	204.8	87.4	208.6	44.8	245.2	127.3	248.6	122
Th	14.3	11.6	19.5	27.9	16.9	3	1.2	9.9	4.7	2.3	28	28
Pb	1.9	3.6	9.2	1.2	13.7	5.1	0	5.5	0	3.6	5.5	2.7
U	5.8	2.9	5.3	6.8	3.6	3.2	1.1	0.1	0	2.1	3	9
Ga	24.7	23	24.4	25.3	21.1	22.6	24.4	20.6	25.8	21.9	20.3	17.5
Cu	29	10	11	10	40	11	1	10	65	21	37	13
Zn	18	15	13	16	67	72	57	15	94	41	39	10
Ni	1	8	9	1	47	78	74	4	55	93	4	7
Ba	51	181	188	77	324	94	1778	745	955	745	432	285
Sc	10.3	6.3	9	6.8	24	46.3	44	1.7	44.6	41.7	11.7	2.9
V	75.2	44.5	43.5	69.6	199.4	337.8	417.9	16.1	464.2	330.7	74.3	16.7
Co	174.6	144.2	60.4	187.6	85.4	57.4	76.2	86.5	81.7	70.6	136.1	96.9
Ce	62	59	46	71	58	26	41	10	58	24	99	48
Nd	21	17	17	26	28	11	23	7	23	13	48	20
La	36	33	29	36	34	8	8	5	18	3	49	25
Cr	11	8	8	5	141	240	109		71	147	12	3

	1004-2	1004-5	1004-6	1004-33	1004-38	1004-39
	PG g2	PG g2	PG g2	PG g2	PG g2	PG g2
	73.42	72.46	73.53	74.36	75.24	72.13
	13.77	13.67	13.32	13.19	12.87	13.68
	2.4	2.93	2.38	2.15	1.79	2.49
	0.01	0.02	0.01	0.01	0.01	0.01
	0.63	0.79	0.58	0.51	0.43	0.6
	1.76	2.07	1.51	1.48	1.15	1.62
	3.94	3.83	3.86	3.44	3.27	3.88
	3.55	3.53	4.01	4.32	4.45	3.59
	0.38	0.46	0.37	0.34	0.29	0.4
	0.08	0.09	0.07	0.06	0.06	0.08
	0	0	0	0	0	0
	0.2	0.21	0.2	0.22	0.25	0.32
	100.17	100.07	99.85	100.07	99.82	98.8
Y	70.4	47.5	33	32.8	27.5	35.5
Sr	71.9	87.4	95.6	73.5	64.4	86.2
Rb	122.9	121.9	145.8	156.6	164.9	160.2
Nb	21.4	18.3	15.3	14.4	15.5	18.2
Zr	206.9	219.9	181.6	183.1	161.7	239.4
Th	27.9	22.9	29.2	21.6	32.8	17.4
Pb	1.5	3.9	2.4	2.9	2	3
U	4.5	2.2	5.6	3.9	5.5	5.1
Ga	18.1	19.6	20	19.7	19.6	19.9
Cu	10	14	8	10	14	19
Zn	12	16	12	12	13	14
Ni	6	10	9	6	5	6
Ba	268	305	306	309	224	292
Sc	5.6	5.1	5	4.5	4.3	5.4
V	36.4	42.7	33.4	30.9	28.2	38
Co	82	83.4	87.5	72.6	79.1	73
Ce	65	65	51	49	47	67
Nd	37	30	21	22	17	30
La	27	38	27	29	18	32
Cr	5	11	4	3	3	3

	1004-25	1004-46	1004-44	1004-14	1004-13	1004-42	1004-19	1004-30	1004-31
	intermediate	intermediate	mafic	mafic	mafic	mafic	xenolith	xenolith	xenolith
AP	0.37	0.35	0.09	0.54	0.77	0.91	0.33	0.05	0.23
IL	2.19	1.47	2.13	4.04	5.03	5.8	1.39	0.21	0.84
MT	2.76	1.7	4.36	4.79	5.23	5.52	1.6	0.42	1.15
OR	9.68	16.65	4.72	7.85	13.83	7.62	6.61	21.08	15.24
AB	29.69	28.84	23.93	16.49	8.63	15.56	42.12	33.58	39.67
AN	16.59	12.87	24.18	23.33	25.32	23.29	12.84	7.71	9.56
DI	13.02	1.1	22.98	10.47	6.04	8.5	1.13	0	0
HY	9.64	5.84	7.18	18.44	22.34	19.39	6.32	1.47	4.74
C	0	0	0	0	0	0	0	0.72	0.06
OL	0	0	7.96	0	0	0	0	0	0
Q	14.26	29.99	0	6.51	7.83	8.55	26.34	34.07	28.14
total	98.2	98.82	97.42	92.47	95	95.14	98.68	99.3	99.63
D.I.	53.63	75.48	28.65	30.85	30.29	31.73	75.07	88.73	83.05

	1004-41	1004-3	1004-7	1004-17	1004-16	1004-21	1004-33	1004-35	1004-4
	xenolith	PG group2	PG group2	PG group2	PG group2	PG group2	PG group2	PG group2	PG group2
AP	0.37	0.02	0.02	0.02	0.14	0.02	0.14	0.07	0.05
IL	1.35	0.32	0.19	0.32	0.74	0.21	0.65	0.48	0.4
MT	1.42	0.31	0.19	0.36	0.93	0.21	0.73	0.58	0.44
OR	6.91	27.34	40.16	26.45	25.22	37.43	25.39	25.39	20.85
AB	43.22	26.81	19.88	24.61	28.76	22.47	28.76	31.21	32.4
AN	12.87	2.76	1.72	2.66	2.48	1.45	7.05	4.81	9.68
DI	0.43	0	0	0	0	0	0	0	0
HY	5.06	0.83	0.67	0.99	2.7	0.74	2.67	1.85	2.28
C	0	0.75	0.49	1.24	1.81	0.89	0.36	0.68	0
OL	0	0	0	0	0	0	0	0	0
Q	27.5	40.36	35.44	42.24	36.2	36.5	33.71	34.4	31.2
total	99.14	99.71	98.77	98.91	98.98	100	99.46	99.48	97.92
D.I.	77.63	94.51	95.48	93.3	90.18	96.4	87.86	91	84.45

	1004-15 PG interm.	1004-1 PG group1	1004-2 PG group1	1004-5 PG group1	1004-6 PG group1	1004-34 PG group1	1004-36 PG group1	1004-37 PG group1	1004-38 PG group1
AP	0.3	0.19	0.19	0.21	0.16	0.14	0.12	0.14	0.44
IL	1.05	0.86	0.72	0.88	0.7	0.59	0.53	0.7	0.55
MT	0.73	0.76	0.83	0.44	0.87	0.73	0.58	0.87	0.61
OR	19.55	23.33	20.97	20.85	23.62	23.15	22.8	22.74	26.28
AB	30.87	30.71	33.33	32.4	32.99	30.03	31.97	30.11	27.66
AN	6.09	8.05	8.21	9.68	6.98	6.55	6.72	7.05	5.31
DI	0	1.23	0	0	0	0	0	0	0
HY	1.99	2.27	3.06	2.28	2.97	2.47	2.31	2.95	2.28
C	0.77	0	0	0	0.01	0.51	0.4	0.37	0.73
OL	0	0	0	0	0	0	0	0	0
Q	36.72	31.26	31.78	31.2	30.98	35.08	33.36	34.44	35.73
total	98.07	99.64	99.51	97.92	99.3	99.24	98.79	99.37	99.29
D.I.	87.14	85.3	86.08	84.45	87.59	88.26	88.13	87.29	89.67

	1004-23 PG group1	1004-32 PG group1	1004-39 PG group1
AP	0.12	0.09	0.19
IL	0.11	0.46	0.76
MT	0.1	1.1	0.86
OR	32.88	26.1	21.2
AB	25.88	29.1	32.82
AN	2.45	5.89	7.51
DI	0	0	0
HY	0.32	1.62	3.1
C	0.77	0.47	0.66
OL	0	0	0
Q	37.1	35.19	30.9
total	99.7	100.2	98.07
D.I.	95.86	90.39	84.92