CONTACT METAMORPHISM AND GRANITIC EMPLACEMENT IN THE TAMWORTH AREA

DAVID HALES

1993

STATEMENT

All results and interpretations reported in this thesis are the original work of the author except where otherwise acknowledged. This work has not been submitted previously to this or any other university.

This thesis was done in partial requirement of the degree of BSc (Hons.).

David Hales

David Hales

MACQUARIE UNIVERSITY

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BSc Honours Thesis

DAVID HALES
MACQUARIE UNIVERSITY
1993

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ABSTRACT:

The Moonbi Adamellite is a Permo-Triassic 'I'-type pluton which has intruded into the upper crust in the New England Orogen, N.S.W. The wall rocks covered in this study make up part of the Tamworth Terrane. They consist of argillites, arenites, conglomerates and limestones. The limestones have been separated into autochthonous or allochthonous deposits. The mafic igneous rocks are considered to be intrusive. They include an as yet unrecognised intrusion: the Oaky Creek andesite, which is found to the north of the Tamworth area.

Contact metamorphism has been recognized within an aureole 3-4 kms wide. Rocks of the upper hornblende hornfels facies are found at the highest grades along the contact. The biotite isograd was seen as the boundary between the contact metamorphic rocks and the regional Tamworth Terrane. The regional geology in the Tamworth Terrane indicates a confining pressure of approximately 1 kbar at the time of emplacement of the adamellite. Prograde metamorphic assemblages indicate that the contact metamorphic fluids were water rich ($X_{CO_2}<0{\cdot}25$). The source of the fluids is from prograde reactions and from meteoric water. The precursor magma rose through the crust as a water under-saturated magma. The magma is considered to have absorbed fluids from the contact rocks through fractures and permeable units. The water is hypothesised to have been then released through pegmatite dykes as the magma crystallised.

A model of transport and emplacement of the Moonbi Adamellite involves a two-stage mechanism. Initial space was made through roof lifting along faults and fractures in the cold country rocks. Then as the rocks became hot and infiltrated by fluids they became susceptible to deformation as increasing magma joined the intrusion through a feeder dyke. This caused weak syn-intrusive deformation in the wall rocks.

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XP - crossed polars.

PPL - plane polarised light.

1·25 - base of plate is 12·0 mm long.

2·5 - base of plate is 4·0 mm long.

6·3 - base of plate is 1·75 mm long.

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1·1 INTRODUCTION;

The emplacement mechanisms for high-level plutons into areas such as the New England Orogen (NEO) are very poorly understood. Many studies of metamorphic aureoles surrounding such plutons have provided clues regarding possible emplacement mechanisms (Pitcher and Read 1963; Marsh 1982; Castro 1987; Paterson et al 1991). However, these studies show that each block of crust and each rising magma body is a unique system. Hence each pluton has a unique set of conditions under which it was be emplaced (Clements and Mawer 1992).

The aim of this study is to research the Moonbi Adamellite and it's surrounding contact metamorphic aureole. In doing this, the thesis presents an investigation into:

- the metamorphic petrology of the meta-igneous and meta-sedimentary rocks.
- the deformation within the aureole caused by the emplacement of the pluton.
- the origin, composition and significance of the metamorphic fluids.

as well as investigating:

- the nature of the sediments and mafic igneous rocks of the Tamworth area.
- the origin and environment of deposition.

The results of the petrological and geochemical research are used to define a model of transport and emplacement of the Moonbi Adamellite. As well as this. contact metamorphic zones are suggested on the basis of mineralogy.

The Moonbi Adamellite is a large Permo-Triassic 'I'-type pluton (248 km^2) situated 5km north-east of the city of Tamworth (Chappell 1978) and 400km north of Sydney (figs.1 and 2). The field area is situated in the south-western corner of the intrusion covering about 120 km^2, and is bound to the north by Oaky Creek and follows the contact of the intrusion south to the Peel Fault (fig. 2). Previous studies of contact metamorphism in the NEO have concentrated on the sediments east of the Peel Fault. This study investigates contact metamorphism of the fore-arc sediments from the Tamworth Terrane.

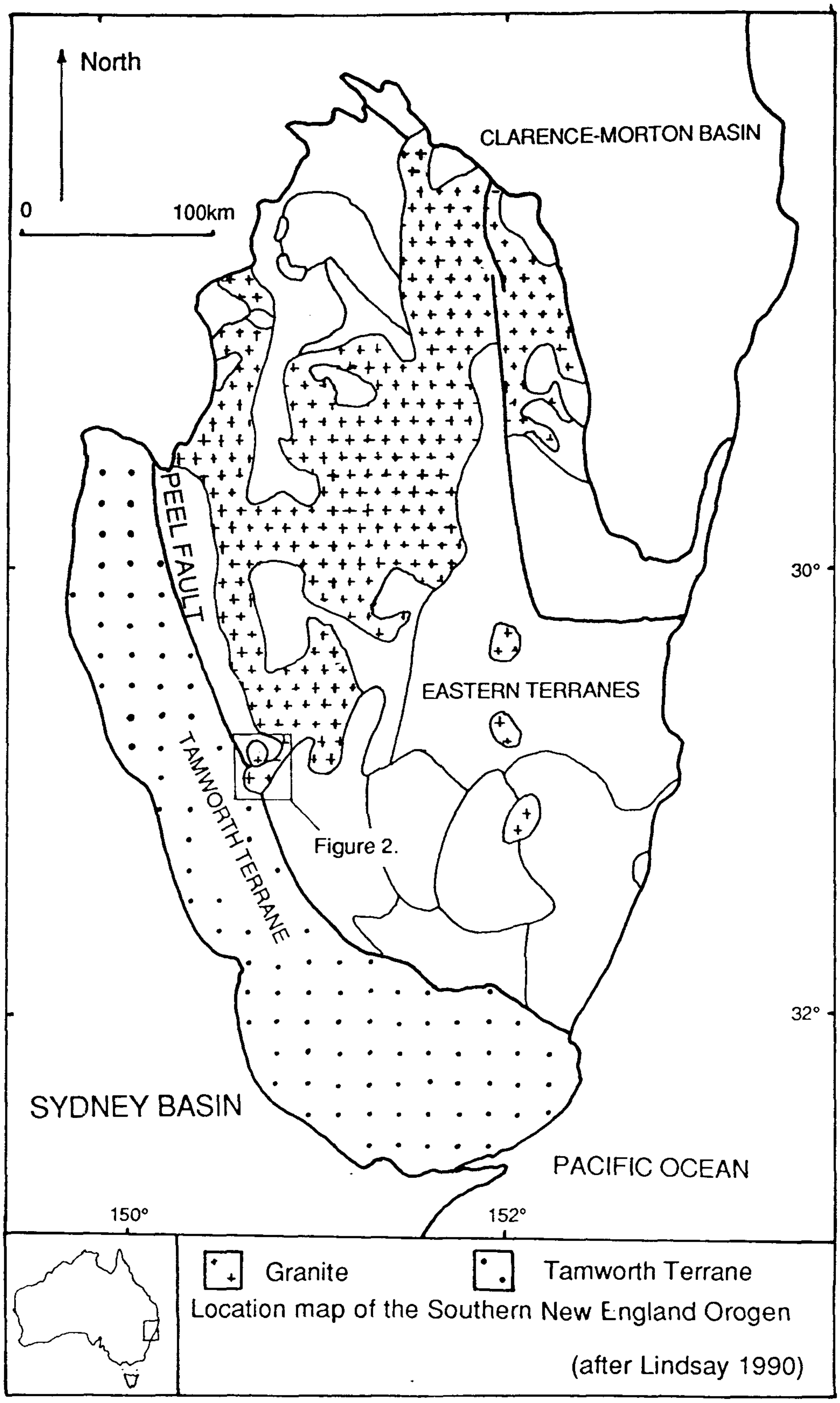

North
0
100km
CLARENCE-MORTON BASIN
PEEL FAULT
TAMWORTH TERRANE
EASTERN TERRANES
Figure 2.
30°
32°
SYDNEY BASIN
PACIFIC OCEAN
150°
152°
Granite
Tamworth Terrane
Location map of the Southern New England Orogen
(after Lindsay 1990)

Figure 1.

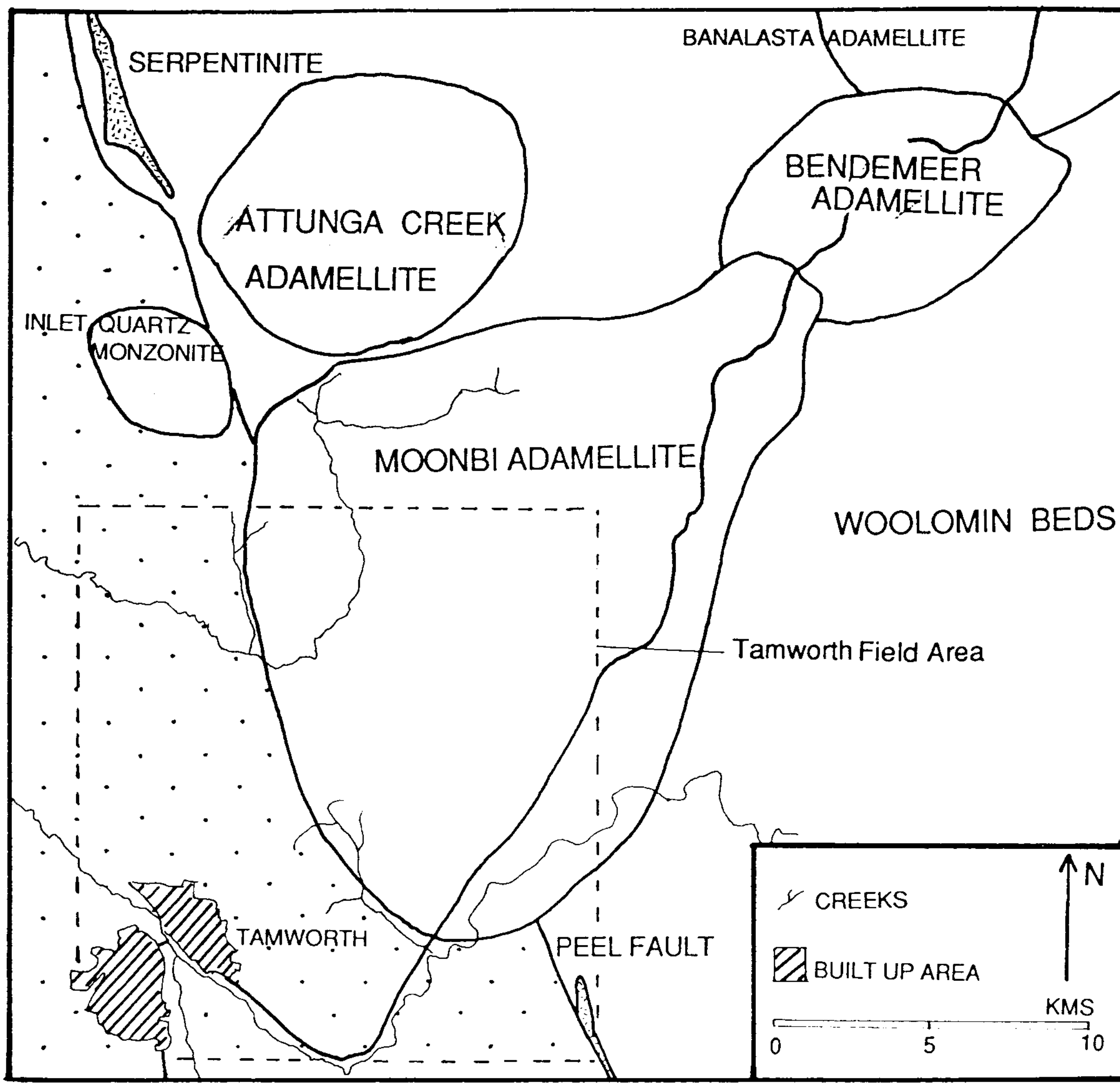


Figure 2. Tamworth field area, showing neighbouring plutons of the Moonbi district (after Chappell 1978)

The geology of the field area has been covered extensively by Benson (1915) and Crook (1960-61) who discussed the stratigraphy and petrology of the Tamworth area. It is noted that Benson's comprehensive field observations were almost indisputable.

Analytical techniques:

Mapping for this study was completed using the Tamworth, Attunga and Moonbi 1:25 000 topographic sheets, 1:40 000 air photos and Benson's 1915 geological map of the Tamworth area. Approximately 200 samples were collected in the field for a lithological study. The samples have been referred in the text with the prefix 'Tw'. The location of each sample is given in the appendix by a grid reference from the 1:25 000 topographic map sheets.

From the samples collected in the field 87 thin sections and 3 polished sections were made. The thin sections were examined optically for microstructural and mineralogical changes in metamorphic grade. The three polished thin sections were examined using an electron microprobe located at Macquarie University. The object of the microprobe analysis was to:

- Confirm the existence of the mineral axinite.
- Compositional zoning in garnets from a calc-silicate.
- Variation in the composition of plagioclase through the aureole.

The raw data of these investigations are presented in the appendix.

1·2 REGIONAL GEOLOGY

The contact metamorphic rocks and the granitic plutons of the Tamworth area form part of the New England Orogen (NEO) in N.S.W. The geology of the region is in part the result of convergent plate motions during the Palaeozoic (Leitch 1974). Principal tectonic elements are shown in figure 1.

Initially Benson (1912-18) and Voisey (1959) used a geosyncline model to describe the NEO. Leitch (1974, 1975) adapted the NEO into a plate tectonic framework. The latest study used the terrane concept to account for the geological subdivisions (Cawood and Leitch 1985) and eleven tectonostratigraphic terranes have been delineated by Aitchison (1988) and Flood et al (1988).

The NEO is recognised as a series of 'blocks' or terranes bounded to the west by the Hunter-Mooki Thrust Zone. To the North it is covered by the younger Great Artesian Basin and Clarence-Moreton Basins. The Eastern boundary is unknown, as it lies below the sea. Nonetheless Leitch (1974) has speculated that it may be present under the Lord Howe Rise. Largest of all the terranes is the 'Gamilaroi' or Tamworth Terrane (Zone A of Leitch 1974), which is the focus of this study. The Tamworth Terrane is the most western terrane, bound in the east by the Peel Fault System and to the west by the Hunter-Mooki Thrust Zone. It has a different depositional setting, less regional deformation, and far fewer igneous intrusions than the eastern terrains of the NEO.

The tectonic developments that can be recognised in the NEO began in the Early Devonian with a volcanic arc in the west, a shelf fore-arc basin, a deep water accretionary wedge and presumably a subduction trench in the east (Roberts and Engel 1987). Erosion of the volcanic arc produced fore-arc sediments with components of volcanic origin (Leitch and Wills 1987; Cawood 1983; Morris 1988). Cawood (1983) used the chemical variations of pyroxene and amphibole in the sedimentary rocks to show the diversity of arc volcanism over time. Initially the eruptions were of andesitic and dacitic compositions. By the Early Devonian, the eruptions became more mafic, with extrusions of basalt and andesite, until the Carboniferous, where rhyolitic rocks were produced in addition to andesites and dacites (Morris 1988, Cawood 1983). The volcanic arc rocks are not exposed but covered by younger sedimentary basins. Hence, the variations in the volcanism have been identified by examining the amphibole and the clino-pyroxene grains found in the sediments from the fore-arc basin (Morris 1988, Cawood 1983).

The sediments in the fore-arc basin are characterised by mass flow breccias and conglomerates, arenites rich in volcanic material, banded silt stones, shales and limestones. The Lower Devonian Tamworth Group is the lowest recognisable unit deposited in the Tamworth Terrane (Crook 1961). No base to this sequence has yet been recognised (Crook 1961). Therefore deposition may have begun before the Lower Devonian rocks of the Tamworth Group. Fossil ages have been dated as far back as the Cambrian. However, these were obtained from a limestone clast within a conglomerate. This then can not therefore, truly relate to the timing of sedimentation (Leitch 1982).

Deposition continued in the Tamworth Terrane until the Lower Permian (Leitch 1974). However during the Carboniferous a change in the tectonic style lead to the sediments in the fore-arc basin to be regressive (Roberts and Engel 1987). Hence, during the Carboniferous terrestrial sediments were deposited in the west of the fore-arc basin.

The first significant orogenic events began in the Late Carboniferous (Roberts and Engel 1987; Leitch 1974). Folding in the Tamworth Terrane and injection of serpentinite into the Peel Fault System took place in the Early Permian, in conjunction with low-grade regional metamorphism (Leitch 1974). The Permian folding generated active sedimentary basins, and later uplift associated with the New England Batholith caused the detachment of the Carboniferous blocks (Roberts and Engel 1987).

The Peel Fault System is a series of fractures that separate two different geological provinces. Displacements along the fault appear to be approximately

400 km of strike-slip movement (Corbert 1971). A belt of serpentinite bodies can be found intermittently along the fault zone. Within the serpentinites are pods of ultramafic rocks. Voisey (1959) concluded that they were transported as cold bodies and not as melts, because contact metamorphic effects on the surrounding rocks are absent.

The first period of plutonism in the NEO occurred in the Upper Carboniferous with the emplacement of S-type granites followed by the I-type granites during the Upper Permian and Triassic (Shaw and Flood 1981). The I-type Moonbi suite, of concern in this study, is the only granite found west of the Peel Fault System. All other granites can only be found in the eastern terranes. Shaw and Flood (1981) produced a comprehensive work on the granites of the NEO and concluded that the melts were produced by crustal thickening due to the trench complex being over thrusted during the Permian. Chappell (1978) and Kleeman (1988) suggested that the melts, especially the I-types, formed in the lower crust, after a major influx of heat from the mantle triggered melting. These melts were then emplaced higher up in the crust, causing contact metamorphism and local deformation of the country rocks. This latter aspect of the granitic emplacement will be addressed in the following chapters.

Chapter 2. GEOLOGY OF THE TAMWORTH AREA;

The geology of the area covered by this thesis comprises mafic igneous, sedimentary and granitic rocks. The mafic igneous and sedimentary rocks are considered in this chapter, while the granitic rocks are discussed in chapter 5.

2·1 SEDIMENTS:

The stratigraphy and petrology of the Tamworth area has been described by Benson (1915b) and Crook (1961). The purpose of this study is to examine the sedimentary textures; mode of deposition of the sediments (e.g., Bouma sequences); with special attention paid to the limestones. The localised structures in the sediments, resulting from the emplacement of the pluton will also be examined.

The sediments in the field area (the Tamworth area), belong to the Tamworth Group and the Parry Group (Crook 1961). The Pipeclay Creek, Drik-Drik, Silver Gully, Yarrimie, and Seven Mile Formations are all part of from the Tamworth Group. This study found that these formations are characterised by radiolarian argillites, siltstones, arenites and rudites, with coralline limestones. Material in the coarse grained sediments includes sedimentary clasts including limestone clasts (plate 18) and igneous clasts from the arc (plate 19). The Baldwin Formation, the lowest unit of the Parry Group, is essentially a conglomerate.

2·1·2 Sedimentary Textures, the Bouma Sequence and the Mode of Formation

This study suggests that the Lower to Middle Devonian sediments in the Tamworth area resemble deposits from large subaqueous mass-flows, like those described by Cas (1978; 1979; 1983) from the Lachlan Fold Belt. Examples in the field showed the bases and tops of sedimentary units being sharp or gradational. Sharp contacts were either planar or irregular and often included scouring of the lower layers (plate 1). The gradational boundaries occurred between breccia and

Plate 1. An abrasive surface at the base of a massive arenite. Railway cutting, (Gr: Tam, 083 552)

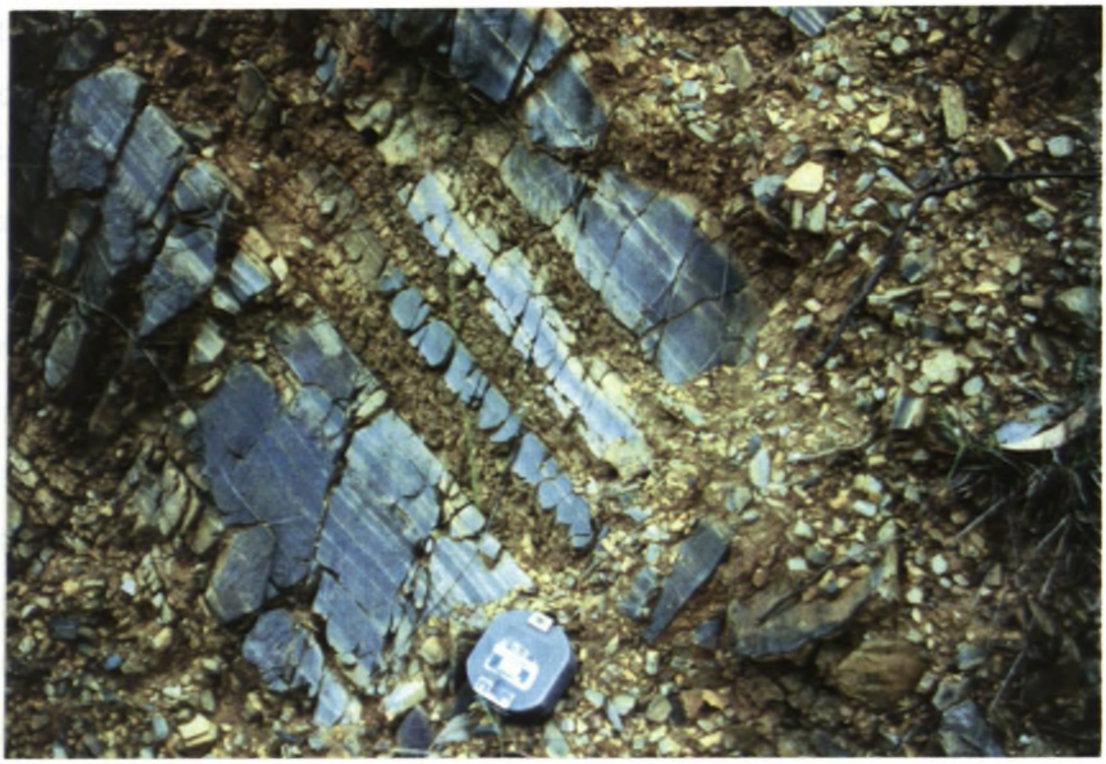


Plate 2. Laminated argillite. (Gr: Tam, 072 549)

arenite, or arenite and argillite. These features characterise the complete Bouma sequence presented in fig.3. which was observed in the Tamworth group.

Sedimentary sequences, such as those found in the Tamworth area, were described by Bouma (1962). He recognised five divisions within his complete sequence but, as suggested by Cas (1979), the divisions are not always complete and anomalies can be noted when analysing a sedimentary sequence with respect to the Bouma sequence.

Grading textures, grain size and sedimentary structures can be used to determine the mode of emplacement using Bouma's model. Deposition of the units largely took place under upper flow-regime conditions from non-viscous mass-flows (zone a). The laminated argillites (plate 2) on the other hand were deposited under much lower flow regimes (zones d-e). The finely laminated material shows the best examples of graded bedding and way-up structures. Some evidence of traction flow occurs in the thin laminated units (zone b-c) but, in general cross-bedding is rare.

Results of this study concludes that the deposition sequence was at first rapid, usually before the lower unit was consolidated, thus forming small unconformities. The currents would have had high sediment concentrations as demonstrated by the massive nature of the arenites. The currents commonly destroyed the lower layers, causing rip-ups (fig. 4) and internal shearing. The laminated argillites are considered to form as the result of currents slowing. Deposition of the argillites appears to occur in pulses. Grain size appears to be dependent on the sediment supply and current flow. The sequences are indicative of turbidity flows. However it is difficult to determine water depth from these sediments. Depth of deposition was probably below storm wave base due to the rarity of traction current structures.

The previous descriptions of the Tamworth Group have not included a complete Bouma sequence. However Crook (1960) concluded that the Tamworth Group is dominantly of deep water origin. The sedimentary textures in the Tamworth area were originally described by Benson (1915b, p. 567 and 570). He suggested that the textures were indicative of pyroclastic rocks from an igneous zone. The concept

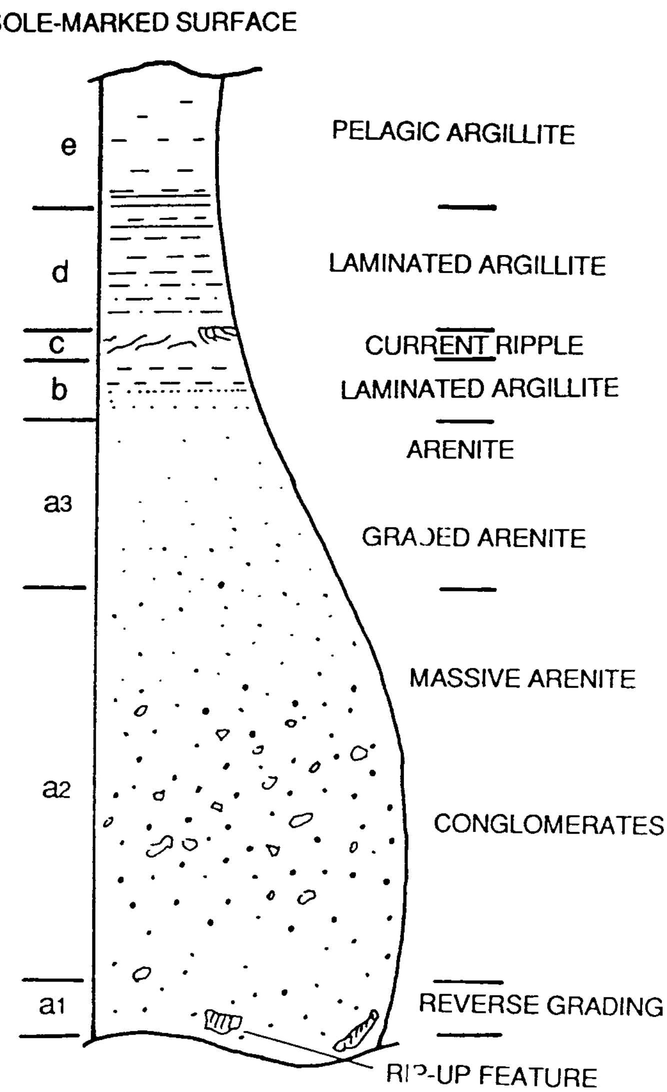


Figure 3 BOUMA SEQUENCE OBSERVED IN THE TAMWORTH GROUP

Scale?

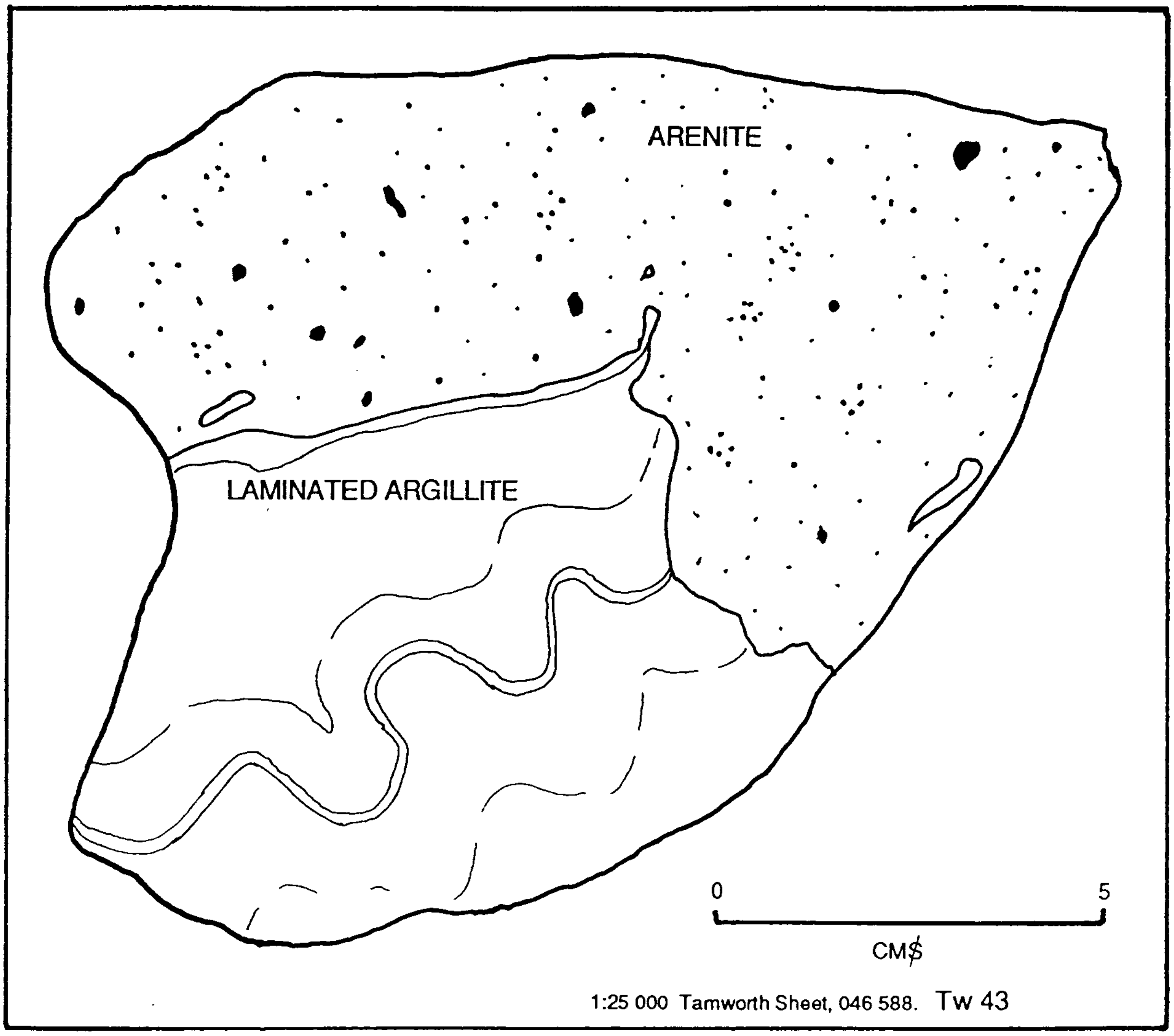

ARENITE
LAMINATED ARGILLITE
0
5
CMS
1:25 000 Tamworth Sheet, 046 588. Tw 43

Figure 4.

of an igneous zone was dropped in favour of a model of a cold state of deposition through mass flow deposits of a sedimentary origin (Benson 1918).

2·1·3 The Limestones:

This study has divided the limestones in the Tamworth area (fig.5.) into two types: (1) isolated lenses of limestone, such as the Nemingha Limestone and, (2) large or coherent units, such as the Moore Creek. The first type of limestone is found as a series of bodies that lie along the regional trend. Field observations suggest that this type of limestone is associated with a mass flow rudites, conglomerates or breccias. The lenses of limestone are formed either large elongate blocks (<50m in length) or by conglomerates (plate 3.). This study concludes that this type of limestone is allochthonous. It suggested in this thesis that the limestone material is transported in channels to greater depths and deposited at the base of a slope.

The second type of limestone in the Tamworth area is thought to be in situ (autochthonous). Field observations suggest that they are always associated with the laminated argillites at the base. The bodies tend to be massive and more extensive than type (1). This group of limestones is very rich in fossils (plate 5), especially corals which appear to be of shallow marine origin. It is suggested that they are found at the top of a sedimentary sequence. Brecciation of the limestone was seen at the top of the Moore Creek Limestone, which is the most extensive limestone in the area. It is possible that the breccia is evidence of the limestones being broken up by latter mass flows.

The most important example of these two limestone types was seen in the Seven Mile Creek Limestone (fig 5.). In a recent road cut made for a power line a calc-silicate lens is interbedded within laminated argillite (plate 6). These rocks are very close to the contact of the Moonbi adamellite and have been extensively metamorphosed. The calc-silicate is made up of calcite-wollastonite-garnet, and is

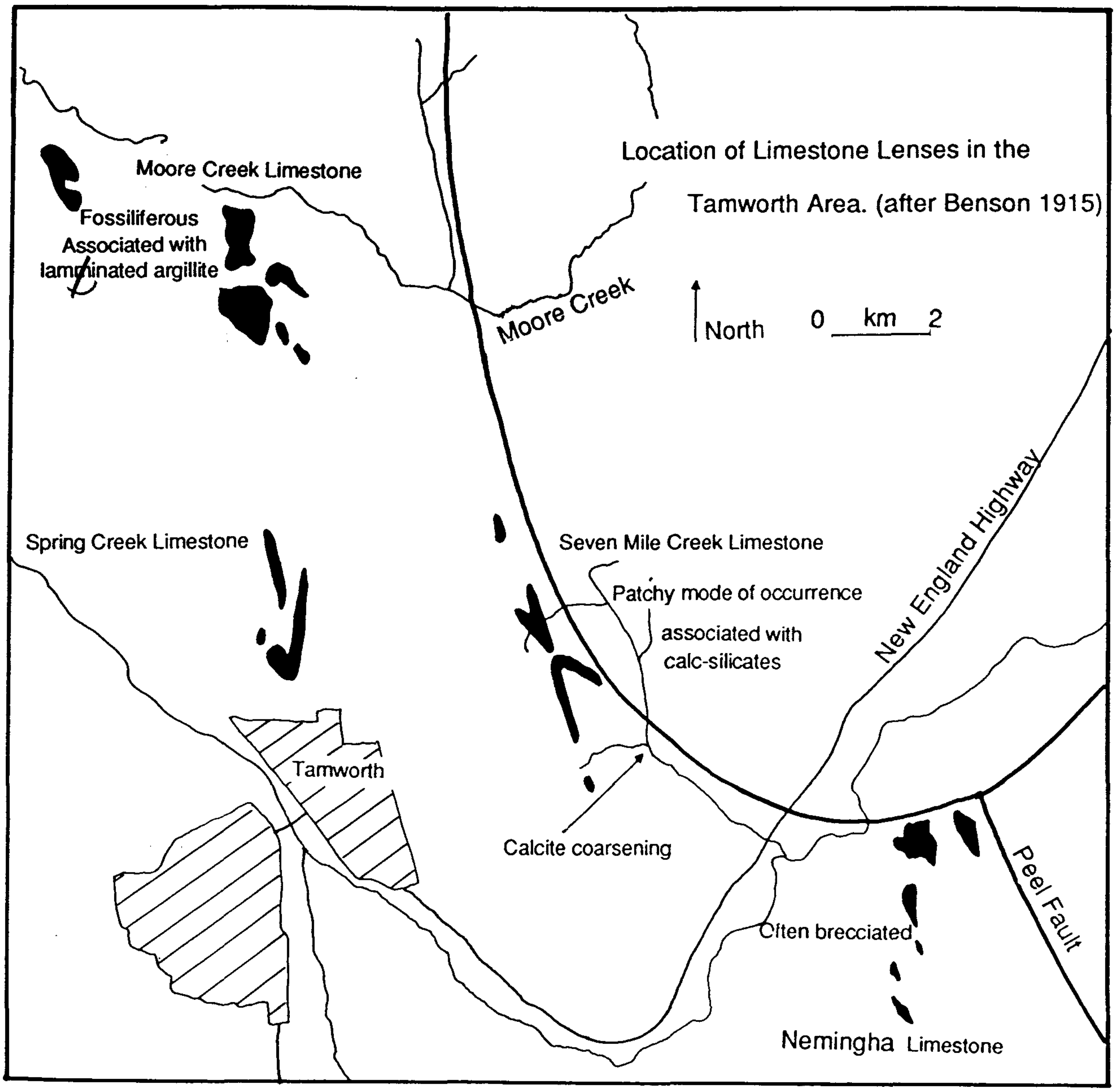

Location of Limestone Lenses in the
Tamworth Area. (after Benson 1915)
Moore Creek Limestone
Fossiliferous
Associated with
laminated argillite
Moore Creek
North
0 km 2
Spring Creek Limestone
Seven Mile Creek Limestone
Patchy mode of occurrence
associated with
calc-silicates
New England Highway
Tamworth
Calcite coarsening
Often brecciated
Peel Fault
Nemingha Limestone

Figure 5.

Plate 3. Conglomerate with clasts of marble. (Gr: Tam, 072 608)

Plate 4. The Moore Creek Limestone, rich in fossil material. (Gr: Tam, 023 667)

Plate 5. Brecciated Moore Creek Limestone. (Gr: Tam, 022 667)

Plate 6. Calc-silicate lense inter-bedded with laminated argillites, Seven Mile Creek. (Gr: Tam, 073 607)

suggested to represent an in situ limestone of type (2). Approximately 50 m north of this location, stratigraphically younging, a coarse conglomerate outcrops (e.g. Tw 90, 168, 169). Within this unit are clasts of volcanic material (plate 7) and a high concentration of limestone fragments, and possibly represent the type (1) transported limestones.

Previous studies on the limestones in the Tamworth area were completed by Aitchison (1988) and Crook (1960). Aitchison (1988) used radiolarians when dating the rocks of the Yarrimie Formation to conclude that shallow water limestones such as the Moore Creek Limestone are allochthonous. Aitchison found that the radiolarians in the Yarrimie Formation were younger than the massive limestone, Which lead him to conclude that the limestone was allochonous. This study found no sedimentary evidence suggesting that large limestone bodies such as the Moore Creek Limestone have been transported as a block.

Benson (1915b) and Crook (1960) reconsigned the graditional relationship between the laminated argillites and limestones. He concluded that the limestones were part of continuous deposition from argillite to limestone. This is the same as the type (2) limestones identified by this study. Crook (1960) suggested that the pod-like nature of the limestones was the result of differential compaction between the argillite and limestone material. Crook (1961) mentions the Seven Mile Creek Limestone as being cavernous in outcrop due to the solution of the limestone blocks. This thesis infers that this is the type (1) limestone, deposited as a result of mass flows incorporating limestone fragments and depositing them as lenses or clasts within a coarse conglomerate.

2·2 MAFIC IGNEOUS ROCKS

Two different mafic igneous rock suites have been identified in the Tamworth area. The first suite is found in the southern portion of the field area, east of Tintinhull, and consists of Middle to Lower Devonian dolerite and spilites, which were first recognised by Benson (1915a). A second rock suite is found in the

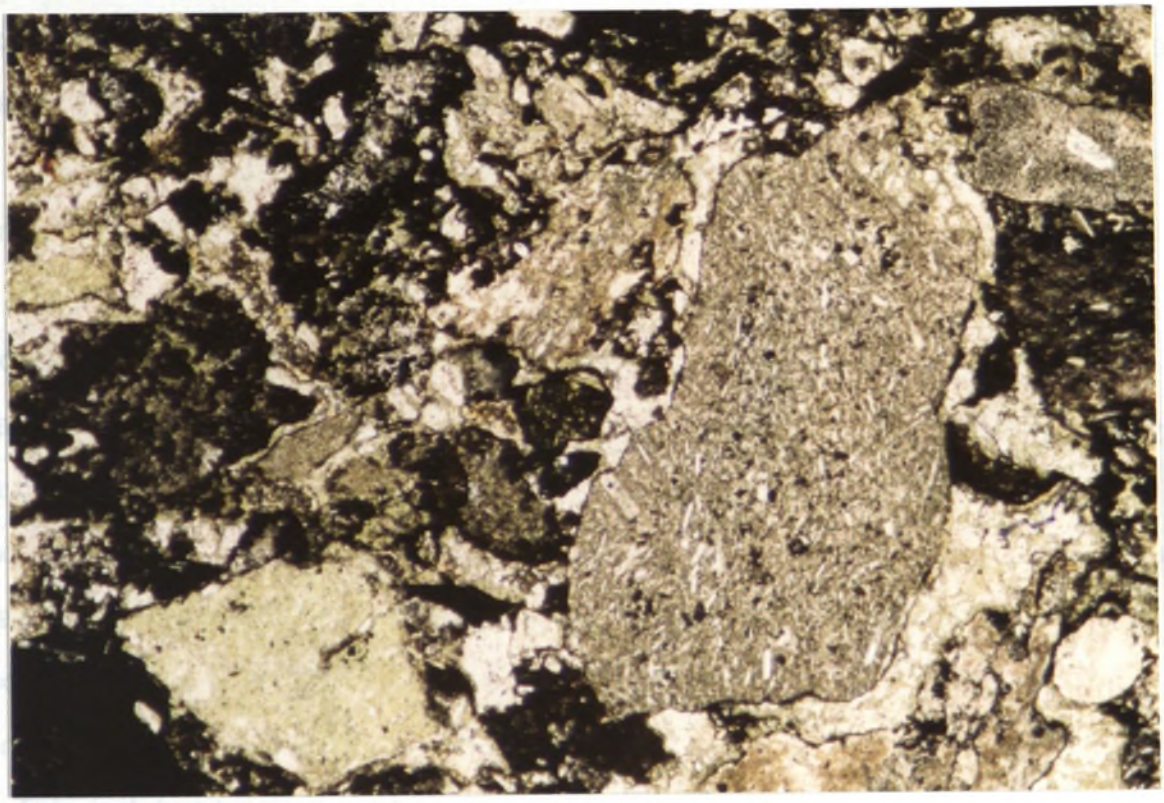


Plate 7. Tw 100. Clast of igneous material in a conglomerate. (PPL 2·5)

northern portion of the study area in Oaky Creek, and is described herein as an andesite. This rock type appears to be hitherto unreported. Figure 6 (plates 8, 9, 10 and 11) shows the distribution of mafic igneous rocks in the Tamworth area.

The Oaky Creek Andesite is located near Oaky Creek in the north of the Tamworth area (fig.7). Two thin (<10 m wide) bodies have been recognised in this study. The two bodies are different in their textures and chemistry and it is likely that they are unrelated.

The eastern body is characterised by large phenocrysts of plagioclase and amphibole, with some minor pyroxene. It was found between a laminated argillite to the east and massive hornfels to the west, and was inferred to be about 5-10 m wide and about 1 km long. However, outcrop was often obscured by the path of Oaky Creek. The body is close to the contact of the Moonbi Adamellite (<20 m) and has therefore been contact metamorphosed. However, the porphyritic igneous textures can still be seen in the rock. The phenocrysts of plagioclase are aligned. A measurement taken in the field showed that the alignment was parallel to the bedding in the neighbouring laminated argillite. The plagioclase phenocrysts commonly show oscillatory zoning.

This rock has been termed an andesite~~s~~, rather than basalt, due to the lack of olivine (or the products of olivine after contact metamorphism), low abundance of pyroxene and a groundmass rich in biotite, the product of metamorphism. No bulk rock chemistry was investigated on the andesite due to the metasomatic veining through the rock.

The second body found to the west of Oaky Creek is characterised by a purple-red colour in outcrop, caused by secondary haematite in the matrix. The rock has a glomeroporphyritic texture, where phenocrysts of plagioclase are bunched or clustered in aggregates (MacKenzie et al, 1982). The second body is finer-grained, with less amphibole and no pyroxene. The alignment of the phenocrysts is not as strong as the eastern body. This study suggests that the alignment is a response to deformation caused by the intrusion of the pluton, as discussed in Chapter 2·3.

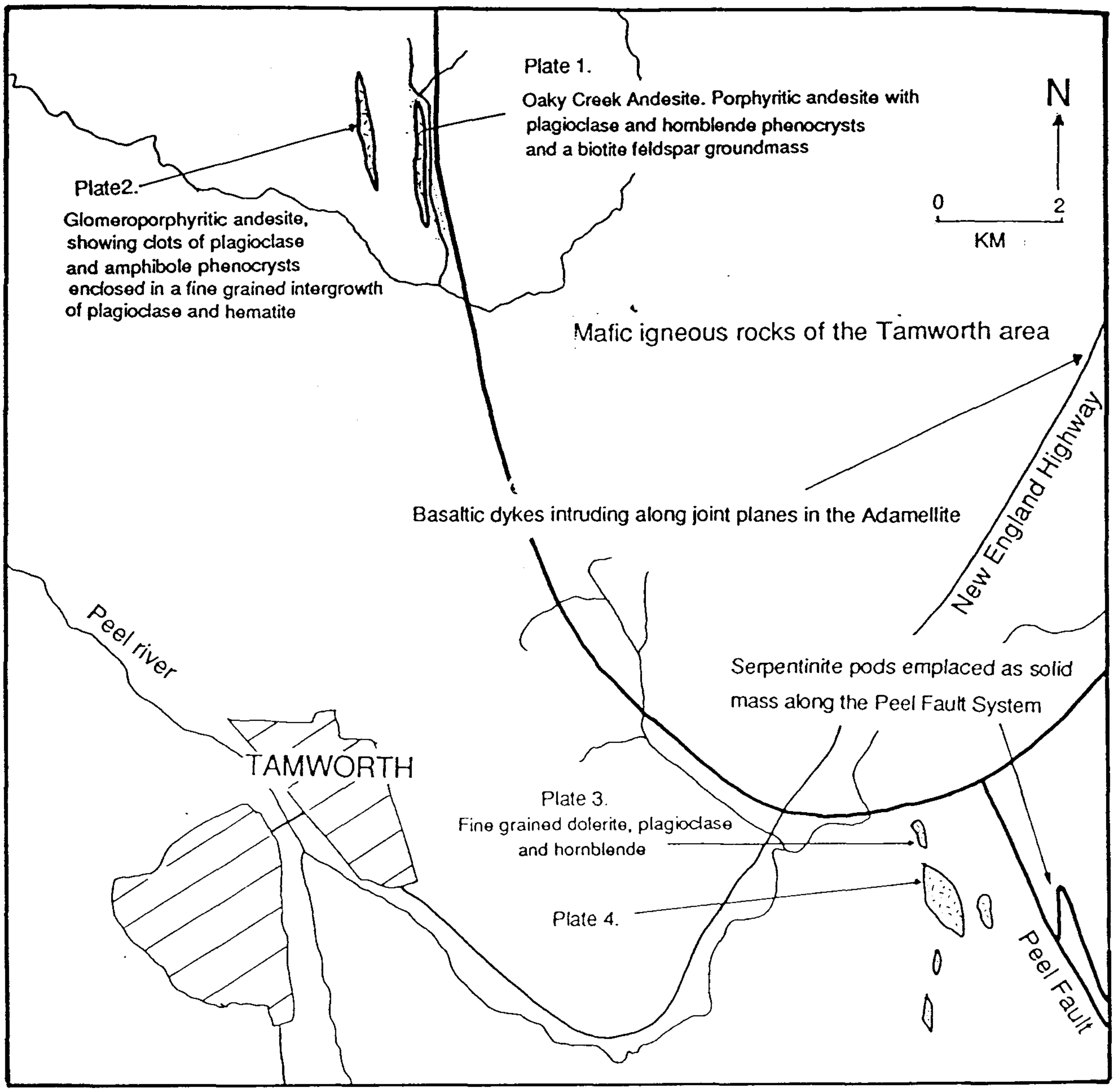


Plate 1.
Oaky Creek Andesite. Porphyritic andesite with plagioclase and hornblende phenocrysts and a biotite feldspar groundmass
N
0
2
KM
Plate2.
Glomeroporphyritic andesite, showing clots of plagioclase and amphibole phenocrysts enclosed in a fine grained intergrowth of plagioclase and hematite
Mafic igneous rocks of the Tamworth area
New England Highway
Basaltic dykes intruding along joint planes in the Adamellite
Peel river
Serpentinite pods emplaced as solid mass along the Peel Fault System
TAMWORTH
Plate 3.
Fine grained dolerite, plagioclase and hornblende
Plate 4.
Peel Fault

Figure 6.

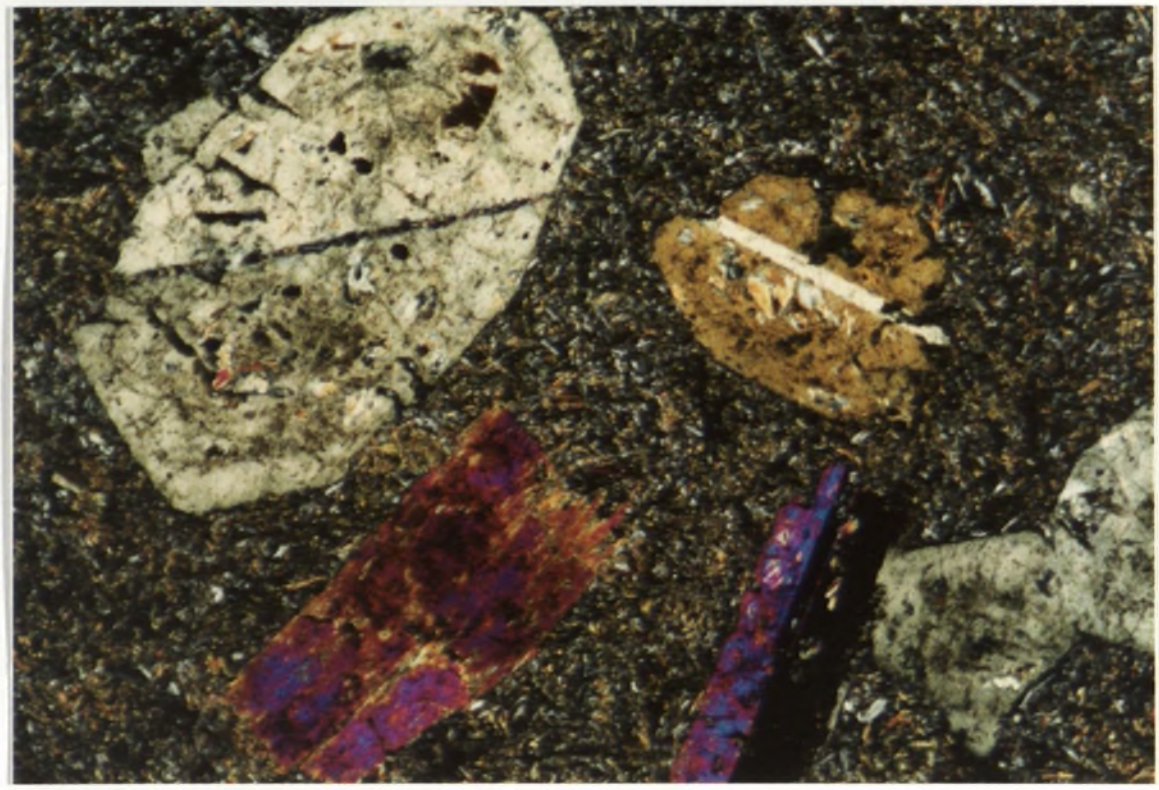


Plate 8. Tw 67. Oaky Creek Andesite, upper hornblende hornfels facies. Porphyritic igneous texture with phenocrysts of plagioclase and hornblende, and a groundmass of biotite and plagioclase. (XP 1·25)

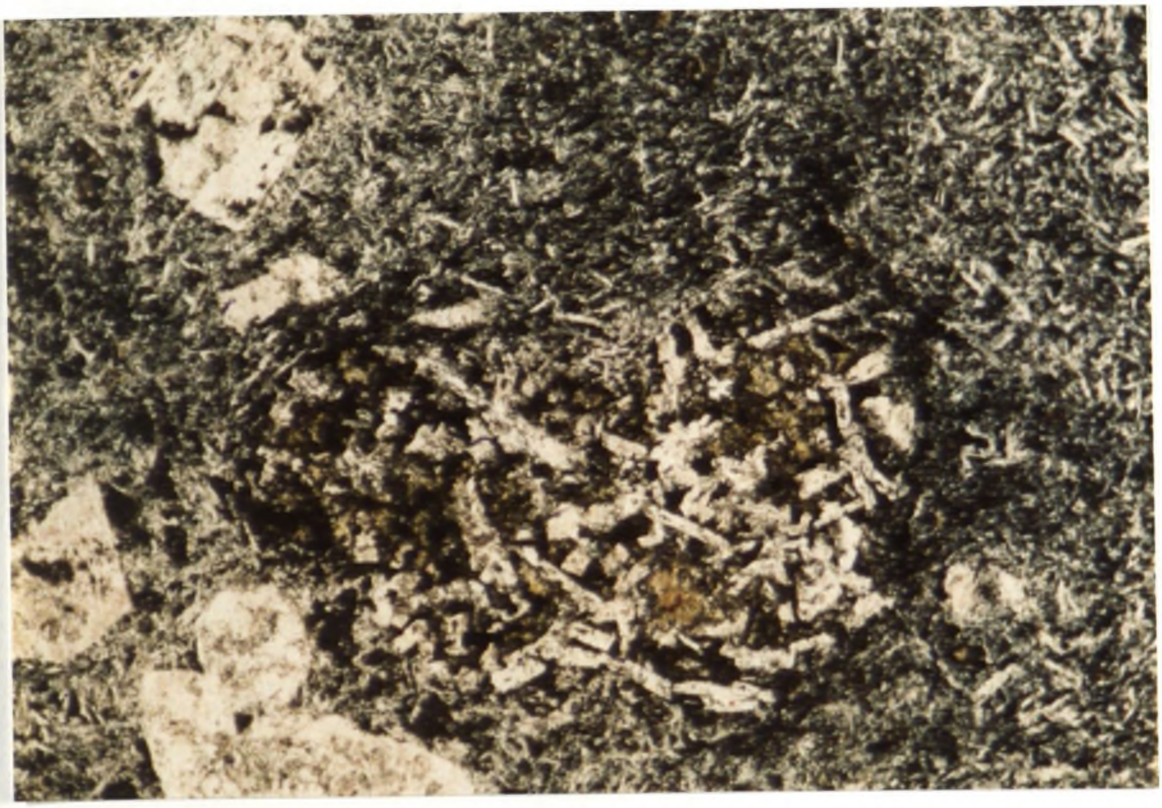


Plate 9. Tw 77 Oaky Creek Andesite (western intrusion). Finer grained than Tw 67 with a glomerophyritic texture. Mainly plagioclase phenocrysts with abundant opaque hematite in the groundmass. (PPL 1·25)

Plate 10. Tw 176. Dolerite from southern area. Green-brown hornblende and aligned plagioclase grains. (PPL 6·25)

Plate 11. Tw 147. Dolerite. Plagioclase grains do not show alignment as Tw 176. (PPL 1·25)

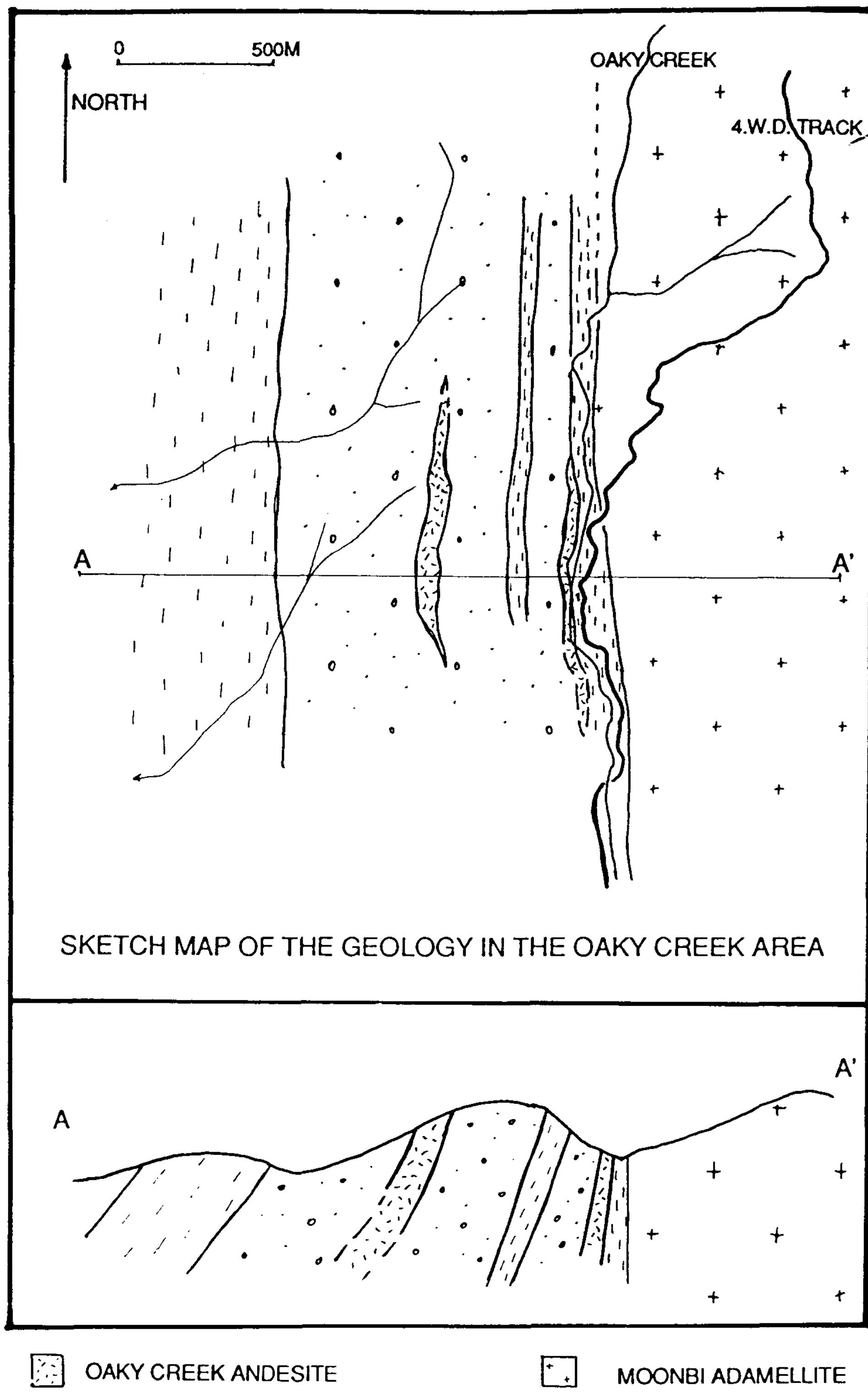

0
500M
NORTH
OAKY CREEK
4.W.D. TRACK
A
A'
SKETCH MAP OF THE GEOLOGY IN THE OAKY CREEK AREA
A
A'
OAKY CREEK ANDESITE
LAMINATED ARGILLITE
MOONBI ADAMELLITE
MASSIVE ARENITE

Figure 7.

There is no conclusive evidence to suggest whether either of the bodies were intrusive or extrusive. Contact relationships with the surrounding rocks were difficult to obtain, due to the lack of exposure. The only contact observed in the field was found in a loose block in Oaky Creek (Tw 99, fig.8, plates 12, 13 and 14). It shows a fine chilled margin between the andesite and a quartz rich hornfels. Only a small part of the country rock is represented in Tw 99. However, it is noted that it does resemble the laminated argillite which lies below the intrusion. Hence the chilled margin does not necessarily indicate that the andesite is intrusive. It is possible that the contact marks the base of a flow as the residual structures and compositional layering are parallel to the contact.

An example of a mafic dyke intruding into a laminated argillite has been recognised in sample Tw 75 (fig. 9, plates 15, 16 and 17). The relationship between this dyke and the larger bodies that make up the Oaky Creek Andesite is unknown. However the main minerals found in the dyke (amphibole and biotite) are similar to those seen in the andesite. The dyke is opened along a sinistral thrust, evidenced by two remaining slices of wall rock (fig. 6). A small thermal metamorphic imprint on the fine grained quartz-rich hornfels is indicated by a lighter coloured band along the contacts. A quartz vein (with some feldspar) has been deposited later, possibly by further opening along the fracture. It is assumed that the quartz came after the dyke due to the large numbers of biotite and amphibole inclusions within the large vein crystals. Though the dyke has no connection to the larger andesite bodies, its existence indicates that intrusion along fault planes has occurred.

The Oaky Creek Andesite appears to be similar to other mafic igneous rocks recently discovered in the Tamworth Terrane. The Browning Vale Andesite in the Yarramanbully district (McMinn 1977) and the Kingsmill's Peak Andesite (Cook and Dawson 1988) are two examples.

The Browning Vale Andesite is described as a series of flows interbedded with argillite and conglomerate. Five distinctive flows were recognised by McMinn

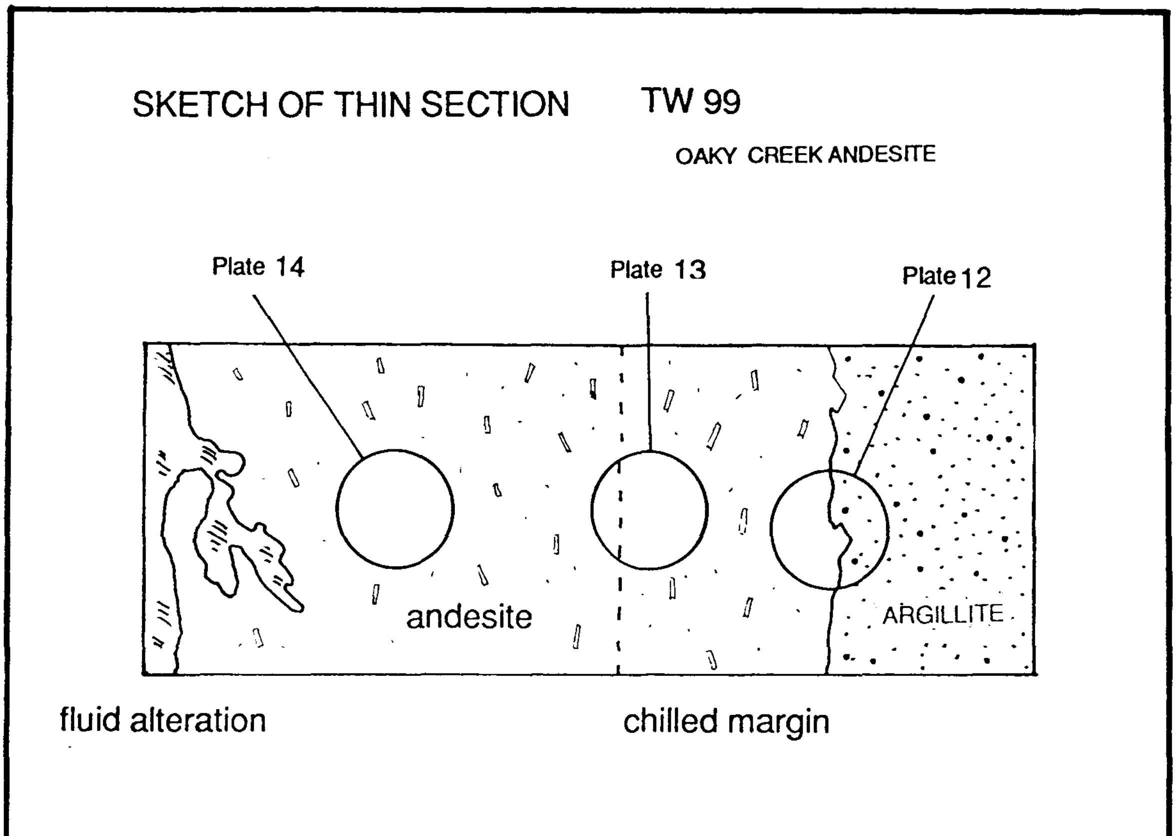

SKETCH OF THIN SECTION
TW 99
OAKY CREEK ANDESITE
Plate 14
Plate 13
Plate 12
andesite
ARGILLITE
fluid alteration
chilled margin

Figure 8.

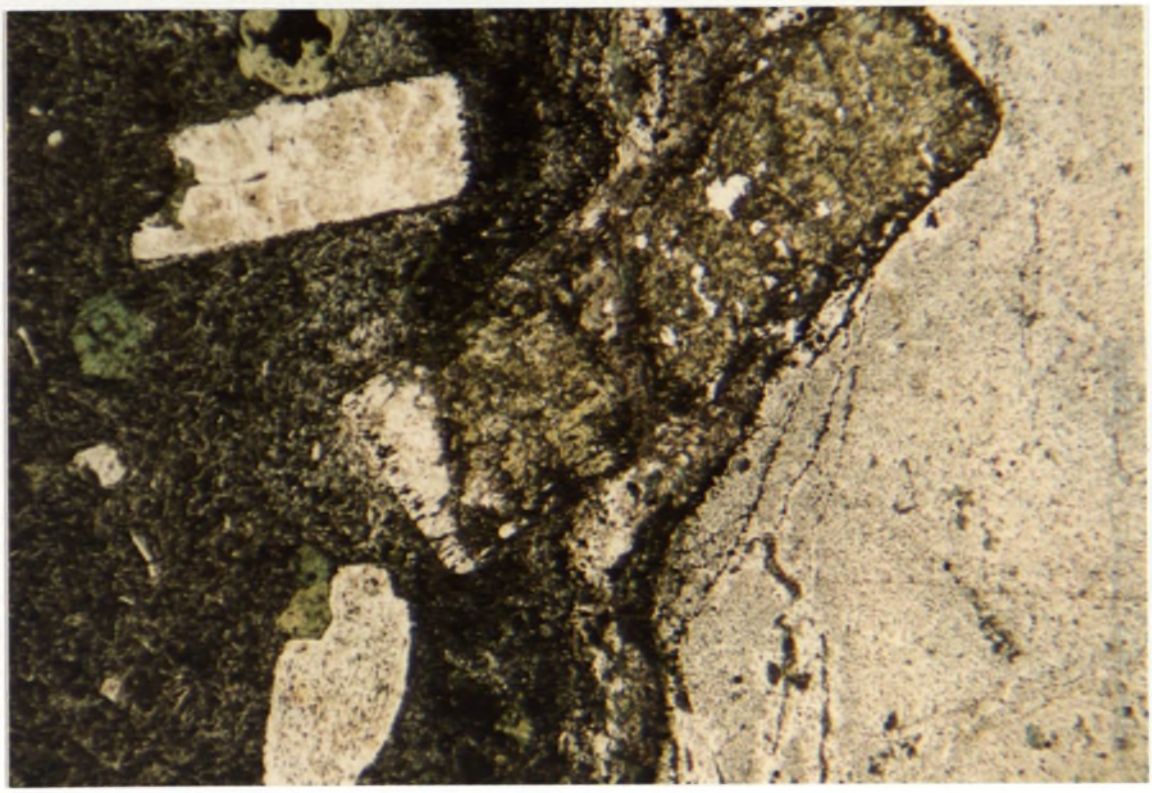


Plate 12. Tw 99. Porphyritic chilled margin between the Oaky Creek Andesite and a quartz rich argillite. The large plagioclase grain that intrudes into the country rock has been altered to epidote. (XP 1·25)

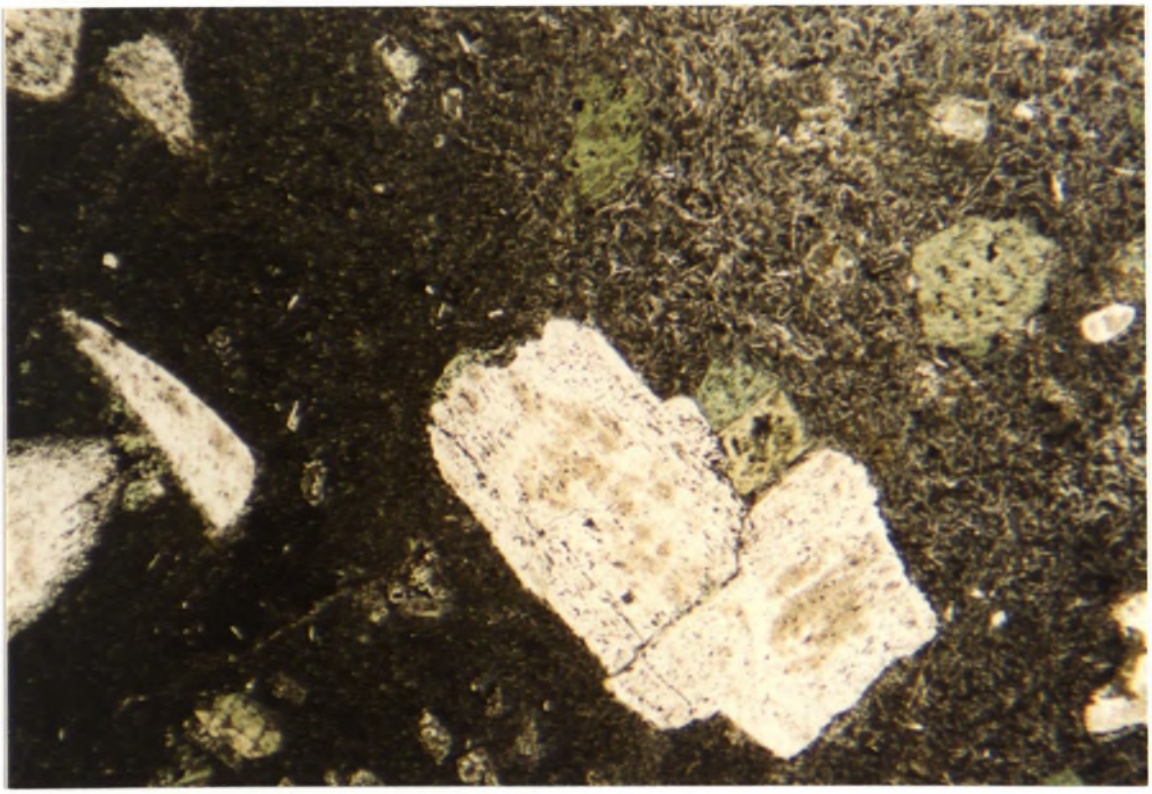


Plate 13. Tw 99. Ground mass varies from hematite poor to hematite rich. (XP 1·25)

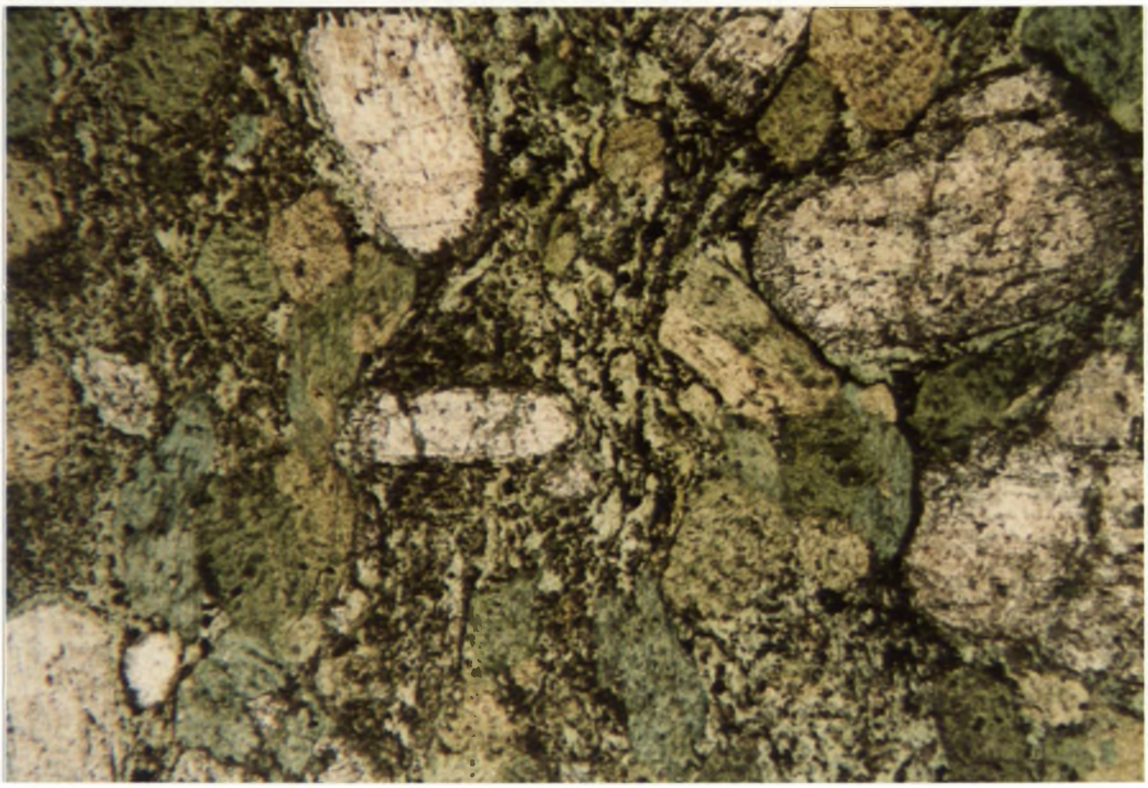


Plate 14. Tw 99. Groundmass becomes altered to epidote by influx of fluids moving through the rock. (XP 1·25)

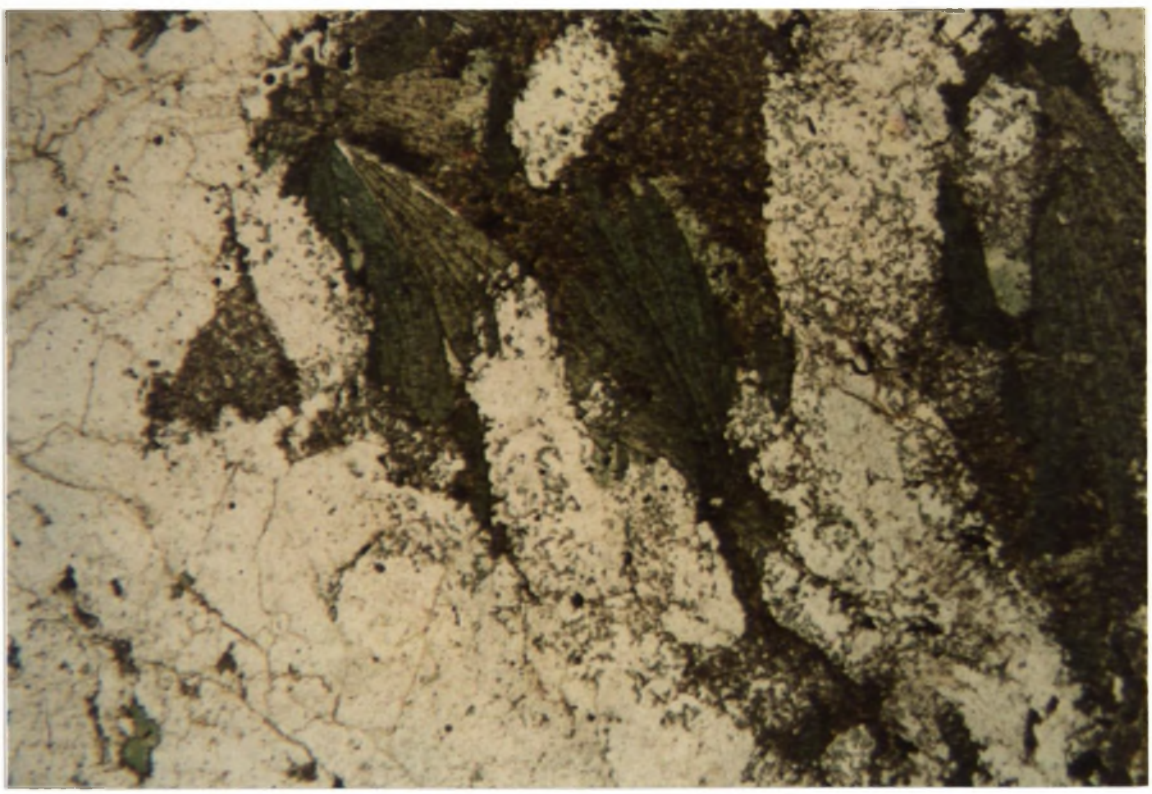


Plate 15. Tw 75. Radiating coarse grained amphibole and fine grained biotite characterise the mafic vein. (PPL 1 25)

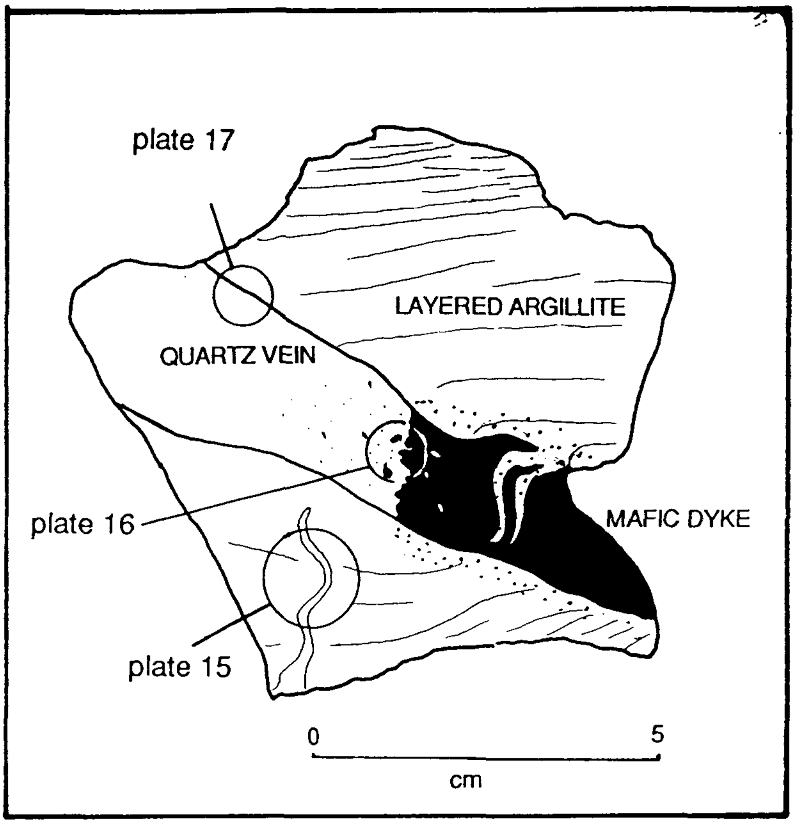


plate 17
LAYERED ARGILLITE
QUARTZ VEIN
plate 16
MAFIC DYKE
plate 15
0
5
cm

Figure 9.

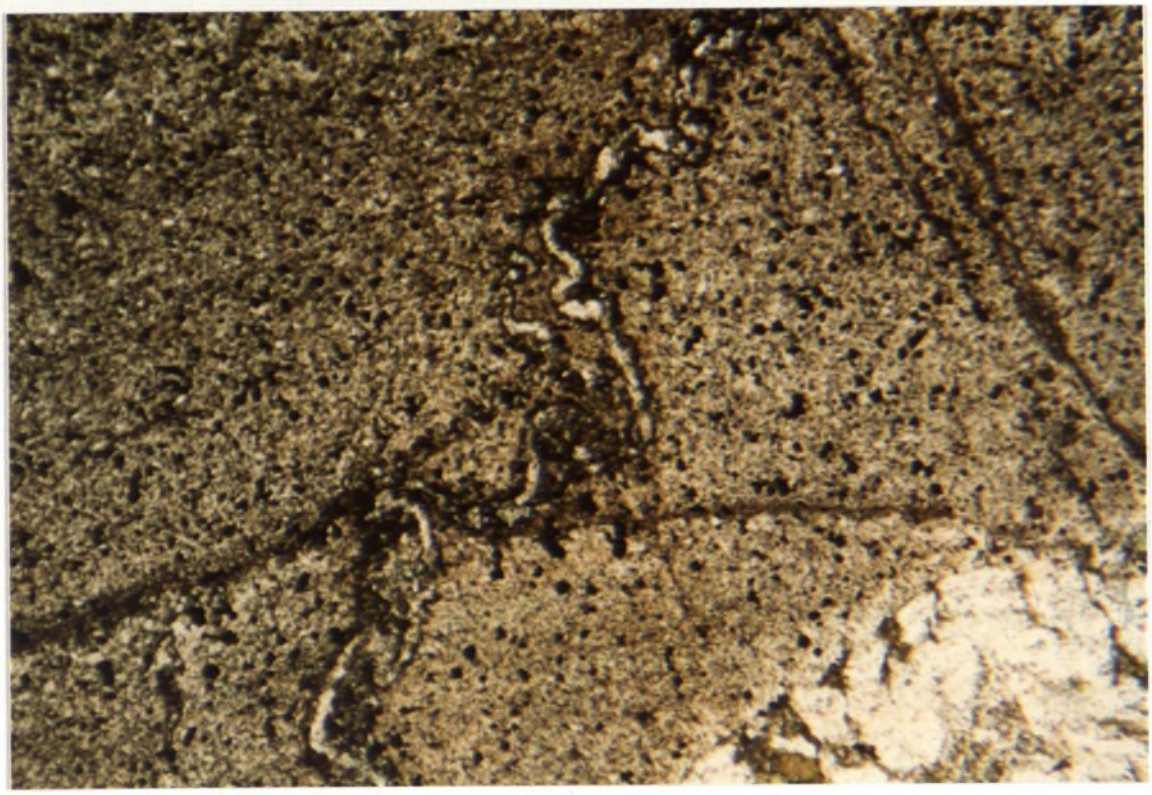


Plate 16. Tw 75. Early quartz vein that has been folded by the opening of the fracture. Folding of the vein is localised to the area close to the fracture. (PPL 2·5)

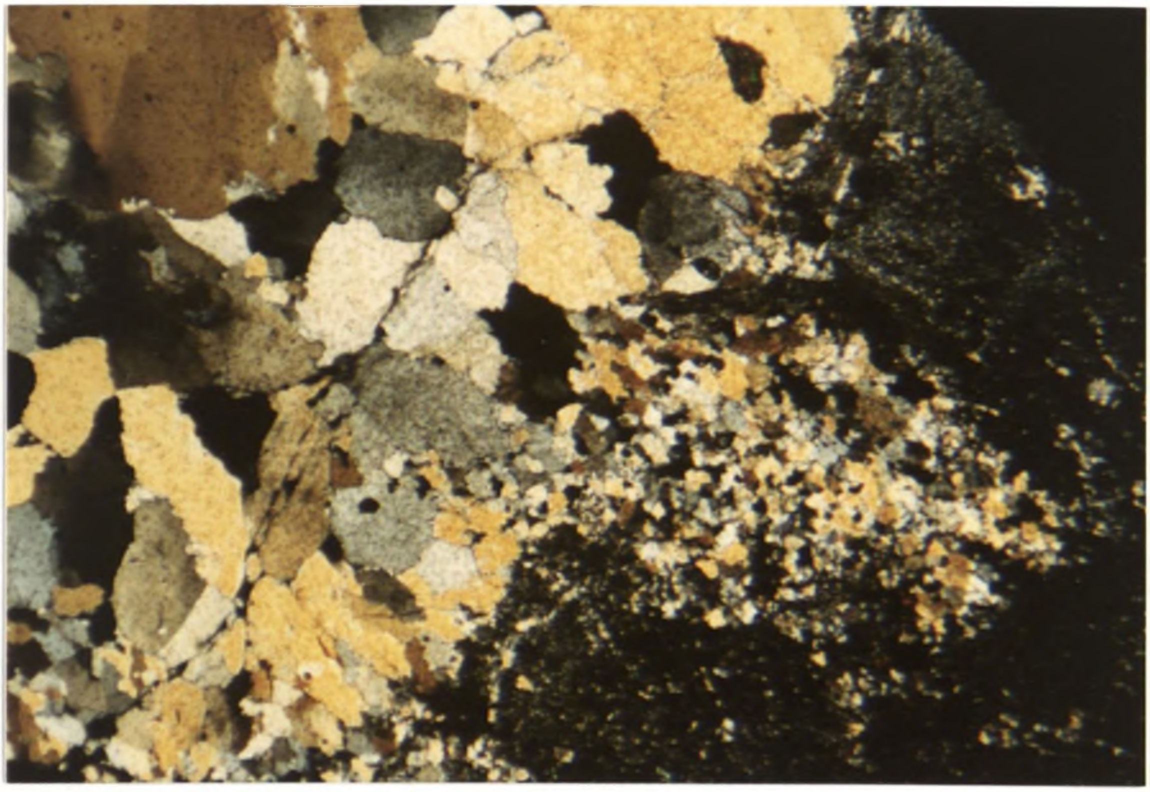


Plate 17. Tw 75. An embayment in the country rock contains fine vein quartz. This suggests that there was two stages in the growth of the vein. (XP 6·3)

(1977) and the rock is described as "inequigranular and felsophyric" (p. 10) with phenocrysts of plagioclase and pyroxene scattered throughout a groundmass of fine grained plagioclase. McMinn (1977) concluded that two generations of feldspar exist, one magmatic and one metamorphic, the latter being more calcic.

Cook and Dawson (1988) were not prepared to decide whether the Kingsmill's Peak Andesite is intrusive or extrusive. Unlike the Browning Vale Andesite, it is calc-alkaline, having both clino- and ortho-pyroxene phenocrysts. The groundmass is very fine-grained, dark grey and made up of glass and/or microcrystalline aggregates.

This study can not conclusively determine whether the Oaky Creek andesites are intrusive or extrusive. However, it can suggest that intrusion of mafic dykes has occurred in the Tamworth area.

The mafic igneous rocks found in the south of the field area are characterised by spilites and dolerites (fig. 6). The dolerites have abundant, medium-grained phenocrysts of plagioclase and amphibole. The phenocrysts of plagioclase are aligned, implying a magmatic flow alignment (plate 11). Pyroxene phenocrysts are absent in the dolerites. The spilites found in the Tamworth area are characterised by chlorite replacing pyroxene. Both, dolerites and spilites were found to cross-cut bedding and thus suggests that these rocks are intrusive.

Benson (1915a) completed an intensive study of the spilites, dolerites and keratophyres in the Tamworth area as well as the Nundle area south of the Tamworth area. Benson (1915a) concluded that the mafic igneous rocks in this area were often penecontemporaneous. This was illustrated by an example where hot magma intruded into soft wet sediments in the Nundle district. Benson (1915b) described the dolerites in the Tamworth area as intrusive because the bodies cross cut the sediments. Crook (1960) did not elaborate on Benson (1915b) suggesting the mafic igneous igneous rocks were penecontemporaneous to intrusive.

2.3 Structures of the Tamworth Area

This section discusses evidence for structures associated with the intrusion of the pluton. The ramifications of which are considered in chapter five.

The non-pluton related, regional structures were formed by the earlier Carboniferous Orogenic event. The deformation is characterised by low angle thrust faults (plate 18), tight parasitic folds (plates 19 and 20) and cleavages (destroyed by the contact metamorphic effect), generally with a north-south orientation. Moving from west to east, the frequency of the structures increases. This is a characteristic of the eastern boundary of the Tamworth Terrane rather than being the result of the intrusion of the Moonbi Adamellite (Benson 1915b; Chappell 1961).

The pluton related structures are local features found within the aureole. They are used to determine an emplacement model of the pluton (Chapter 5) as well as to determine the timing of metamorphism with respect to deformation. The following features were identified in the field and appear to be related to the pluton;

- Bending of the Tintinhull anticline (fig. 10).
- Foliations around garnet porphyroblast (plate 21).
- Folding of a granitic vein at contact (plate 22).
- Foliation parallel to contact (plate 23).
- Bedding parallel to contact within 10 m of the pluton (fig.7).

This study suggests that they formed at the time of emplacement rather than after the intrusion because there are no deformational effects within the Moonbi Adamellite.

Studies in the timing of the metamorphism and deformation from other plutons in the NEO suggest similar results. Vernon (1989) suggested that the syndeformational contact metamorphism was active in the Walcha Road Adamellite, which is part of the Moonbi Plutonic Suite (Shaw and Flood 1981).

While the structures are syn-intrusive, they do not necessarily represent deformation caused by a forceful intrusion of the pluton. As the temperature increases in the country rocks, prograde metamorphic reactions occur throughout

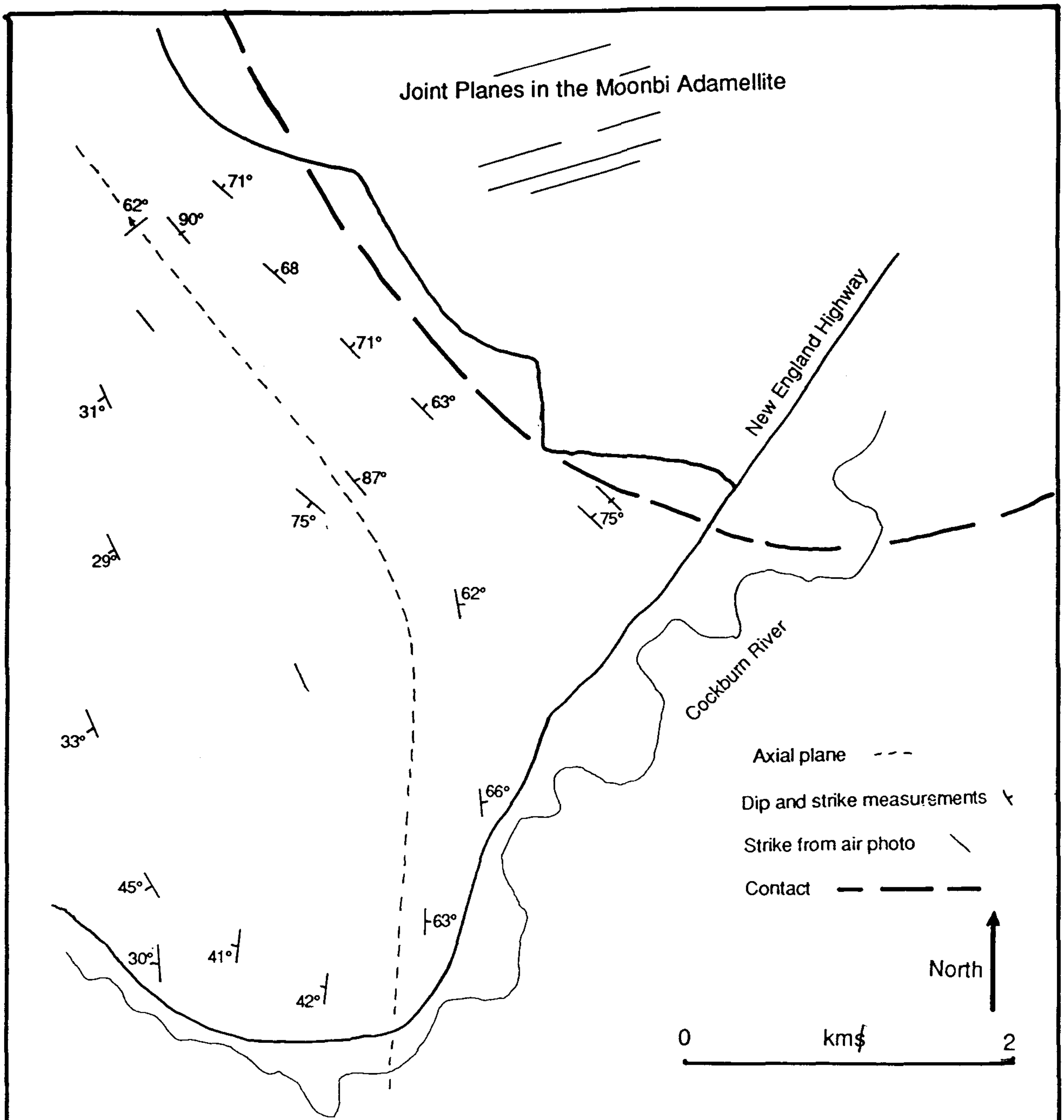


Figure 10. Structural map of the Tintinhull Anticline

Plate 18. Tw 150. Low angle thrust fault cutting a biotite-quartz hornfels. (PPL 2·5)

Plates 19 and 20. Tight parasitic folds. Fold axis; 340° 20°. (Gr: Moonbi, 109 575)

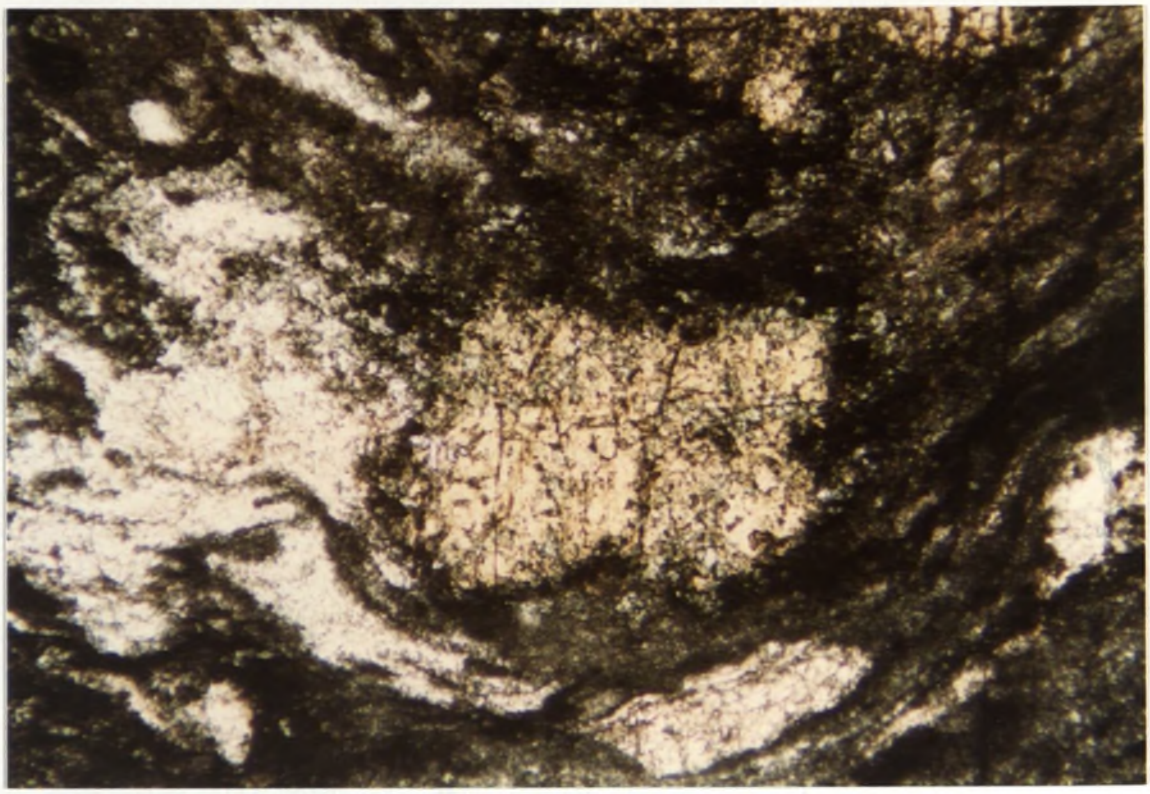
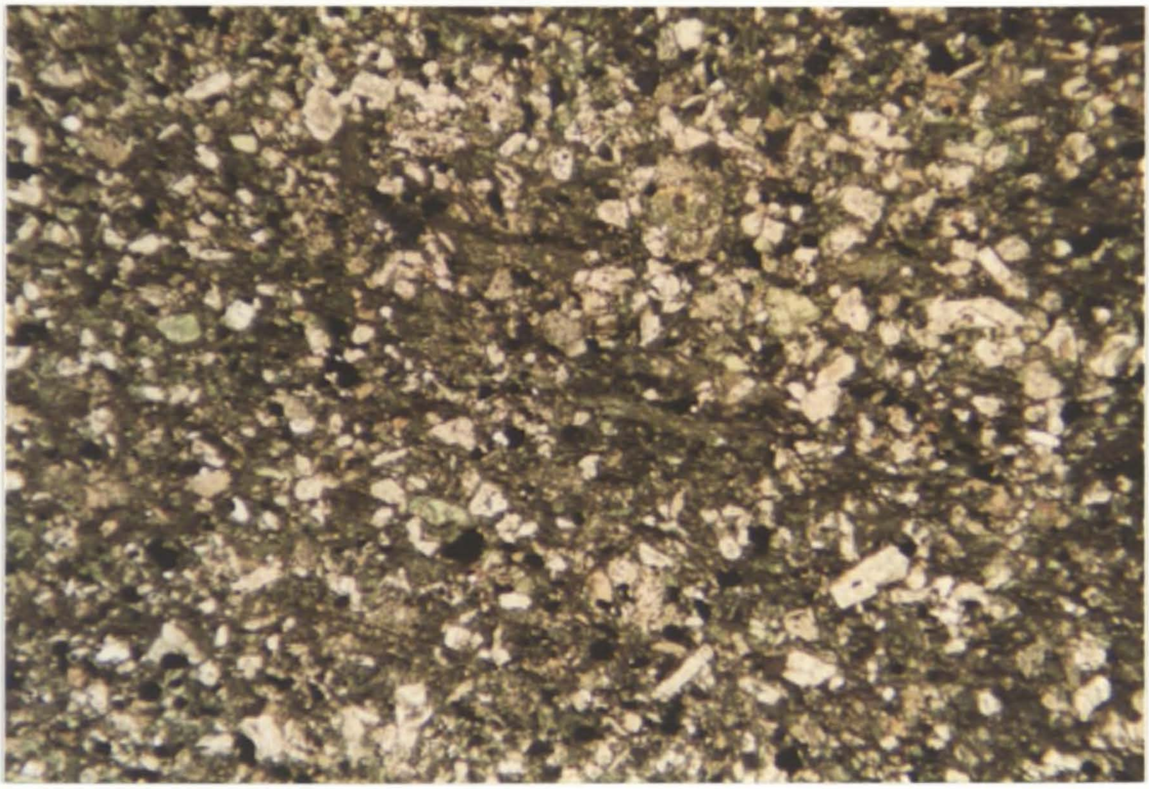


Plate 21. Tw 134. Wollastonite is foliated around the garnet porphyroblasts. (PPL 1·25)

Plate 22. Folded granitic vein found in the Oaky Creek (Gr: Att, 046 691)

Plate 23. Tw 142. East-west foliation, caused by a north-south compression. (PPL 1:25)



the aureole. Many of the reactions produce fluids such as water (chapter 3 and 4). Deformation of hot, fluid rich rocks can occur with minimal stresses on an area (Ramsay and Huber 1987). Hence the rocks within the aureole are more susceptible to deformation than the cold rocks outside the aureole.

Many of the prograde metamorphic reactions, especially in the calc-silicate rocks, result in the growth of porphyroblasts. Vernon and Powell (1976) suggested that local synmetamorphic deformation can occur due to the volume changes between solid reactants and products. This is exemplified in Tw 134 (plate 21), where a gneissose texture is produced by a matrix of wollastonite and calcite being bent around garnet porphyroblasts. This microstructure suggests that the growth of porphyroblasts occurred during the deformation.

Rubenach and Bell (1988) considered that a syn-intrusion regional deformation would penetrate the hot aureole rocks. This could occur where a weak regional stress exists during the emplacement of the pluton. The regional deformation would not penetrate the cold rocks outside the aureole. Instead the hot, easily deformed rocks within the aureole would have a strong deformational signature. However, this is not thought to have occurred during the emplacement of the Moonbi Adamellite on the basis of work by Kleeman (1988). Kleeman (1988) concluded that the rocks in the NEO were under no tectonic stress during the time of emplacement of the Moonbi Adamellite.

Evidence collected for this study from the aureole rocks all suggest that contact metamorphism and deformation occurred together. Other features in the rocks can indicate more about the relationship between the two. In the finer-grained laminated argillites the structures have been obliterated as the quartz and biotite have coarsened. This would suggest that heating out lasted deformation (Vernon 1989). The rocks in the Seven Mile Creek area in the central part of the field site show other constraints in the timing of the deformation. The calc-silicate rocks which have been fractured, presumably at the highest deformation, have had minerals which crystallised in the fracture. These minerals are all of high grade, suggesting that peak metamorphism occurred after peak deformation. However this study interprets that the deformation had changed its style. As the rocks heat up they would change from brittle deformation such as fracturing and faulting, to plastic deformation observed as bending of foliations around porphyroblasts and micro folding.

This study considers that the main cause of the aureole deformation is due to the intrusion itself. Structures such as the bending of the Tintinhull anticline (fig. 10), and bedding being deflected into parallelism (fig. 7 and 10) indicates shouldering aside of the country rocks (Bateman 1985). The folded granitic vein (plate 22) supports the interpretation that the deformation was at a later stage in the emplacement of the pluton. A strong foliation is seen in Tw 142 (plate 23) located in the southern part of the field area, where the units are perpendicular to the contact (S_o: 350°82°W). Hence the foliation is parallel to the contact. It is difficult not to designate the foliation to the forceful intrusion of the pluton. However the foliation is irregular and can not be identified elsewhere in the area.

This study concludes that the pluton related structures are syndeformational contact metamorphic. Local deformation is directly related to the forceful intrusion of the pluton as well as volume changes in the metamorphic rocks. Evidence suggests that the deformation occurred after metamorphism began, but that the heating outlasted deformation.

CHAPTER 3.

CONTACT METAMORPHISM

3.1 Preamble:

Contact metamorphic aureoles in the NEO has been examined in detail by many authors (e.g., Clare 1988, Howarth 1974, Binns 1966). However, these aureoles are all found east of the Peel Fault System, and as yet no detailed contact metamorphic work has been completed on the sediments to the west of the Peel Fault, because of the small number of plutons found in the region.

Benson (1915b) was first to comment on the Moonbi 'Granite' (later termed the Moonbi Adamellite by Chappell 1974), and the metamorphic effect on the country rocks. Benson (1915b pp.587) described the metamorphism as; "...considerable, especially noteworthy in the limestones and the pyroclastic rocks..." (Pyroclastic rocks are now considered to be mass flow sedimentary rocks, Crook 1960). From Benson' s (1915b) description of the contact metamorphic rocks it can be inferred that hornblende hornfels facies was the peak assemblage.

The previous contact metamorphic studies (Binns 1966, and Howarth 1974) on the Moonbi intrusion were concentrated on sediments east of the Peel Fault. They found that the hornblende hornfels facies was reached at the peak of contact metamorphism. While pyroxene is present, it was found not to be the product of isochemical metamorphism, but it may have been yielded from metasomatic fluids. The nature of the metamorphic fluids is covered in chapter 4.

The regional metamorphic event predates the contact effect, previously explained in Chapter 1. Regional low-grade metamorphism has two styles in the NEO (Leitch 1974). The Tamworth Terrane was affected by burial metamorphism with a range from sub-green schist to prehnite-pumpellyite in the peak facies (Offler and Hand 1988). The reason for the variation is uncertain. While the depth of the sediments is related to the grade (Offler and Hand 1988), a complex geothermal gradient has been responsible for complicating the regional metamorphic zoning. Leitch (1974) reports the grade varies from zeolite to prehnite-pumpellyite facies in the Northern part of the Tamworth Terrane. Offler and Hand (1988) concluded that the Tamworth belt reached "diagenetic to lower anchizonal facies" (subgreen-schist or pumpellyite-actinolite facies). These interpretations were obtained by a geochemical analysis of the white micas. Crook (1969) used vein minerals to conclude that the prehnite-pumpellyite facies was the peak facies reached. These studies, though not consistent, all show a relatively high geothermal gradient in the Tamworth Terrane. Leitch (1974) would have expected this from a fore arc basin which was latter intruded by plutons during an orogenic event. The peak assemblages indicate conditions were approximately 2 kbar and 300°C.

The eastern sections of the NEO were also studied by Offler and Hand (1988). They found, "... that fundamentally different metamorphic imprints are recorded in the sequence from the Tamworth Terrane to the Eastern Terranes." (pp.187). This follows Leitch's (1975) tectonic framework of a fore-arc basin (with low pressure) and an accretionary zone (with high pressure).

The metamorphic assemblages found in the Eastern Terranes also shows a great deal of variation in their grade, from glaucophane-lawsonite schist to greenschist to zeolite facies, but always with a smaller geothermal gradient (Offler & Hand 1988). This diversity of the metamorphism indicates a complex thermal regime (Leitch 1974; Howarth 1974; Lewington 1974), with peak metamorphic conditions approximately 2-3 kbar and 200-300°C.

The relationship between the two metamorphic events is uncertain. Emplacement of the granites in the Permo-Triassic (Shaw and Flood 1981) may have produced a high geothermal gradient However it is unlikely that this is related to the heat during the regional metamorphism, as the peak conditions of the burial metamorphism occurred before the emplacement of the granite and the contact metamorphic event.

3.2 Contact Metamorphism

The sedimentary rocks of the Tamworth Area which were the subject of this study are marine mass flow deposits from an andesitic source (chapter 2). The rocks are described herein as metaluminous, implying that they are deficient in Al_2O_3, yet enriched in Fe, Ca and Mg, and deficient in SiO_2. Hence the metamorphic assemblages resemble those of the mafic rocks. For this reason the igneous rocks and the sediments are grouped together. The limestones and calc-silicates are also grouped together, as they share a comparable metamorphic history.

At low to medium metamorphic grades original igneous textures and sedimentary structures in the rocks can be recognised. The highest grade rocks do not show many of these features. Instead they have a metamorphic imprint and are commonly associated with veins and fractures. The metamorphic imprints are caused by the recrystallisation of minerals and the overall coarsening of the rock which commonly involved the growth of porphyroblasts (e.g. Tw 134).The most distinctive metamorphic transitions involved; biotite, amphibole, plagioclase, epidote, chlorite, and quartz.

3.2.1 Metamorphic minerals.

Biotite. The introduction of biotite is the first indication of contact metamorphism in the lowest grade rocks (Plates 24 and 25). The low grade biotite is not strongly orientated in any direction and tends to grow in the fine grained matrix of the rocks. In the highest grades biotite is commonly orientated parallel to the contact of the granite (Plates 26 and 27). As with the other minerals, biotite becomes coarser and more elongate with increasing metamorphic grade.

Biotite is produced mainly by continuous reactions operating over a broad P-T interval (Brown 1975). The reactions, chlorite+K-felspar=biotite+muscovite and chlorite+K-felspar+/-stilpnomelane+/- actinolite are commonly used to describe the biotite isograd. However, these reactions are not considered due to the lack of muscovite and stilpnomelane in the rocks of the Tamworth area. Hence, biotite is

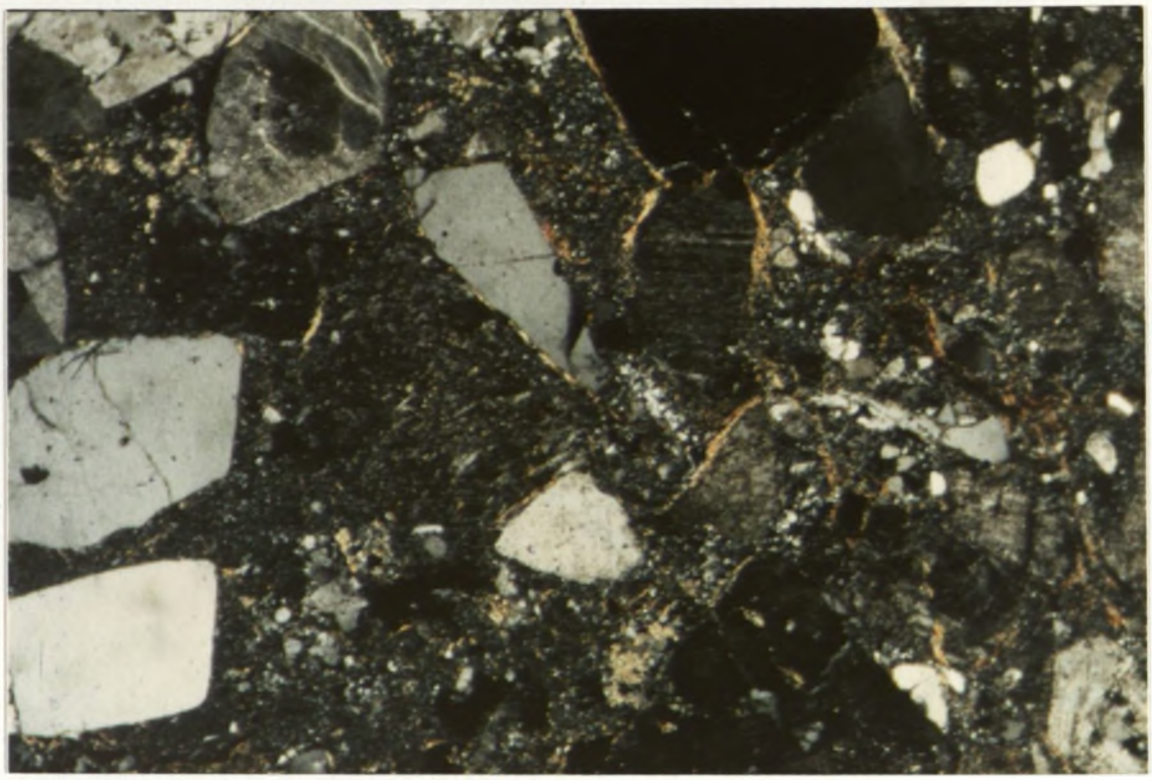


Plate 24. Tw 27. Early biotite growing in the matrix of a conglomerate, marking the biotite isograd. (XP, 2·5)

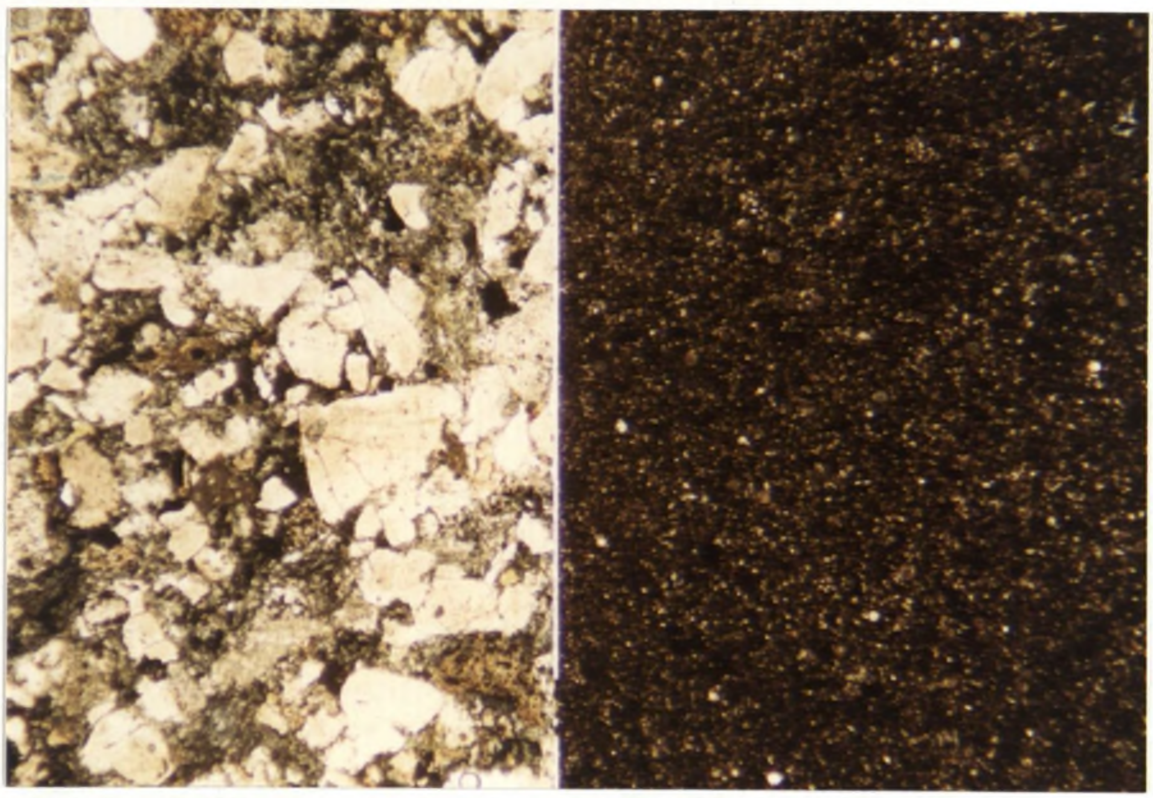


Plate 25. Tw 25/145. Coarse grained arenite (Tw 25) and argillite (Tw 145), neither contain biotite which also marks the outer limit of the biotite isograd. Tw 25 has an iron stained matrix. Plagioclase is An 55-65 (PPL 1·25)

Plate 26. Tw 193. Biotite-quartz assemblage in the lower hornblende hornfels facies. The biotite is platy and is orientated along bedding. (PPL 1·25)

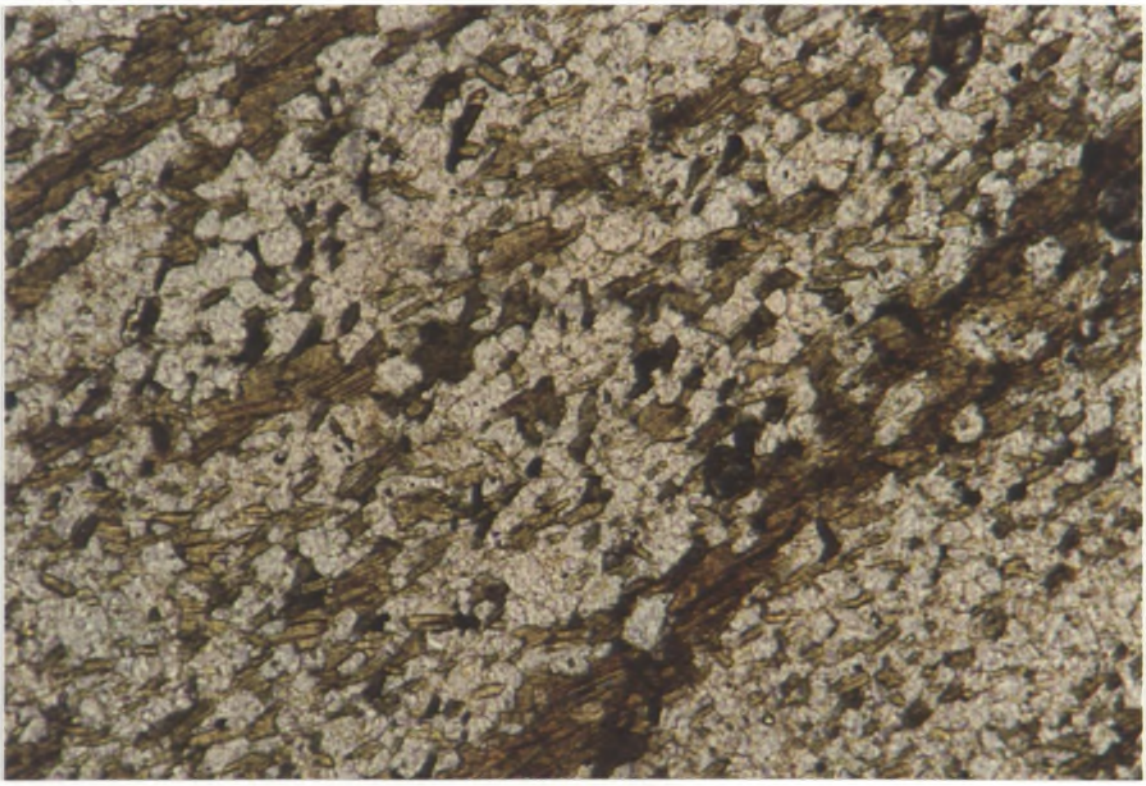


Plate 27. Tw 1b. Granoblastic-polyngonal, high grade quartz-biotite hornfels. Biotite is growing along crude bedding planes. (PPL 6·3)

thought to be the product of the break down of chlorite, K-feldspar and possibly mafic minerals such as amphiboles.

The biotite isograd forms a boundary which separates the areas where contact metamorphic textures can first be recognised. This is most noticeable in the fine grained sediments, which show the development of hornfelsic structures (Plates 26 and 27.), whereas outside the biotite zone they appear well jointed and cleaved in a phyllitic form.

Amphibole. Amphiboles can be seen in the rocks of the Tamworth area from the lowest to the highest grades with varying compositions and textures. The transition in the colour and texture is systematic through the aureole. This transition has previously been reported by Binns (1966). Binns (1966) found characteristic changes of amphibole in mafic dykes throughout the aureole of the Moonbi intrusion east of the Peel Fault. He concluded that the colour of the amphibole changes from brown at the highest grade, to olive-green to blue-green at the lower grades. These changes are due to the changing chemistry (Clare 1988), hornblende forming in the highest grades and actinolite at the lower grades. The textures change from granular at the highest grade through to fibrous at the lower grade.

The sediments of the Tamworth area do not follow the changes that can be seen in the igneous rocks. The colours vary within the sediments e.g. Plate 29. where metasedimentary xenolith shows green granular hornblende, due to the variation in the chemistry between the sedimentary rocks. However the textures of the amphiboles do change from fibrous habits (Plate 30 and 31) to granular habits (plate 29).

Epidote. The occurrence of epidote marks the boundary of the albite-epidote hornfels facies with the hornblende hornfels. Epidote occurs in a wide variety of rocks; from the mafic andesites (Tw 76), through sedimentary hornfelses (plate 28,Tw 55) to the calc-silicates (Tw 129). Within these rocks the epidote is seen in many different habits, varying from fibrous needles to granular grains. The grain

Plate 28. Tw 127. Residual crystal of hornblende in an epidote-plagioclase-quatrz-hornblende hornfels. (PPL 6·3)

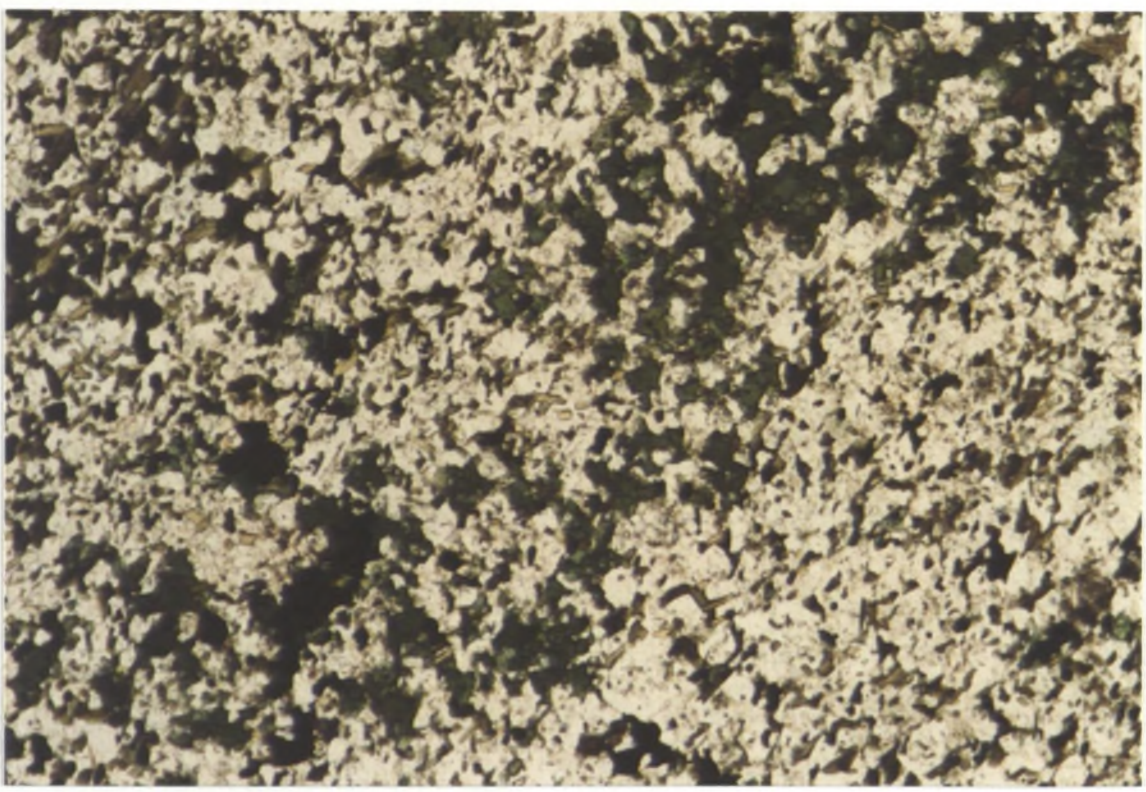


Plate 29. Tw 4. The only meta-sedimentary xenolith found in the Moonbi Adamellite. This represents the highest grade of metamorphism in the aureole. Quartz-biotite-hornblende hornfels. Hornblende is green rather than brown as seen in the mafic igneous rocks (Binns 1966; Clare 1988). (PPL 2·5)

Plate 30. Tw 177. Blue-green fibrous amphibole in albite-epidote hornfels facies. (PPL 6·3)

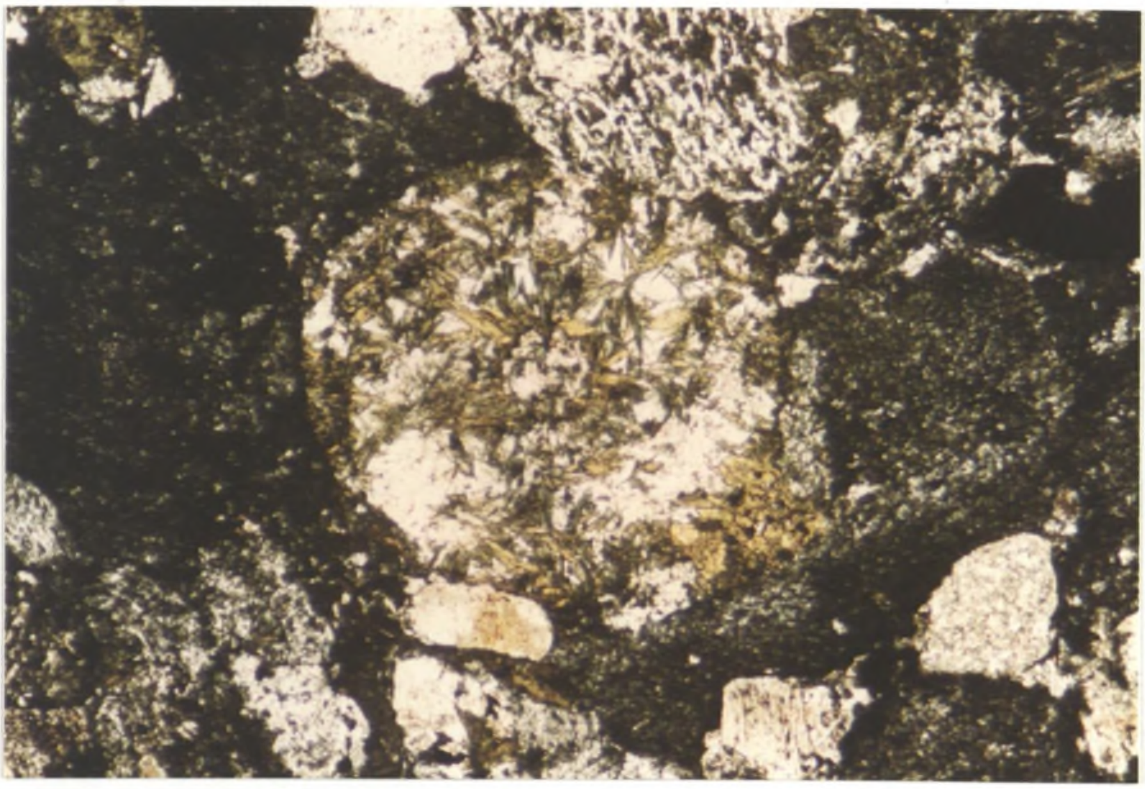


Plate 31. Tw 115. Tan-brown fibrous amphibole within an igneous clast in a coarse arenite. Lower hornblende hornfels facies, An 20. (PPL 2·5)

size does not appear connected to the grade; instead this study suggests that the habit is connected to the parent rock type.

An electron microprobe analysis of the epidote (in Tw14) indicates a Ca, Fe, Al hydrous epidote (Deer et al 1966) of unzoned consistent composition.

Chlorite. Chlorite is found in the outer parts of the aureole, as at higher grades it reacts to form biotite (Plate 32.). It is best represented in the matrix of both the conglomerates and the mafic igneous rocks. Biotite and chlorite are often seen together within the same clast. This study suggests an uncompleted prograde reaction rather than retrogression as biotite is produced from continuous reactions (Brown 1975). Chlorite is also seen pseudomorphing many minerals across the Tamworth area. Plate 33, shows residual pyroxene breaking down to chlorite and plate 34, shows chlorite pseudomorphing plagioclase. These two examples were both seen in the albite-epidote hornfels facies. Hence it is assumed that the break down of pyroxene and feldspar is the result of contact metamorphism rather than regional features.

The chlorites are Fe, Mg, Al, chlorites and may be described as ripidolite (Deer et al, 1966).

Quartz. Though quartz is not a dominant mineral in the igneous rocks and conglomerates, it is abundant in the extensive laminated argillites. This unit shows a metamorphic change throughout the aureole, from a fine grained rock to a fairly coarse grained meta-psammite rich in coarse grained biotite. The quartz rich rocks have a granoblastic microstructure (Plate 27) at high grades and an almost phyllitic microstructure at low grades (Plate 25 and 26).

Plagioclase. Moving towards the contact, metamorphic plagioclase changes chemically from a An_{45-55} to An_{1-5} in the albite-epidote hornfels facies. In the hornblende hornfels facies the plagioclase composition changes to An_{20-30}. The plagioclase in the rocks of An_{45-55}, are assumed to be residual crystals from the volcanic arc. The residual crystals are identified as they are elongate in shape and tend to be less clouded by inclusions than the contact metamorphic plagioclase minerals (Plate 35).

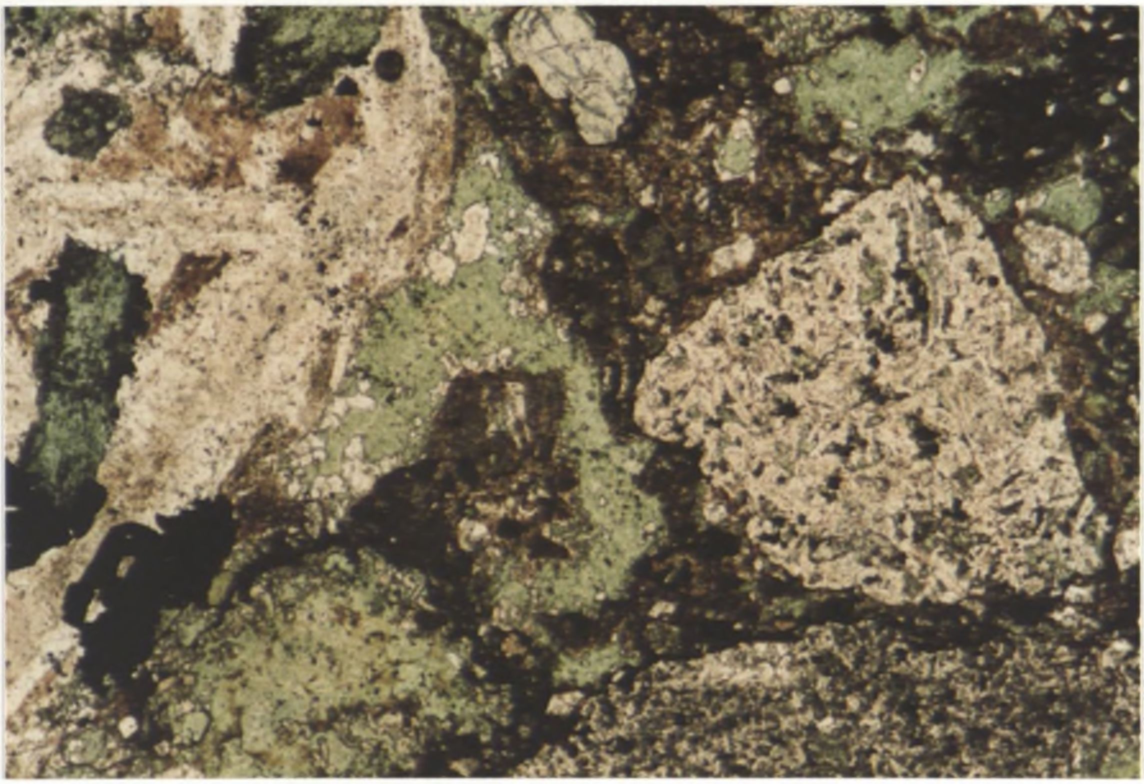


Plate 32. Tw 166. Chlorite and biotite growing in both the matrix and igneous clasts of a conglomerate. Albite-epidote hornfels facies. (PPL 2·5)

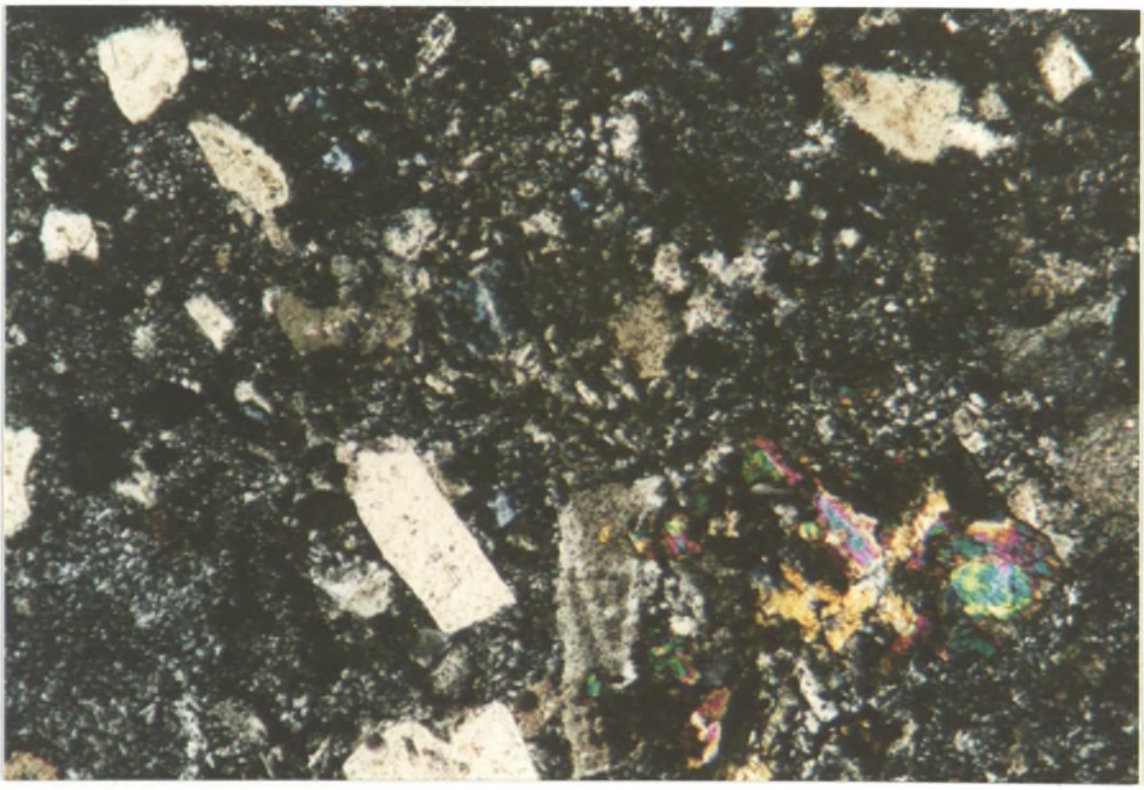


Plate 33. Tw 38. Residual pyroxene breaking down to chlorite in the albite-epidote hornfels facies. (XP 6·3)

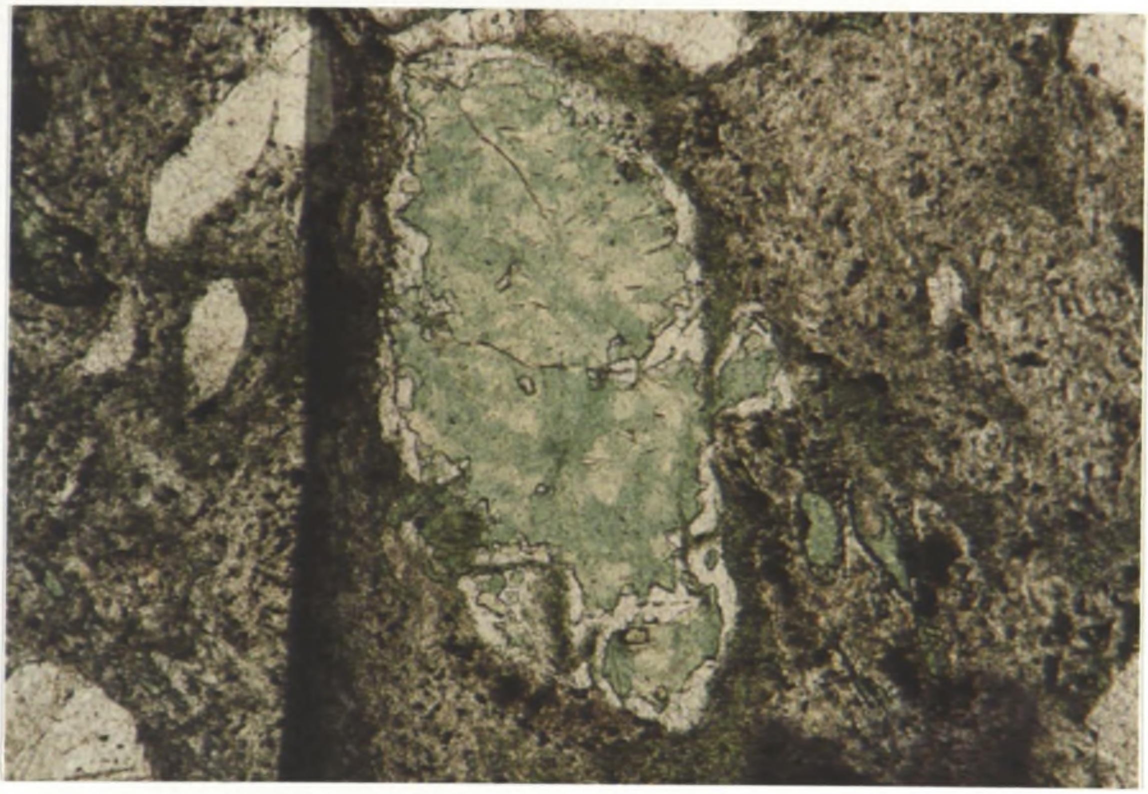


Plate 34. Tw 142. Breakdown of residual plagioclase (An 45-55) to chlorite, in the albite-epidote hornfels facies. (PPL 6·3)

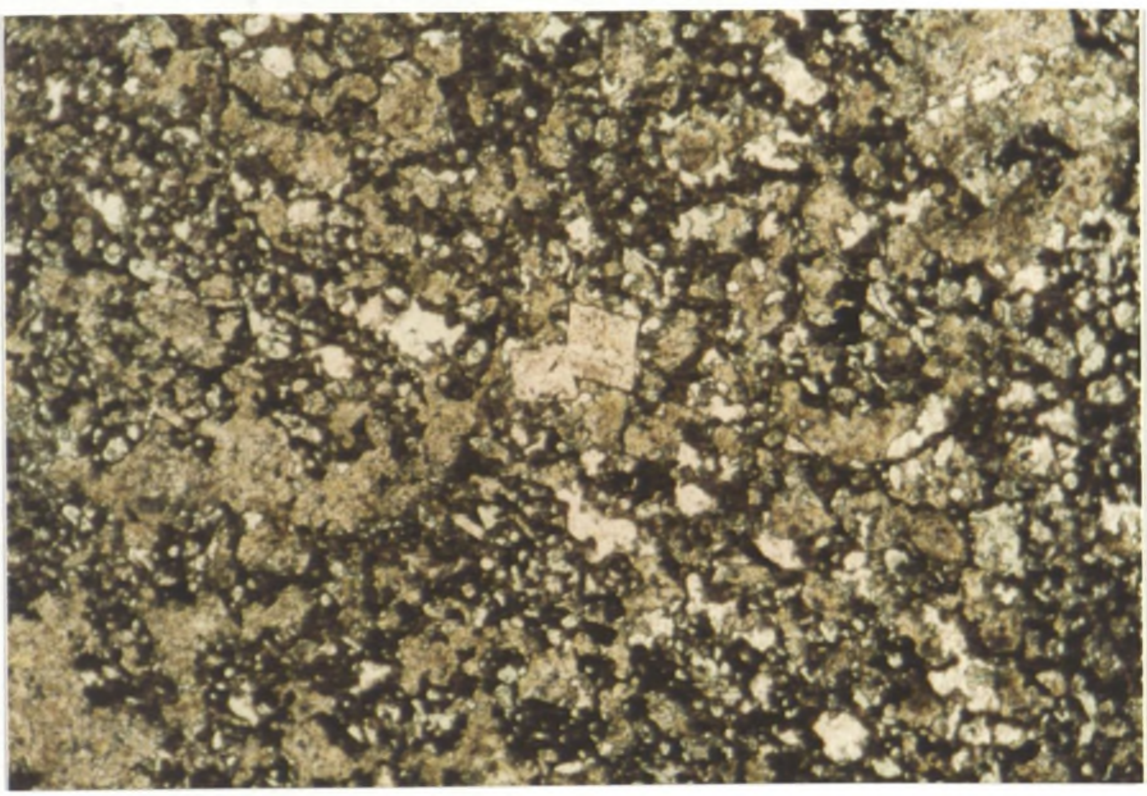


Plate 35. Tw 103. Residual plagioclase crystals in a plagioclase (An 25)- epidote assemblage in the lower hornblende hornfels facies. (PPL 2·5)

Using a combination of optical and microprobe data a plot of the average plagioclase compositions is shown in fig.11. The plot shows that the anorthite content drops dramaticlly in the albite-epidote hornfels facies. This drop has been used to support divisions of the metamorphic zones. The plagioclase compositions change abruptly in the rocks from the Tamworth area. Winkler (1979) concluded that this is due to a series of distinct reactions which produces anorthite with rising temperature. Whereas biotite is the product of continuous reactions (Brown 1975).

Previous authors (Vallance 1968; Benson 1915b) mentioned axinite within the rocks of the Tamworth area. A mineral suspected to be axinite was analysed using an electron microprobe (Plate 36). The results showed that it is a feldspar (An_{1-5}) which has a high iron content in the plagioclase structure. The high iron content is thought to be responsible for staining the mineral orange (in thin section, PPL). The iron is thought to have come from the opaque minerals. The opaque minerals were also considered by the microprobe analysis and found to be Iron oxides and iron sulphides. This study considers that the excess iron in the plagioclase structure is the result of the opaque minerals being involved in reactions in the albite-epidote hornfels facies.

3.2.2. Calc-silicates and marbles.

Many limestone lenses and calcic hornfelses are inter-bedded with the marine mass-flow sediments. These rocks show contact metamorphic assemblages, and they particularly show evidence of the metamorphic fluids and metasomatism.

In investigating assemblages and isograds for the calc-silicate rocks it was not possible to follow a single unit. The limestones are not consistent units; hence assemblages and grades were inferred for stratigraphically different rock types. This caused a problem, as chemical compositions and initial mineral assemblages were not constant from the highest to the lowest grades. Nonetheless these assemblages do indicate the changing metamorphic facies, garnet and

Plate 36. Tw 142. Orange mineral originally described as being axinite is albite (An5). Albite-chlorite-epidote assemblage, rich in opaque iron-oxides and iron-sulphides. (PPL 2·5)

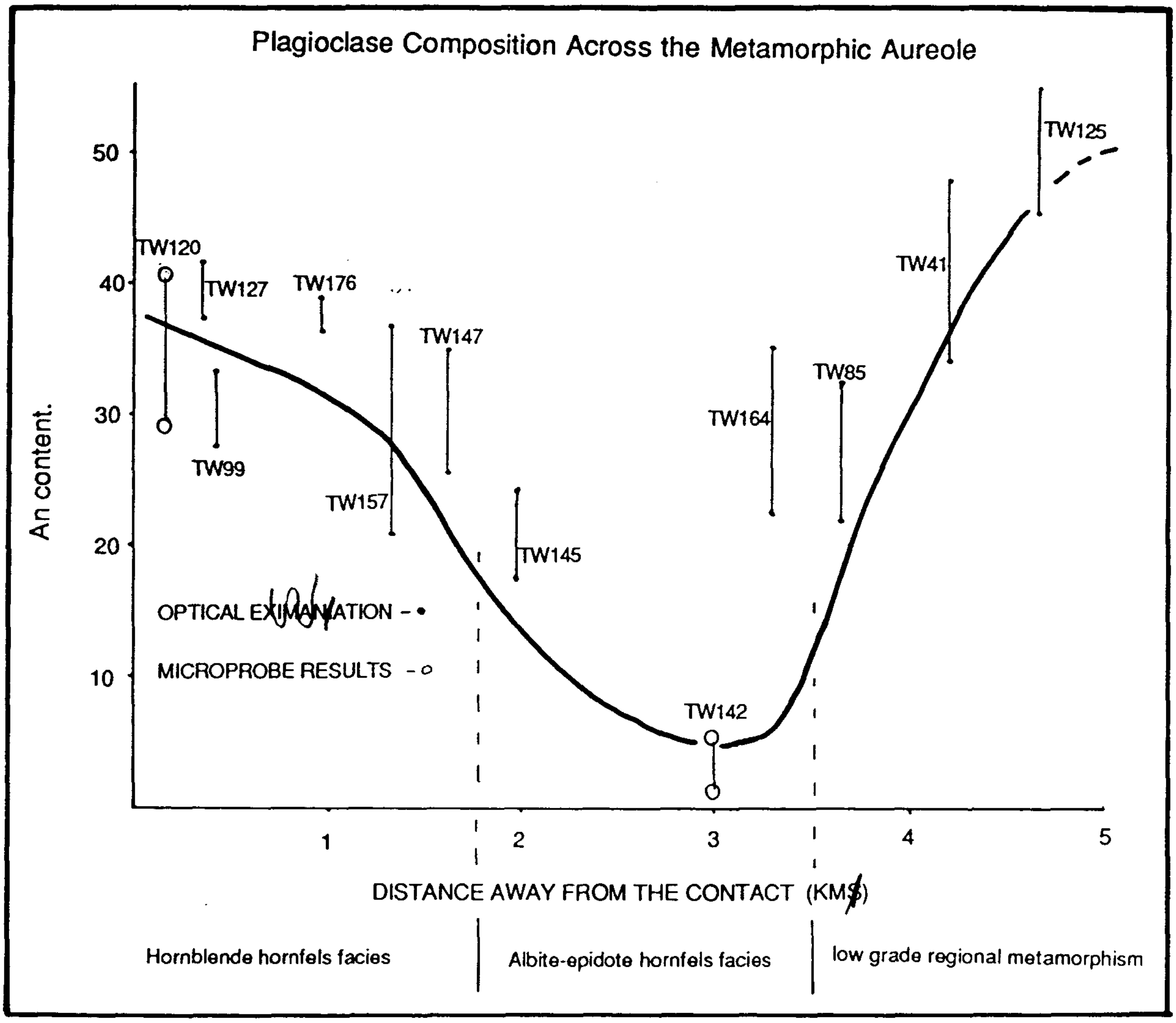

Plagioclase Composition Across the Metamorphic Aureole
An content.
50
40
30
20
10
TW120
TW127
TW176
TW147
TW99
TW157
TW145
TW164
TW85
TW41
TW125
TW142
OPTICAL EXAMINATION - •
MICROPROBE RESULTS - o
1
2
3
4
5
DISTANCE AWAY FROM THE CONTACT (KM)
Hornblende hornfels facies
Albite-epidote hornfels facies
low grade regional metamorphism

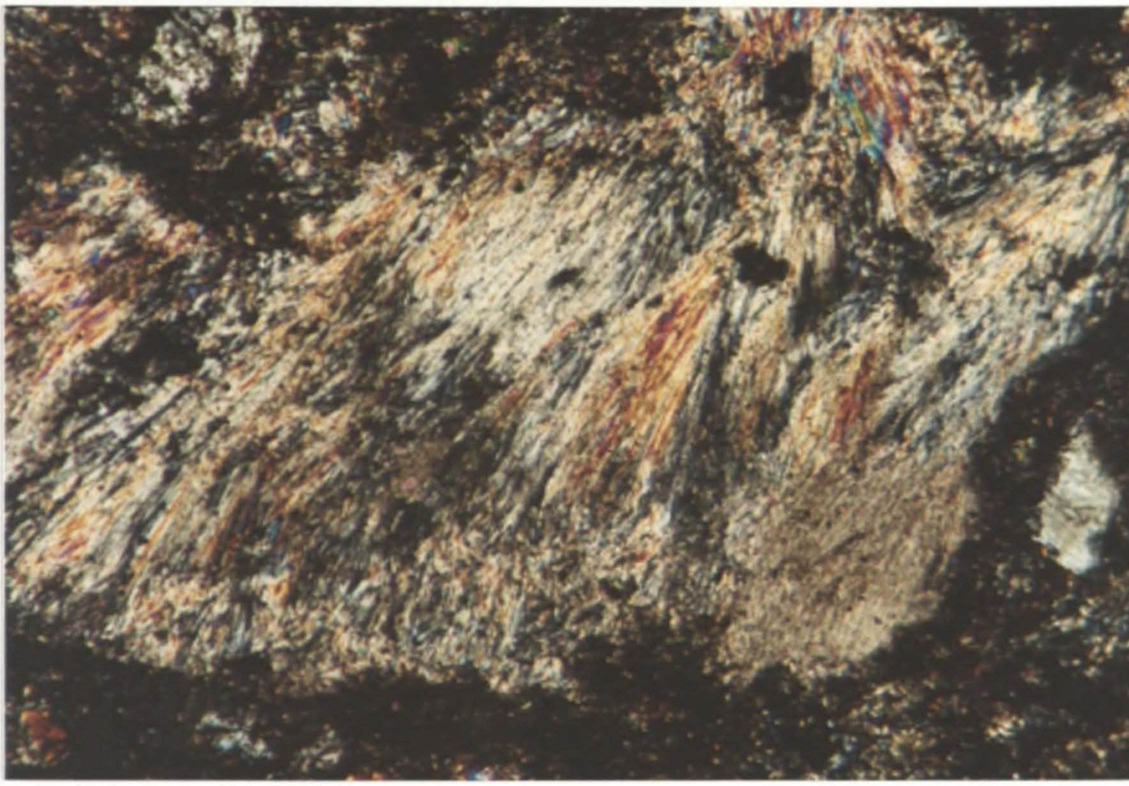
Figure 11.

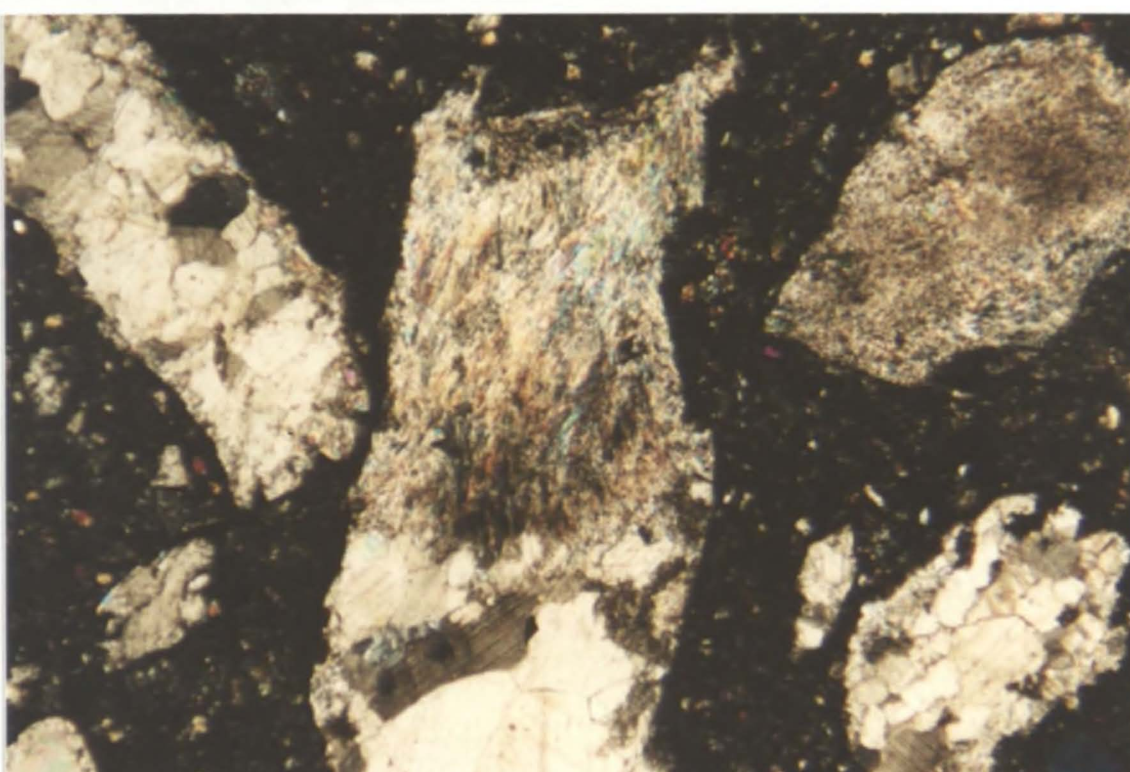
wollastonite being found at the highest grades, chlorite and epidote at the lower grades (Plates 37 and 38).

In addition the textures of the rocks were used, as well as the changing minerals in describing the aureole as significant changes can be observed. The best example of this is the Seven Mile Creek Limestone, which is a thin unit folded along the strike of the contact (fig 5, map of the area). Initially the rock shows recrystallised fossil fragments and some bedding. These react to form garnet, epidote and calcite moving towards the contact . The next textual change is the formation of porphyroblasts of garnet up to 1.5cm and wollastonite. The wollastonite forms a foliation around the garnet porphyroblasts. The wollastonite is formed in the peak of the metamorphism. This suggests that the deformation is syn or post peak metamorphism. The timing of the deformation and metamorphism is discussed in chapter 2.

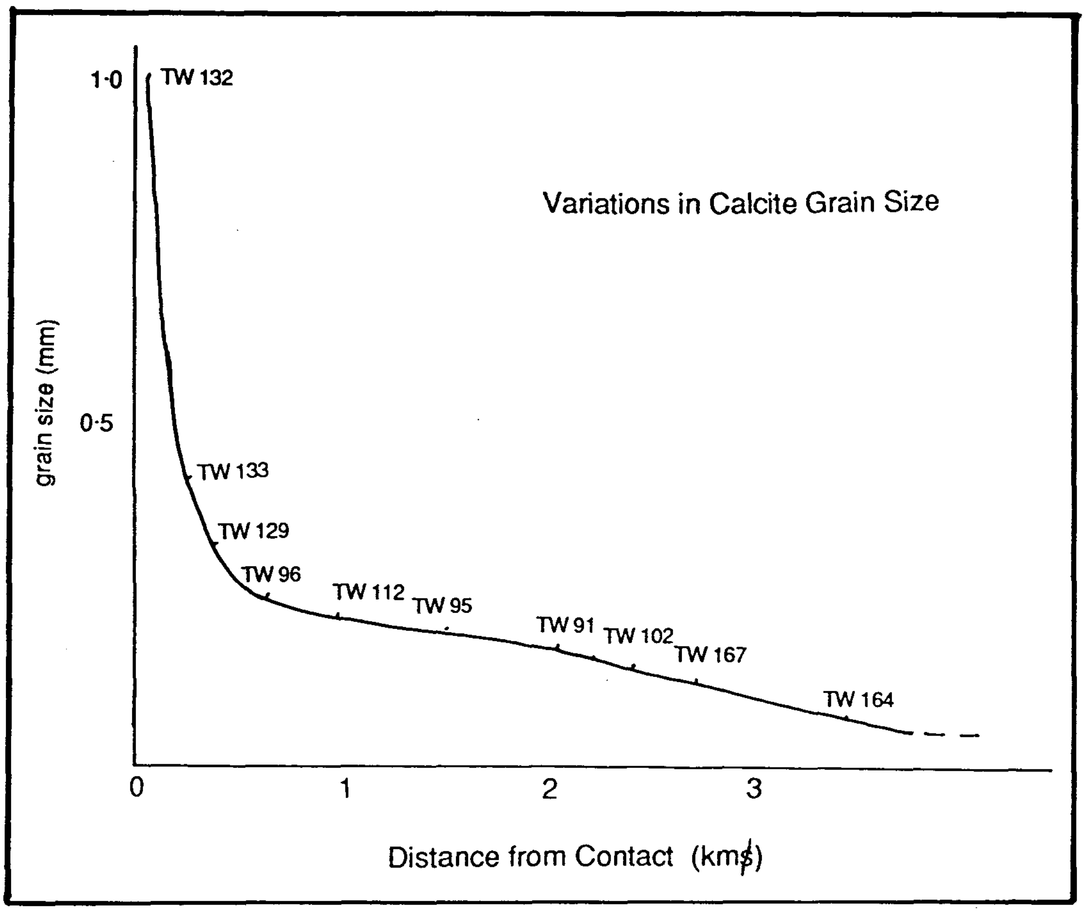
The other limestones also show various mineralogical and textural changes throughout the aureole. The Moore Creek Limestone to the north of the study area is still rich in fossils due to its distance away from the contact. Haematization is evident, but this can be attributed to the regional metamorphism as it occurs close to the contact and at the extreme edge of the aureole. However, the limestone bodies east of Tintinhull and Nemingha show recrystallization of fossils and the formation of marbles (Plates 39 and 40). The progressive changes in the calcite grain size are shown in fig 12. A sharp increase in the grain size occurs within 100 m of the contact. At a distance of three kilometres from the contact, fossils begin to be recrystallised until one kilometre away from the contact, where no fossil material can be recognised. This data was collected from both the limestone bodies and clasts within a conglomerate unit.

The calc-silicate rocks in the Tamworth area have been examined with regard to the metamorphic fluids associated with the intrusion of a large pluton namely the Moonbi Adamellite. The results of this examination are discussed in Chapter 4.





Plates 37 and 38. Tw132. Complete and incomplete reactions of calcite+quartz=wollastonite. This study suggests that it is the amount of SiO_2 that controls the production of wollastonite. (XP 1-25)



Variations in Calcite Grain Size
grain size (mm)
1·0
0·5
TW 132
TW 133
TW 129
TW 96
TW 112
TW 95
TW 91
TW 102
TW 167
TW 164
0
1
2
3
Distance from Contact (kms)

Figure 12.

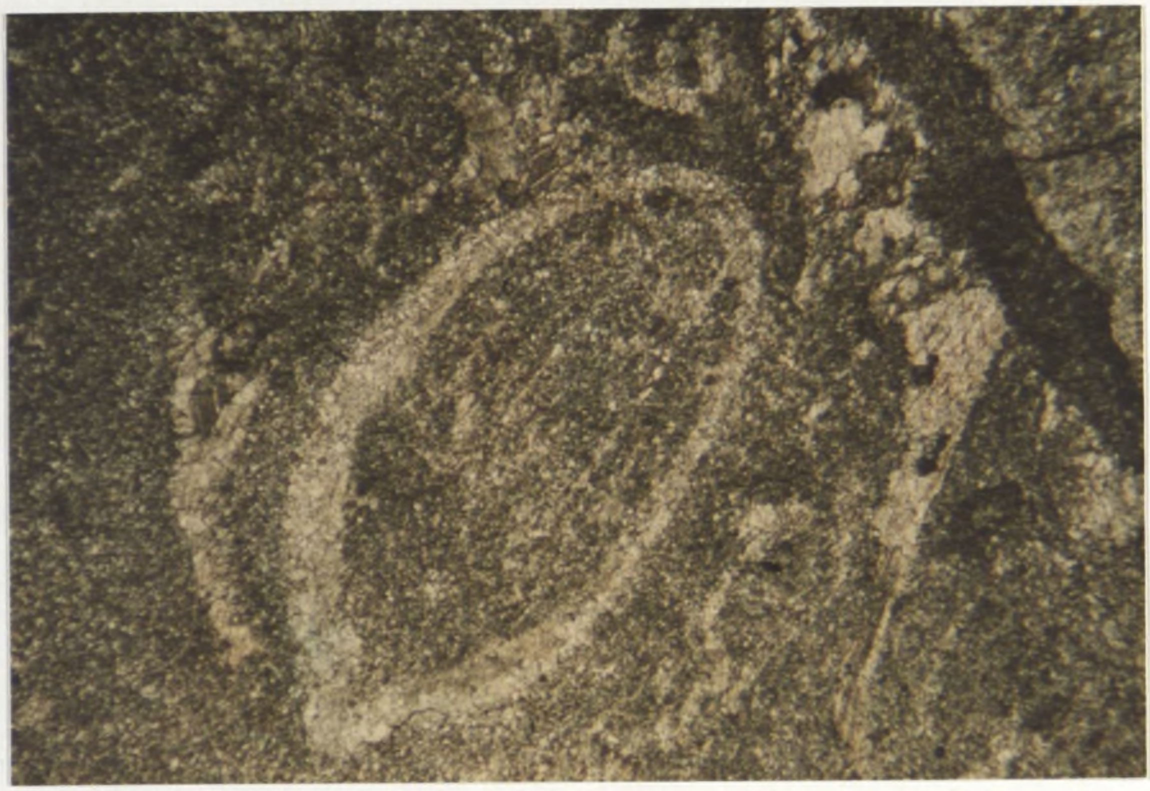


Plate 39. Tw 167. Neminga Limestone. This thin section shows the limestone at 3 kms from the contact is rich in fossils and the calcite is fine grained. (PPL 1·25)

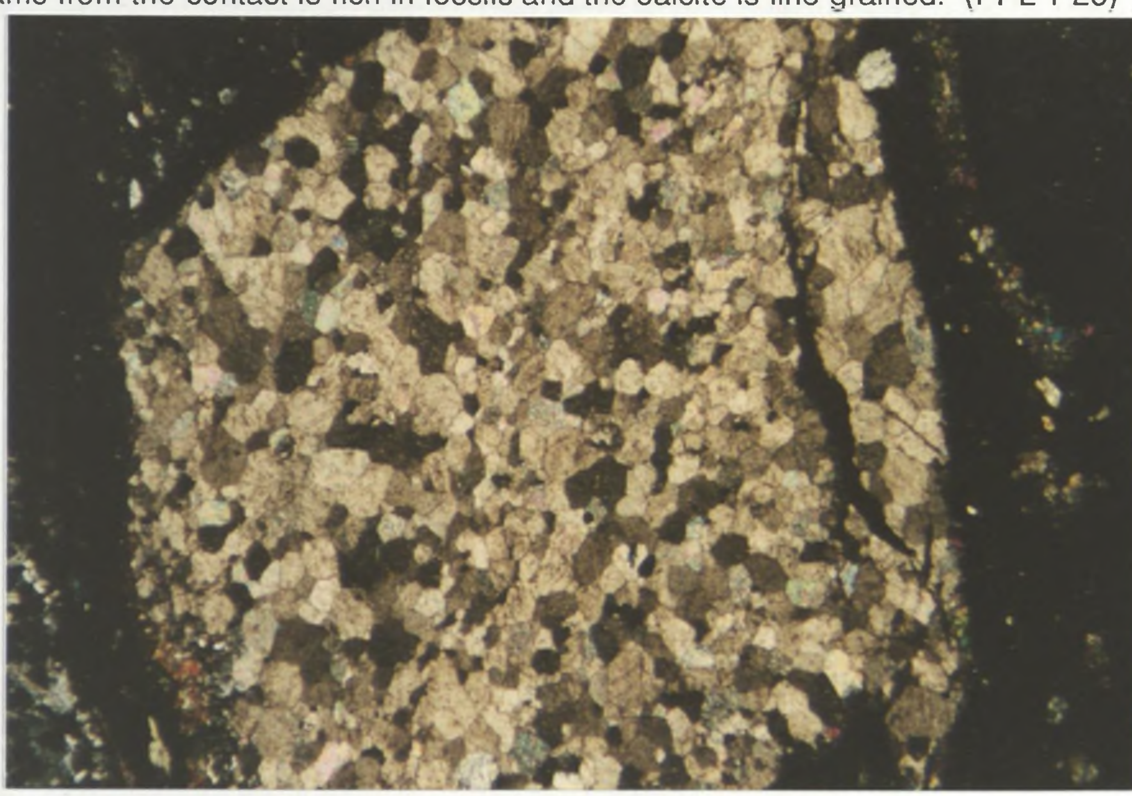


Plate 40. Tw 192 At a distance of 100 m from the contact the calcite is coarse grained and no traces of fossils can be seen. Taken from a marble clast in a conglomerate which is associated with the Neminga limestone. (XP 1·25)

3.2.3. Metamorphic Zones

The following three metamorphic zones have been differentiated using microstructural and compositional criteria, as shown in fig.13 and 14.

Low Grade Zone. The lowest grade assemblages are separated from the purely regional assemblages by the production of biotite within the matrix of the conglomerates and mafic igneous rocks. Amphiboles have a fibrous habit and are blue-green. The calc-silicate rocks show evidence of recrystallization of the calcite, garnet being produced towards the upper boundary. Plagioclase has a composition of albite (An 1-5) in the mafic hornfelses.

Medium Grade Zones. The disappearance of chlorite marks the base of the hornblende hornfels faces. Amphiboles become increasingly ragged and are olive green. Diopside and epidote characterise the calc-silicate rocks, with coarsening of calcite. The metamorphic plagioclase in the igneous rocks becomes increasingly polynogal and changes to An 25-30.

High Grade Zone. The high grade zone is separated from the medium grade zone by the production of wollastonite and vesuvianite in the calc-silicate rocks. The amphibole minerals in the mafic rocks is granular and often brown. The highest grade rocks are commonly veined by metamorphic fluid phase. This often leaves the rocks pitted as the vein minerals are often susceptible to weathering.

Due to a lack of indicator minerals this study can not confirm that upper hornblende hornfels facies was reached. However, with the results from previous studies (Binns 1966) on the Moonbi Adamellite, it is the suggestion of this study that the peak contact metamorphic facies is of upper hornblende hornfels facies.

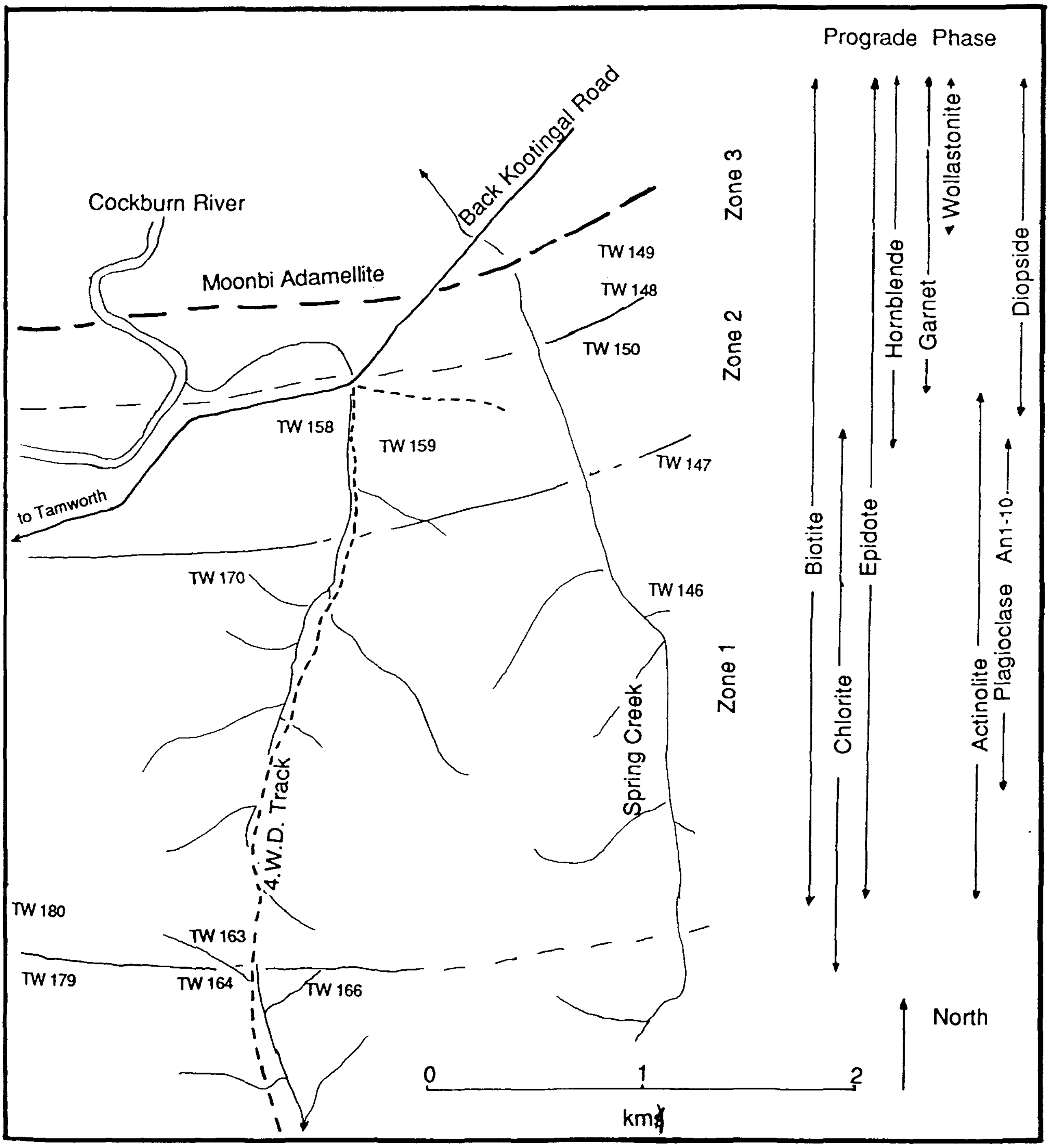


Figure 13. METAMORPHIC ZONES FROM THE SOUTHERN CONTACT OF THE TAMWORTH AREA.

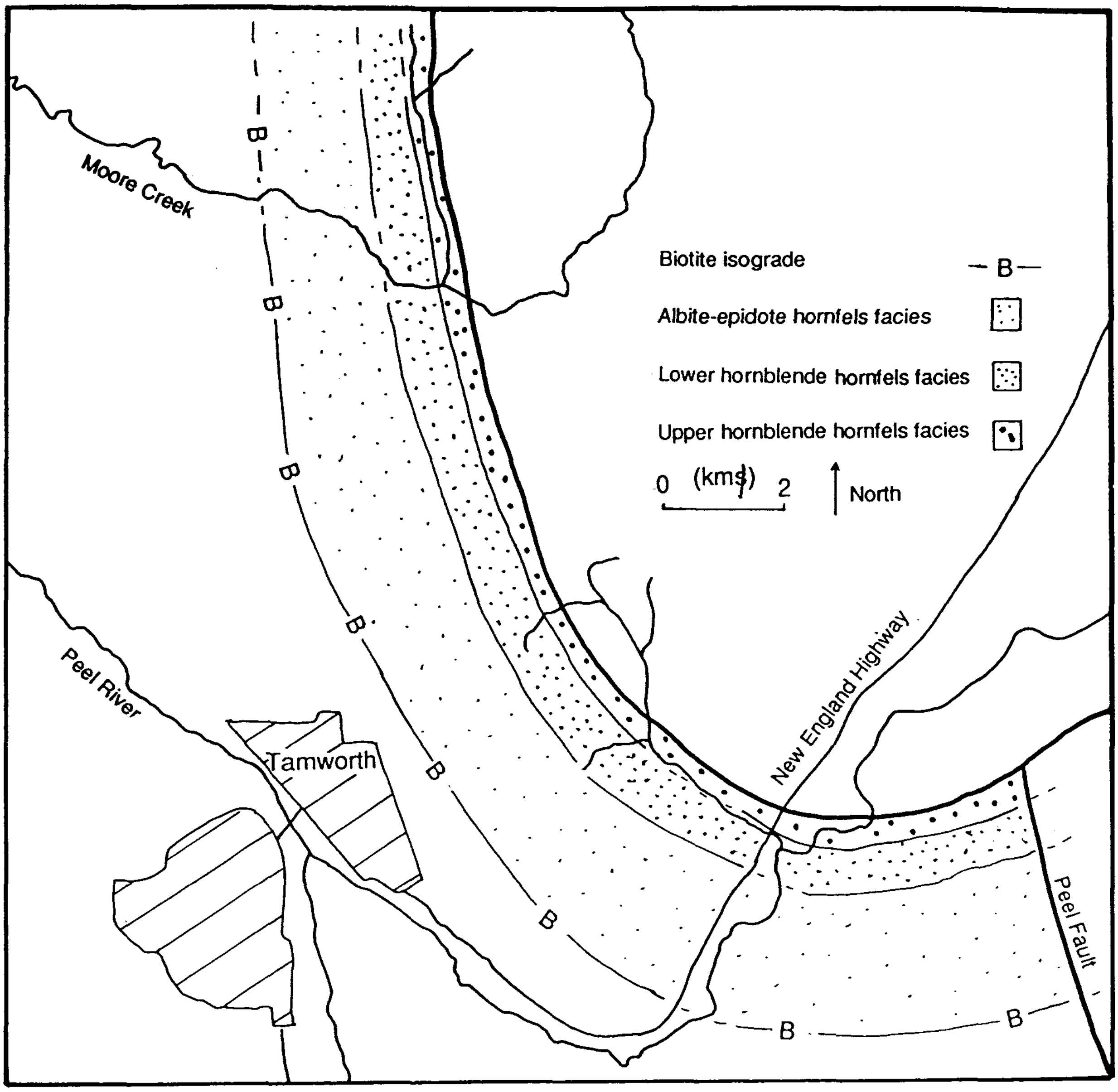


Figure 14. METAMORPHIC ZONES OF THE TAMWORTH AREA.

3.3 Petrogenesis

Mineral assemblages within the aureole of the Moonbi Adamellite attest to progressive contact metamorphism within a low pressure regime. At the highest grades, assemblages may indicate upper hornblende hornfels facies conditions were achieved during peak metamorphism.

Pressure. Estimates of the confining pressure within the aureole could not be made using conventional mineralogical geobarometers as the mineralogy of the Tamworth area is not suitable to do so. However, an approximation can be made using the low grade regional metamorphic rocks. Offler and Hand (1988) indicated a pressure of about 2-3 kbar during the peak regional conditions. However these conditions occurred before the intrusion of the plutons; hence the pressure would have decreased (Leitch 1974). An optimum estimate for the Tamworth area would be 1-2 kbar of pressure during emplacement.

Temperature. The peak temperature of metamorphism is consistent throughout the area with hornblende hornfels facies seen at the contact and in a meta-sedimentary xenolith (Tw 4). Using a confining pressure of 1-2 kbars, the peak temperature, recorded as upper hornblende hornfels facies, is 620°-580°c (Winkler 1979). Temperatures of the lower boundary, between the albite-epidote hornfels and the hornblende hornfels facies, which is marked by the disappearance of chlorite, occurs at 520°c (Winkler 1979). The biotite isograd occurs at a large interval between 370°-420°c.

CHAPTER 4.

CONTACT METAMORPHIC FLUIDS:

4.1 Preamble and literature review;

A review of the current literature provides a basis for interpreting the timing, origin and mechanisms of metamorphic fluids in the Tamworth area. The review indicates that fluids play a significant role in metamorphism and that they deserve special attention.

Metamorphic fluids interact with the contact rocks to change significantly their chemistry and mineralogical evolution during metamorphism (Kerrick 1991). Previous interest in metamorphic fluids has had an emphasis on related economic deposits and metals carried by the fluids. Recent studies have concentrated on the source and composition of the fluids, and transport models to determine flow paths.

The fluids found in contact metamorphic aureoles have various sources: (1.) from meteoric waters (Hanson 1992), (2.) from igneous intrusions, as fluids may be associated with devolatilisation of plutons as they crystallise (Chenhall et al 1988), (3.) fluids can be produced by prograde metamorphic reactions (Winkler 1967), producing both water and carbon dioxide, (4.) metasomatic fluids which are exotic fluids that flow along large temperature gradients (Ferry & Dipple 1991).

Water is generally the most voluminous constituent of metamorphic fluids and, combined with carbon dioxide, acts as an important control on certain assemblages and reactions (Brickle and Barker 1990). Models of real situations, in which fluids contain several other components such as salts, have found that the behaviour of the mineral-fluid equilibrium would change considerably. Labotka (1991) shows the effects of increasing the quantities of salts and carbon dioxide increasing the solubilities on the quartz-H_2O and calcite-H_2O systems. Sterner and Bodnar (1991) used a synthetic fluid inclusion technique to measure P-V-T-X relationships in the CO_2-H_2O system. They found that the P-T conditions for contact metamorphism do not allow coexisting water and carbon dioxide, unless there other solutes such as NaCl present. Metamorphic rocks can commonly contain fluids with salinities of 0-25wt% NaCl (Brickle and Barker 1990).

The rate at which prograde metamorphic reactions proceed is dependent on the ability of fluids to migrate (Brenan 1991). Migration can occur through the pore spaces and crack networks of the rocks, and this may be thermally induced, where the fluid pressure exceeds the strength of the rock (Brenan 1991). The driving force behind fluid movement is heat, i.e.when a convection cell is set up by the fluids. The surface tensions of the fluids themselves can also account for some of the movements where fluid particles attract one another (Brenan 1991). However, fluids which travel through cracks caused by deformation is possibly the most common transport mechanism (Hanson 1992).

Hanson (1992) produced a model which suggests that the movements are at a maximum during the initial part of the thermal evolution along the side of the contact. The main path of flow is upward and away from the contact, towards lower temperatures. As time continues the maximum fluid pressures can be found further away from the contact, which implies that fluids flow towards the contact, then up and away from the heat source. The problem with the Hanson (1992) model is that fracturing of the rocks has not been accounted for, as this would allow flow of fluids to be directed along pathways.

Rock type is a major factor in fluid flow. Different rock types have different permeabilities and can channel fluids differently according to pore space. Calc-silicate rocks often have a high permeability and can act as sinks for fluids. Prograde metamorphic reactions tend to be dependent on the compositions of the fluids,e.g. the formation of wollastonite in the presences of CO_2. The carbonate-free meta-pelites are deformed and metamophosed without being dependent on fluids (Ferry 1991). Hence, in some areas fluids could be channelled along certain rock types, e.g. calc-silicate units which are interbedded with peraluminous rocks.

The effects of fluid production are strongly time dependent, as the energy driving the aureole system is being lost as the intrusion cools (Hanson 1992, Ferry 1991). A quantitative idea of the time involved can be obtained using the measured progress of prograde reactions, by the sequence spacing of mapped isograds in the contact rocks (Ferry 1991). If an estimate of time could be made, the amount of fluid can be estimated, using the permeability of the rocks and possible fluid contents.

4.2 **Metamorphic Fluids in the Tamworth Area;**

The production of metamorphic fluids in the Tamworth area can have two sources namely: (1) solely the product of prograde metamorphic reactions; or (2) the Moonbi pluton, by release of magmatic water during crystallisation. Large amounts of water driven off by the pluton would have a pronounced effect on the contact rocks (Kerrick 1970), and would produce a retrograde metamorphic facies. This would occur because the water would be slowly driven off after the peak metamorphism had been reached (Kerrick 1970). In the Sierra Nevada, Kerrick (1970) failed to find any retrogression, and then concluded that the plutons did not contribute to the fluid content. No retrogressed rocks were indentified in the Tamworth area and this study suggests that the magmatic fluids were released along the abundant pegmatite dykes found along the contact (plate 41).

Yardley and Long (1981) concluded that the Easky adamellite in the Ox Mountains, Ireland, was emplaced as an H_2O-undersaturated magma. Water was taken from the aureole as the pluton crystallized. They quote (p. 131) "It has been pointed out (Brown and Fyfe 1969) that granite magmas must be deficient in H_2O in order to rise in the crust, and they will therefore tend to take up water from the country rocks." This study suggests that the Moonbi adamellite rose as the Easky adamellite, as a H_2O undersaturated magma. The fluids are the product of prograde reactions and meteoric waters, and that the fluid flow was towards the pluton.

The fluids appear to travel along fractures in the rocks. In hand specimen the less permeable rocks such as the massive hornfels and igneous rocks, are commonly veined. During the peak deformation, the introduction of the fluids caused the rocks to fracture and then open, allowing fluids to move through the

Plate 41. The contact of the Moonbi Adamellite is characterised by abundant pegmatites. This photo was taken in Oaky Creek in the north of the area.

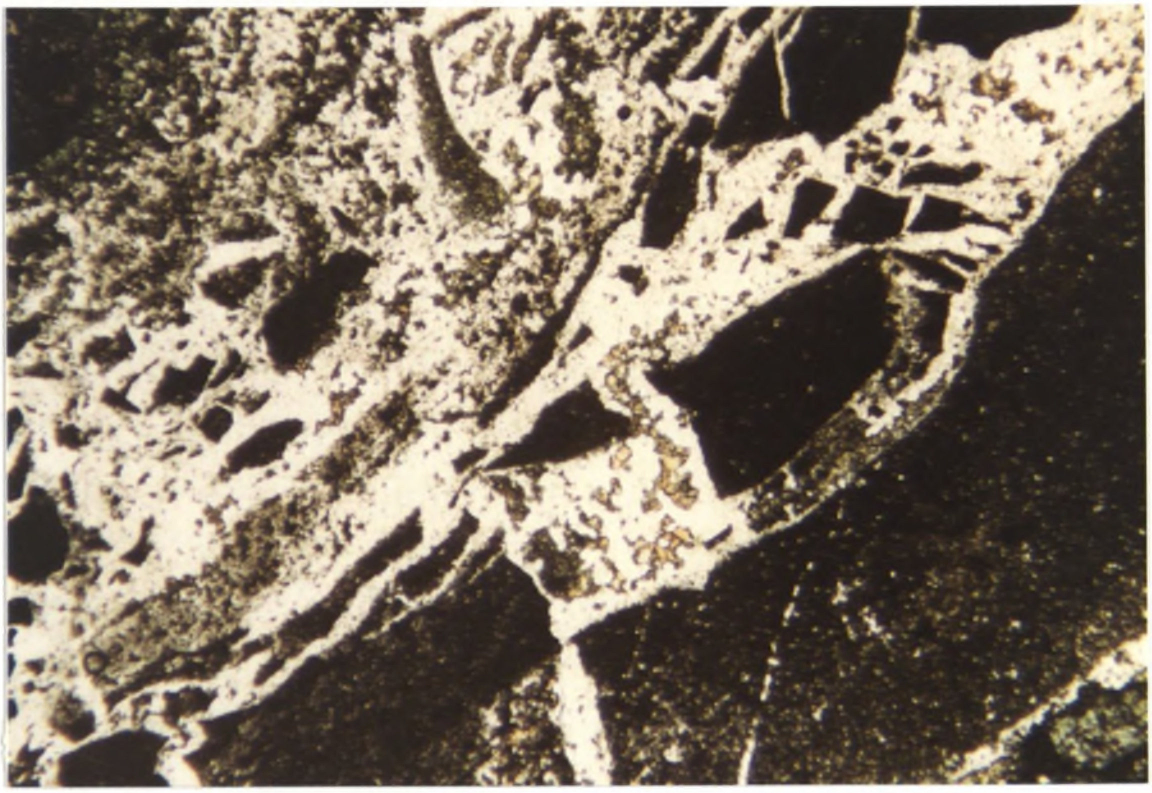


Plate 42. Tw 5. Evidence of forceful fracturing of the country rocks. The result is that veins are often brecciated and contain material from the country rocks. (PPL 1·25)

rock and crystallise minerals along the openings (Plate 42). In the Oaky Creek Andesite, veins are seen where no forceful fracture of the rock occurred; rather the fluids reacted with the matrix and moved along passively, possibly using pore spaces.

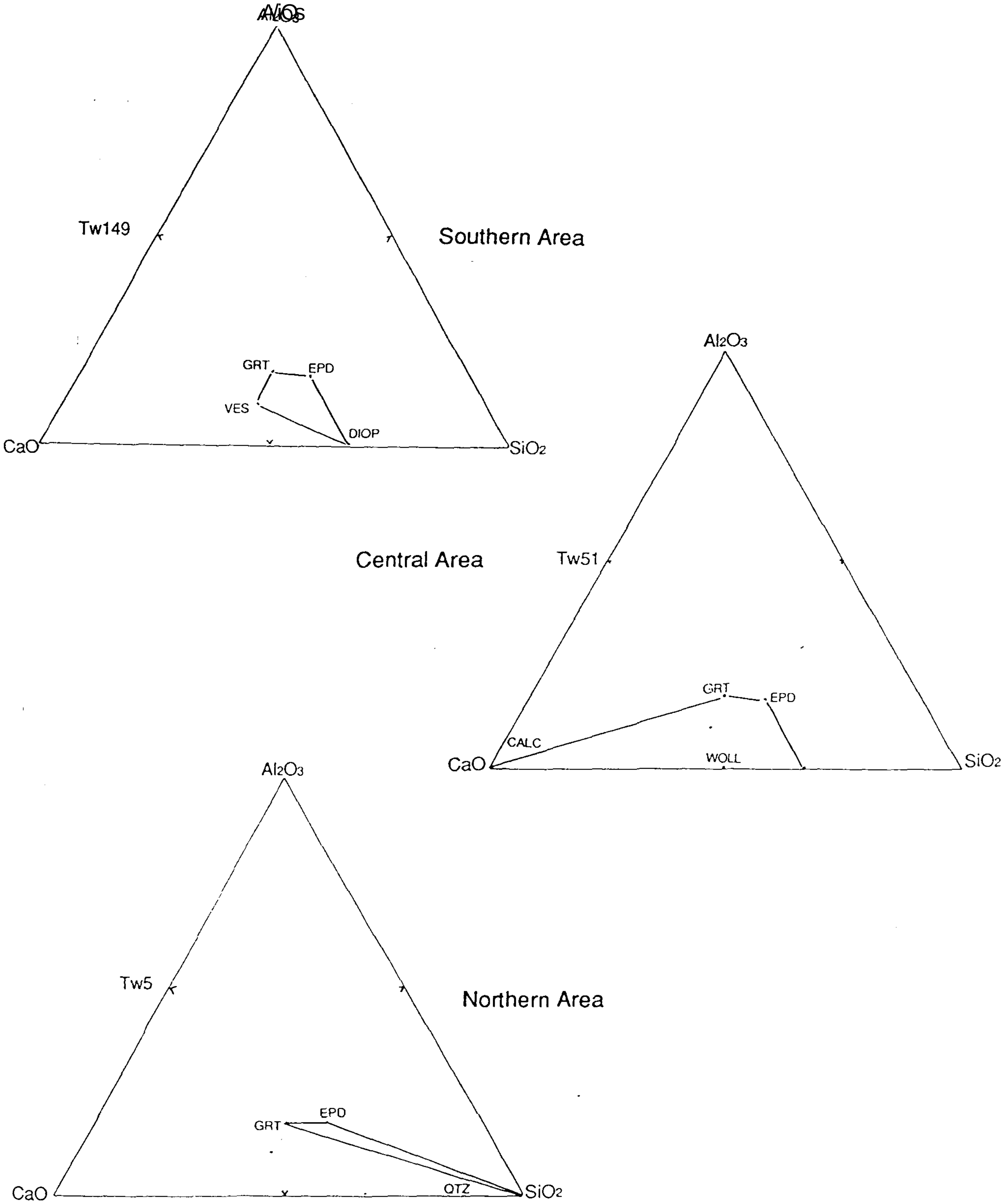
There is great variation in the types of veins in the area (figs.15). To the north, where calc-silicates are less abundant, the vugs and veins in the hornfels contain epidote, garnet and quartz assemblages (Plate 43). In the centre of the area the veins contains calcite, wollastonite, and garnet (Plate 44), whereas the veins to the south contain diopside, vesuvianite, garnet and epidote (Plate 45). The variation is due to the different local rock types from which the fluids originated and then moved through. Lasaga (1989) outlined a model for fluid flow and chemical reaction kinetics. In this model the reactions caused by the presences of the fluids are controlled by: (1), the heating rate, i.e. closeness to the pluton, (2) the surface area of the reactive minerals as seen in Tw 5 where the amphibole was not effected by the fluids but the finer grained matrix reacted to form epidote and garnet, (3) porosity, as seen in Tw 13 and 14, where the porous nature of the rock allowed fluids to travel through the rock without fracturing it.

Minerals related to metamorphic fluids;

Vesuvianite. Vesuvianite-rich hornfelses were studied by Vallance (1974) in the Lachlan Fold Belt. He found that vesuvianite is stable in calcareous rocks in medium-grade contact metamorphism. Vallance (1974) concluded that vesuvianite forms under H_2O rich conditions. The presents of small quantaties of CO_2 can reduce the production of vesuvianite.

The vesuvianite in the Tamworth Terrane is thought to indicate the direct composition of the fluid phase in that area as it is found in vugs with diopside, epidote, and grossular garnets.

Figure 15. Variation in the metamorphic fluid phase assemblages across the Tamworth area



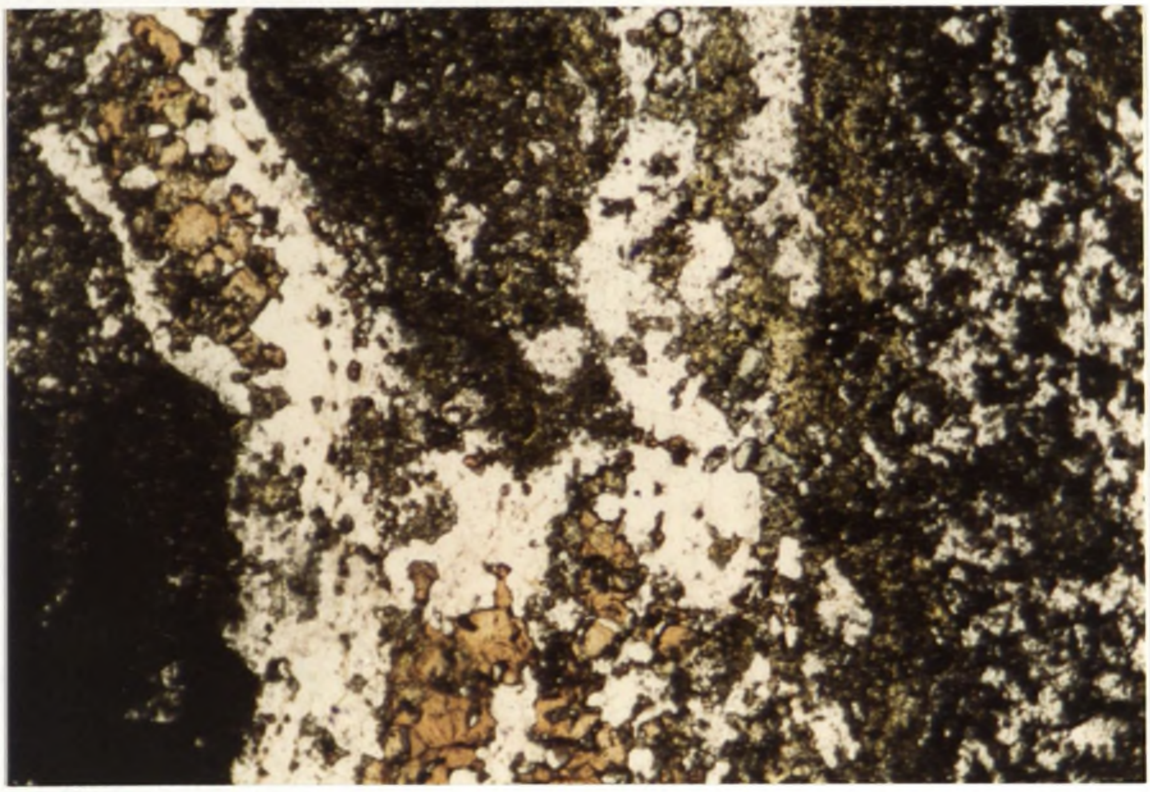


Plate 43. Tw 5. Fluid phase assemblage from the northern area. Orange garnet, yellow epidote and clear quartz. (PPL 1·25).

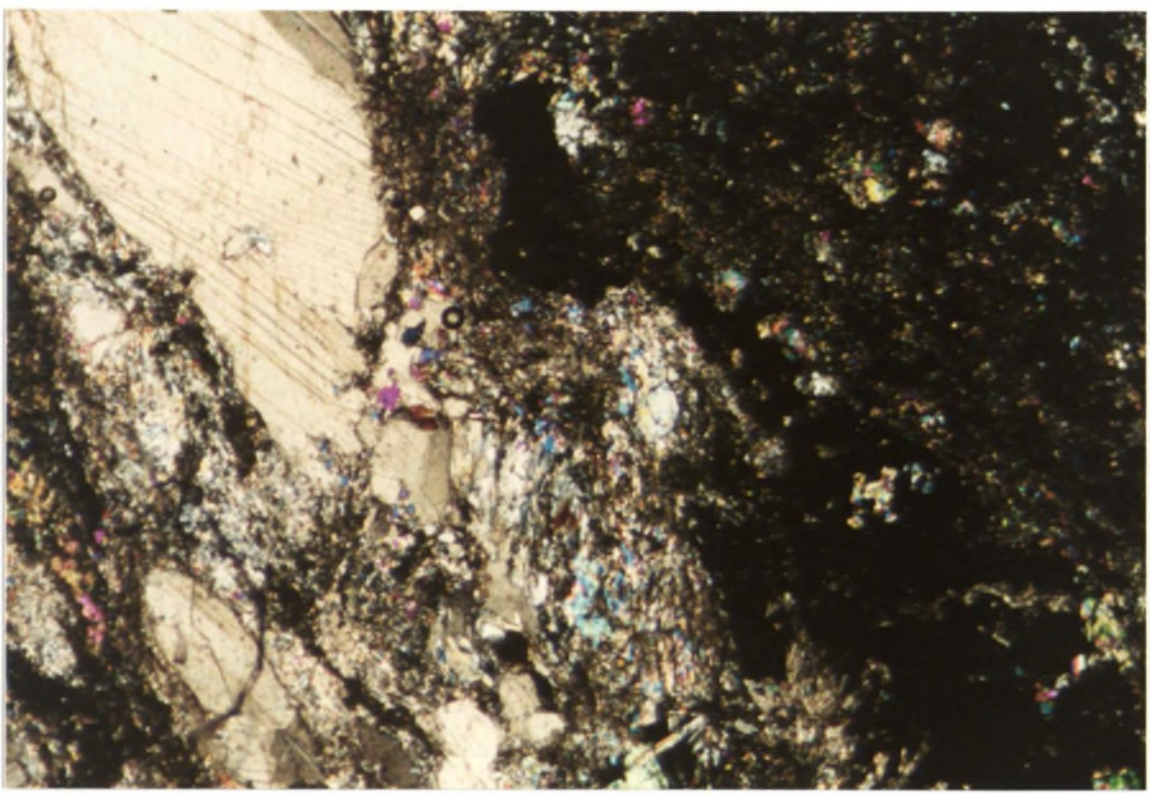


Plate 44. Tw 51. The fluid phase assemblage of the central area. Calcite, wollastonite and garnet. (XP 1·25).

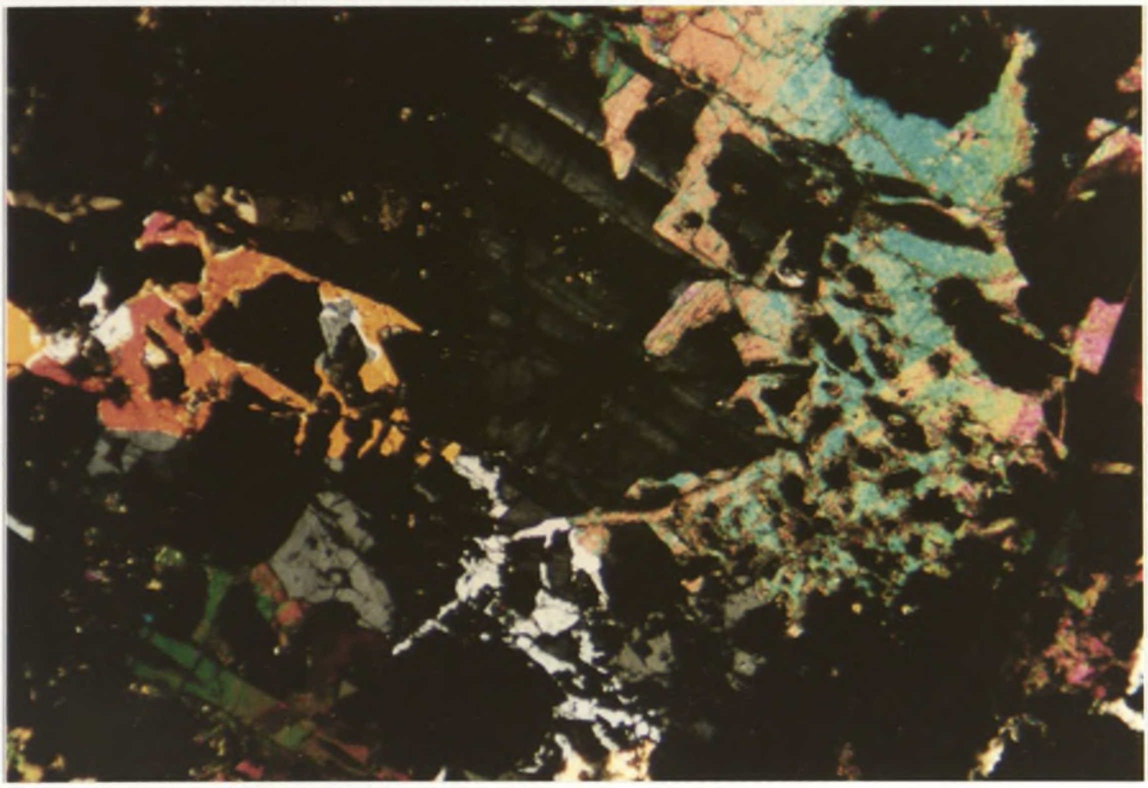


Plate 45. Tw 149. Coarse vein minerals from the southern area. Diopside, zoned garnet and vesuvianite are shown in the plate. However epidote is also common in this assemblage (XP 1·25)

Diopside. Microprobe analysis of a calc-silicate rock (Tw 14) shows that two diopside compositions exist. This study proposes that both the pyroxenes are products of contact metamorphism, rather than one being a residual igneous clast. The regional metamorphic event was of too low grade to produce diopside in the calc-silicate rocks, which implies that the two diopsides are products of the contact metamorphism. The larger grains are rich in MgO whereas the smaller diopside grains are FeO rich. This may be due to FeO being involved in other reactions such as the one producing garnet, while MgO was free to produce pyroxene.

Malachite. In the northern section of the field area traces of malachite can be seen in joints and fractures of the massive hornfelses (Tw 71). This copper carbonate mineral is commonly associated with skarn deposits. The origin of the copper is impossible to trace and the localised and minor quantity of the mineral distribution seems trivial to the total fluid phase. However the importance of the malachite is that the copper would tend to travel in a solution containing salts such as NaCl, indicating that the fluids were complex solutions containing H_2O, CO_2, NaCl, as well as metals and and silicates.

Garnet. Most garnets in the Tamworth Area are found in the calc-silicates or fluid phase deposits,i.e. veins and vugs. The compositions of the garnets in Tw14, which was analysed using an electron microprobe, are between grossular and andradite. Low totals from the sample suggest that the grossular is hydrous; this is assumed, as H_2O cannot be identified in the microprobe analysis. Deer et al (1966) argued, that there is no evidence that suggests that the grossular typical of contact metamorphism contains appreciable amounts of water.

Compositional zoning can be seen in thin section (Plate 45) and was the target of a microprobe analysis. The results are seen in fig 16, show that the zoning is caused by a layer rich in Fe and Ti, but low in Al.

Gordon and Greenwood (1971) found that grossular (rich in Al_2O_3) garnets indicate H_2O-rich conditions. However, grossular can form under conditions of up to X_{CO_2}=0·20 (Gordon and Greenwood 1971). The presence of andradite (FeO rich

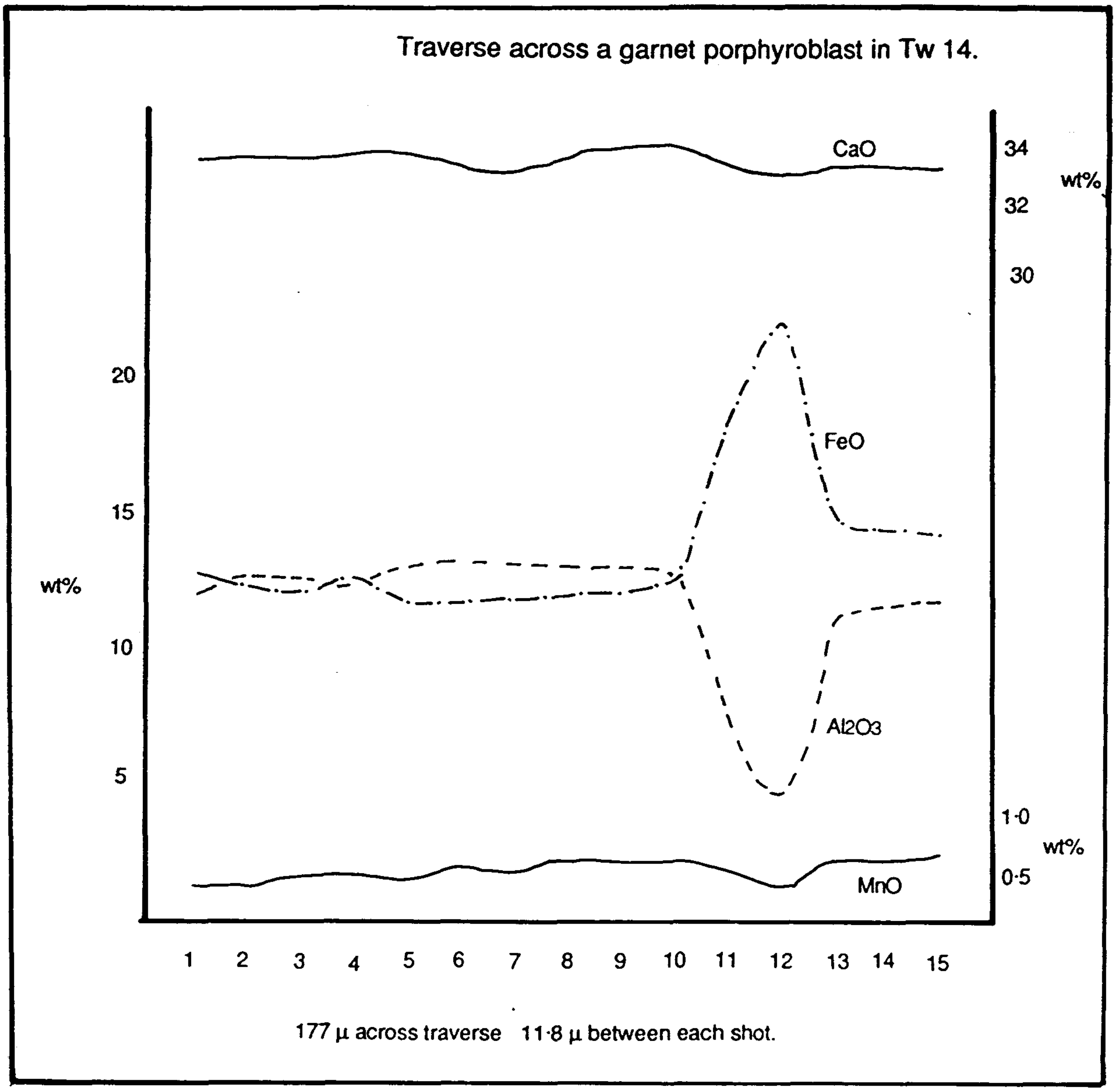

Traverse across a garnet porphyroblast in Tw 14.
CaO
34
wt%
32
30
20
FeO
15
wt%
10
Al2O3
5
1·0
wt%
0·5
MnO
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
177 μ across traverse 11·8 μ between each shot.

Figure 16.

garnets) would allows garnet to be stable at slightly higher X_{CO_2} conditions (X_{CO_2}=0·25 at 600°C, Chenhall et al 1988).

In conclusion, the fluids that characterised the high grades travelled along veins caused by fracturing of the rocks as the fluid pressure increased during peak deformation. The composition of the fluids was H_2O rich with varieties having up to X_{CO_2} ,<·25. Salts such as NaCl were also likely to be present.

CHAPTER 5.

THE MOONBI ADAMELLITE:

The New England Orogen (NEO) is characterized by over a hundred plutons ranging from abundant adamellites to the less common granodiorites, monzonites and gabbros. Shaw and Flood (1981) divided all the granites into five suites, "on the basis of geochemical, mineralogical and isotopic characteristics". The primary interest in this study is the 'I' type Moonbi Plutonic suite which was emplaced in the later of the two major periods of plutonism which took place in this region. The first phase, during the upper Carboniferous, is separated by the Permo-Triassic event by a major phase of metamorphism and deformation within the NEO (Shaw and Flood 1981; Kleeman 1988; Leitch 1974). It has recently been said that the time of emplacement of the Moonbi Plutonic Suite, the crust was under no tectonic movements or strains (Kleeman 1988).

The Moonbi Plutonic Suite is characterized by large pink orthoclase phenocrysts which are generally rich in mafic minerals such as hornblende, biotite, minor augite, sphene and magnetite (Shaw and Flood 1981). The largest of all the plutons in the Moonbi Suite is the Moonbi Adamellite, which is the central topic in this study. Chappell (1978) described the Moonbi Adamellite as essentially massive (plate 47). A weak primary foliation is present at the contact which was gauged in the field by the alignment of phenocrysts or sometimes the enclaves. A chemical variation is present; but it is unsystematic as there are no concentric zones through the pluton.

The mechanisms by which large, high level plutons such as the Moonbi Adamellite (248 km2) intrude through country rocks is one of the largest of all geological problems. It is not a process that can be studied at the Earth's surface; hence many different models, combined with field-based studies, have been brought forward to try to explain possible methods of transport and emplacement of magma, some of which are discussed in this paper.

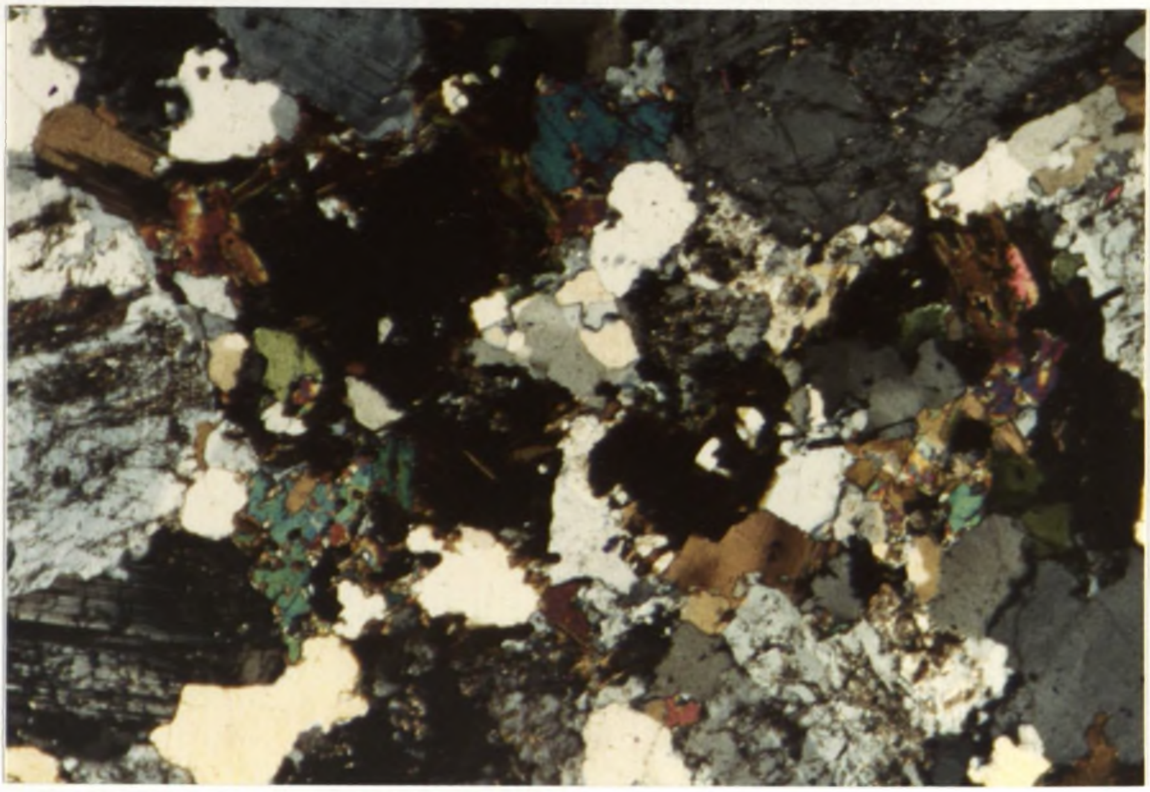


Plate 46. Tw4. Moonbi Adamellite showing no foliation and abundances of mafic minerals, e.g. biotite and hornblende. (XP 1·25)

Stoping: Stoping involves dislodging roof rocks at the top of the magma chamber. This broken-off material is thought to sink to the bottom of the chamber, with magma filling the space it leaves behind (Marsh 1982). Stoping as a mechanism has had a great deal of support from many authors (e.g. Cobbing and Pitcher 1972). However, current literature (such as Paterson et al 1991) overlooks stopping as a logical solution with regard to all plutons.

Application of the stoping model must explain "how wall rocks brake into xenoliths , how the xenoliths sink and where the xenoliths go " (Paterson et al 1991). Explaining how the wall rocks break up has been considered by Marsh (1982), who found that thermally induced stresses can greatly exceed rock strength. However, the greatest difficulty with the stoping model is the lack of wall rock xenoliths found in plutons (Paterson et al 1991). Therefore if stoping has occurred, it must be assumed that the xenoliths have been assilmated into the magma.

Ultimately, stoping is a self-limiting process, as broken up material would take up more room than the un-fractured rock (Paterson et al 1991). Marsh (1982) limits the ascent to a distance of two times the diameter of the pluton. Paterson and Fowler (1993) suggested that for stoping to occur space must have already be made at a lower depth. Even with these limitations, many authors agree that stoping could be significant at low depths (White et al 1974, Pitcher et al 1985), or during the late stages of emplacement (Paterson et al 1991).

Diaprism: "Only bodies of magma with a high crystal content and partly molten country rocks can ascend as diapirs" (Bateman 1984). Diaprism is the classical model of the upside-down teardrop rising due to gravitational forces. As the diapir rises space is made by aureole deformation, i.e. the rim is pushed aside and a down and return flow of wall rock occurs. However, recent studies have exposed many difficulties with diaprism. The experimental results of Van der Molen and Paterson (1979), show that the wall rocks must undergo approximately 30% melting in order to achieve the low viscosities required for diapiric plutonic ascent

(Paterson et al 1991). Most high to medium level plutons lack migmatites around the contacts, which would be the only evidence of partial melts.

Deformation in the surrounding rocks can be accounted for by some element of diaprism, or ballooning (Bateman 1984). Bateman (1984) believed ballooning diapirs occur when a magma becomes too crystalline (25% melt) to continue to rise. As magma continues to arrive at the level, at which the pluton had been immobilized, water is released with other fluids into the aureole, making it susceptible to deformation. This allows in situ radial expansion of the magma chamber (Paterson et al 1991) marked by a foliation around the pluton with some compositional zoning. The ballooning foliation would over print any previous magmatic foliation, as described at length in Paterson et al (1989).

The obvious difficulty in applying this to field examples is the space problem. Paterson et al (1991) suggested that the amount of area that can be made by ductile wall rock flow is in no case more than 50% and in most cases only 15 to 30% of the area required. Hence, the deformation in and around the contact aureole is far too low to account for this type of emplacement alone (Paterson et al 1991).

Recent modeling of diaprism as a transport mechanism suggests that large plutons could not reach high levels in the crust (Clements and Mawer 1992). The results of the most recent studies suggests that a body which is transported as a diapir would suffer thermal death and crystalise in the middle crust, rather than continuing to rise into the upper-crust.

Cauldron Subsidence: As with stoping, cauldron subsidence requires brittle fracture of wall rocks, and tends to occur at shallow depths. The fracturing involves a single, roughly cylindrical block that is 'down-dropped' along steeply dipping ring faults. This creates space for a bell-jar shaped pluton (Paterson et al. 1991).

Laccoliths: Laccoliths are high level intrusions where the roof is lifted to make space for the rising magma due to a density difference between the wall rocks and the magma (Corry 1988). Laccoliths were first proposed in North

America by Gilbert in 1877. The diverse shapes of laccolith intrusions observed in the field can be represented by a continuous series of intrusion modes between two distinct end members (Corry 1988). Laccoliths are formed by forceful intrusion of magma forming sills often along bedding planes. There is no clearly defined point at which a sill becomes a laccolith (Corry 1988). Laccoliths can also have fault bounded margins which can produce asymmetric intrusions. Therefore, laccoliths can be controlled by the country rocks around the intrusion (Corry 1988).

Dyke Propagation One of the more recent transport mechanisms is dyke propagation, as suggested by Castro (1987). This relies on fracture development at depth, due to a constant magma source. It allows granitoids to ascend via narrow channels from their source to their final position of emplacement (Castro 1987). Other mechanisms may then be seen as final emplacement processes rather than magma transport mechanisms (Clements and Mawer 1992).

Dyke propagation has also been seen as significant to other processes such as a ballooning diapir by Bateman (1984). Ballooning diapirs may grow as they are fed by dykes. It maybe possible that dykes are associated with all mechanisms of granitic emplacement. However, the shapes and characteristics of the pluton necessarily reveal anything about the transport of their precursor magmas (Clements and Mawer 1992)

Regional Deformation: An important factor in any mechanism is the fact that granites often intrude into regionally tectonic active areas (Paterson et al. 1991). Paterson and Fowler (1993) concluded that emplacement of plutons must be syn-tectonic with respect to at least some deformation in the wall rocks. However emplacement of magma which is controlled by regional deformation is best developed at depth. This is due to the buoyancy force of the magma at depth being not sufficient to displace the wall rocks (Paterson and Fowler 1993). The regional deformation or the tectonics of the area may control the types of emplacement mechanisms. Paterson et al. (1991) and Pitcher (1979) have brought forward two models that show the effect of regional deformation and the types of mechanisms that ca be expected in different tectonic regimes.

Evaluation of Emplacement Mechanisms: Models that have been produced by authors mentioned above suggest open simplified models of emplacement mechanisms. This is mainly due to a lack of three dimensional exposures. Two such models are summarised by Paterson et al (1991) and Castro (1987). Castro (1987) relies on the type of deformation of the surrounding rocks and the chemistry of the pluton to determine the final structure. Paterson et al.(1991) also defines his model by deformation around the surrounding rock, as well as changes in depth.

If any conclusion can be drawn it is that no one single mechanism can account for any single pluton. More over, many well established ideas can no longer be held in high regard. Rather more likely histories include dyke propagation transporting the magma from depth. Emplacement would then be controlled by the the depth of emplacement, any deformation as well as the wall rocks. It is most likely that emplacement would involve multi-mechanisms; rather than a single emplacement mechanism (Paterson and Fower 1993).

Review of Granitic Emplacement in the NEO:

Research in the NEO has often focused on the plutons which make up much of the central and eastern sections of the NEO. An extensive study of the intrusions in the southern NEO was completed by Flood (1971). He concluded that plutons which have developed a wide contact metamorphic aureole would not have had any substantial upward movements after crystallisation. Other plutons show solid state foliations which implies that these intrusions continued to rise or expand after the magma had crystallization (Flood 1971).

A comprehensive study was completed on the Carrai Granodiorite by Leitch (1976). Steeply dipping margins, an incomplete contact metamorphic aureole, and limited deformation in the surrounding rocks characterize the pluton. Leitch (1976) concluded that stoping was unimportant and that emplacement involved vertical displacement of the roof. Leitch (1976) suggested a close relationship existed between faulting and emplacement as the aureole is terminated on one side of the intrusion. Kleeman (1988) propose that country rock structures influence the shape of the plutons. He also suggested that the area was under no tectonic movement at the time of emplacement of the plutons (Permo-Triassic age). Hence, any faulting that occurred with the emplacement of the plutons is driven by the rising magma.

Clare (1988) proposed an emplacement model based on two 'I' type, Late Permian plutons, the Looanga and Bendmeer Adamellites. He suggested the that magma rose by dyke propagation and diapiric means then stoped its way to higher.levels by a series of single block-stoping events with diapiric forces slightly deforming the country rocks.

The Transport and Emplacement of the Moonbi Adamellite.

The following features were recognised in the Tamworth area as being caused by the transport and emplacement of the Moonbi Adamellite.

- Sharp intrusive contacts.
- Wide, concentric metamorphic zones.
- Low abundances of meta-sedimentary xenoliths.
- Evidence of only minor pluton foliations.
- No reported geochemical contamination of the pluton.
- No concentric compositional zoning within the pluton.
- Bedding is virtually undisturbed except within 10 m of the contact.

These features are seen as constraints on which a model representing the transport and emplacement of the pluton is based.

This study supports the proposal of Paterson and Fowler (1993); that the ascent and emplacement of magma requires multiple emplacement mechanisms. Hence the model proposed in this study includes elements of different mechanisms as the conditions in the aureole change with time.

The constraints which can be seen within and outside the pluton indicates that stoping was unimportant in the emplacement of the Moonbi Adamellite. This is due to the lack of meta-sedimentary xenoliths. The insignificant deformational fabric developed by the intruding pluton on the aureole disregards diaprism as a transport mechanism. However, close to the contact some evidence suggests that ballooning diaprism as an emplacement mechanism is possible. Assimilation of the country rocks is unlikely as no geochemical contamination can be observed in the pluton.

A model of transport of magma from depth and the emplacement of the pluton is presented in fig.17. This model satisfies all the constraints listed above. The transport of magma from depth in the crust, moves through narrow feeder dykes into the upper crust. Movement in the feeder dykes can be rapid as reported by Clements and Mawer (1992). To be capable of rising to high levels , the magma would have been H_2O-undersaturated, as reported in Chapter 4.

The model suggests that initial space was made by the forceful intrusion of the magma into cold upper crustal rocks. The forceful nature of the rising magma, due to buoyant forces, fractured the country rocks and raises the roof. As the pluton expanded the country rocks heat up and P_{fluid} increases to a point where the aureole allowed ballooning of the pluton. The late stage ballooning event is only small scale compared to the earlier block lifting event.

While evidence of the late stage ballooning can be seen within the aureole (Chapter 2·3), Evidence for faulting can not be seen in the Moonbi area. The Inlet Quartz Monzonite (fig.2) is a smaller neighbouring pluton in the Moonbi Suite (Shaw and Flood 1981) and it can be used to support the first stage of development. It shows straight sides unlike the Moonbi intrusion. This study considers that the Inlet intrusion did not mature as the Moonbi did. Hence, it did not balloon in the manor that the Moonbi Intrusion did. This may be due to a shorter metamorphic event (the Inlet intrusion is smaller hence it would have cooled faster than the larger Moonbi intrusion).

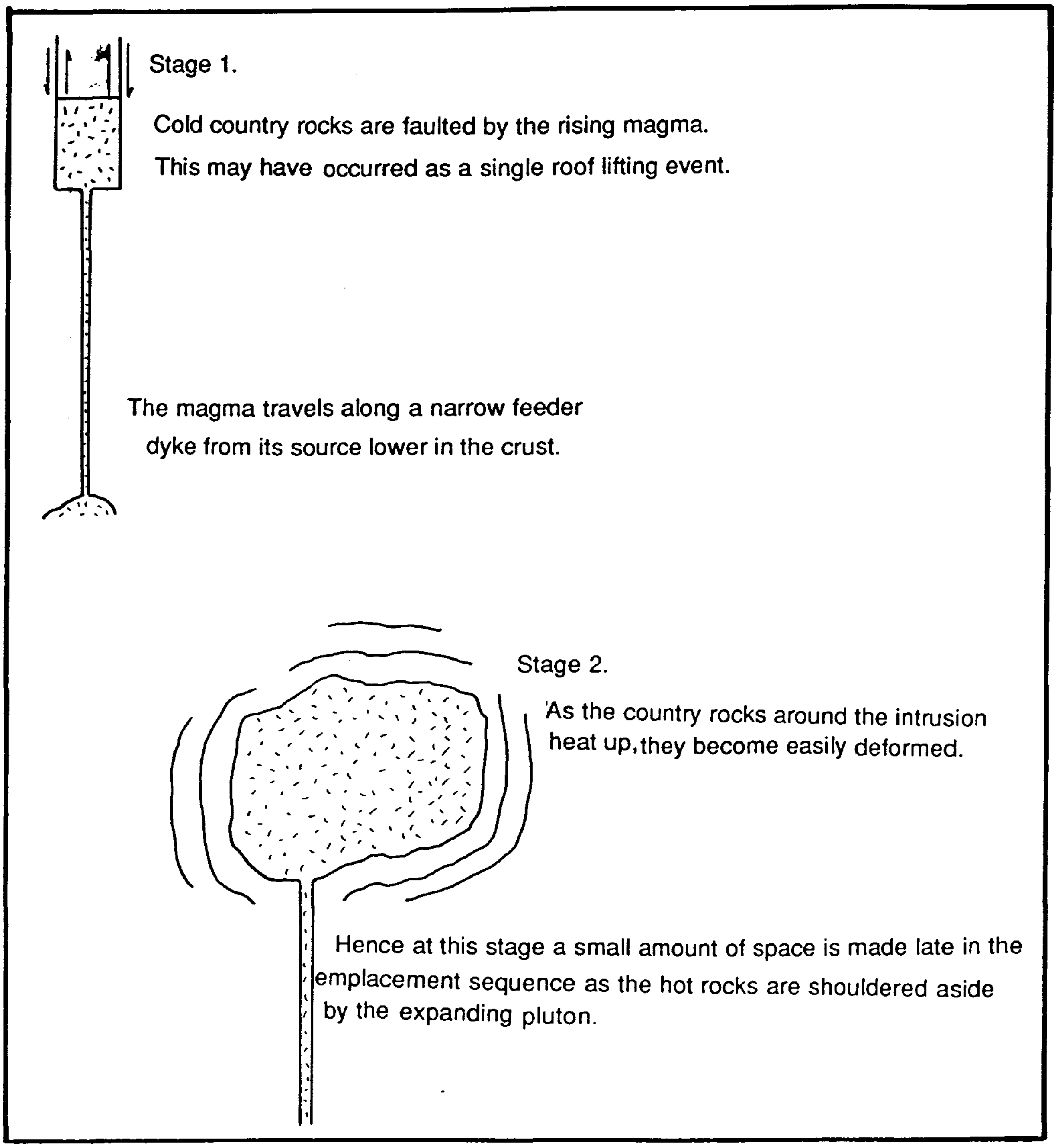


Figure 17. MODEL OF THE EMPLACEMENT MECHANISM OF THE MOONBI ADAMELLITE.

CHAPTER 6.
CONCLUSION:

The purpose of this study has been to define a mechanism of granitic emplacement by investigating the contact metamorphic rocks which surround the pluton. While previous studies have concentrated on the sediments east of the Peel Fault; this thesis examines the fore-arc sediments of the Tamworth Terrane. In doing this the nature of the sediments and mafic igneous rocks of the Tamworth area were discussed as well as the origin and environment of deposition.

The sediments were suggested to have been deposited as turbidite flow sequences as a complete Bouma sequence was recognised. However, this thesis concludes that deposition did not occur at great depths. This is due to the absence of any characteristics that are indicative of deep water conditions, such as cherts. However, no shallow marine features such as beach deposits were observed in the area. The limestones found in the Tamworth area were divided into two types: (1) isolated lenses of limestone, and (2) large or coherent units. Type (1) represents limestone of exotic nature as they have been transported within a mass flow. Type (2) represents limestones that are insitu and do not show any features that suggest that they have been transported.

The mafic igneous rocks identified in the Tamworth area includes the Oaky Creek Andesite found in the north of the area which has not yet been reported. Dolerites and spilites were found in the south of the area. This study found that some intrusion of mafic bodies has occurred. However this was not conclusive and therefore this study can not could not suggest whether the bodies were all intrusive or extrusive.

Structures in the Tamworth area were divided into pluton related and regional deformation. This study concludes that the pluton related structures are syndeformational contact metamorphic. Local deformation is directly related to the forceful intrusion of the pluton as well as small volume changes in the metamorphic rocks. Deformation appears to have occurred after metamorphism began, but that the heating outlasted deformation.

The peak contact metamorphic grade was found to be upper hornblende hornfels facies (620-580°) at 1-2 kbar. The pressure was inferred using the regional metamorphic rocks. Temperatures of the lower boundary, between the albite-epidote hornfels and the hornblende hornfels facies, which is marked by the disappearance of chlorite, occurs at 520°C. The biotite isograd separates the regional metamorphic rocks from the aureole at a distance of 3-4 km from the contact occurs. High grade rocks are characterised by veins from metamorphic fluids. The fluids appear to have two sources: (1) the product of prograde metamorphic reactions; or (2) meteoric water. The metamorphic fluids were varied across the area from H_2O rich to $X_{CO_2} < \cdot 25$. This study suggests that the Moonbi adamellite rose as a H_2O undersaturated magma and absorbed fluids from the surrounding wall rocks as it crystalised.

In conclusion, the Moonbi intrusion is the result of a two stage emplacement mechanism presented in fig 17. Rising magma from lower in the crust made space in the upper crust by roof lifting. As the wall rocks were heated by the magma small expansions occurred as the hot rocks were easily deformed. Supporting evidence for the second stage of the model has been presented in the previous chapters. However, the first stage of the model is only speculative; due to the brittle faulting being unrecognizable.

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APPENDIX:

APPENDIX ONE:

Chemical analyses of samples were completed using the *Cameca, Camebax SX50* electron micro probe located at Macquarie University. The analyses were achieved using an accelarator voltage of 15kV and a measured regulated current of 20nA. The beam size was 5µ, fired at a fixed spot. Counting times were over a 20 second interval, with 10 seconds on peak and 5 seconds on the two back grounds (before and after the peak). corrections to the data used the PAP procedure. Natural mineral standards were used in the analises which were;

Na- Albite

Mg- Forsterite

K - Orthoclase

Ca- Wollastonite

Ti- Rutile

Cr- Chromite

Mn- Spessartine

Fe- Haematite

B- Boron metal

The purpose of the microprobe work was to: test for axinite, to determine broad chemical changes in the amphiboles across the aureole and to determine the chemical composition of garnets in the calc-silicate rocks so as to achieve some constraints on the metamorphic fluid content.

RESULTS OF MICROPROB ANALYSES

note: the data shown are averages of the data collected.

Tw 14

garnet

			Wt.%
SiO2	37.0346	Si	17.3116
TiO2	0.9764	Ti	0.5853
Al2O3	12.3970	Al	6.5613
Cr2O3	0.0000	Cr	0.0000
MgO	0.0000	Mg	0.0000
CaO	34.0605	Ca	24.3433
MnO	0.2671	Mn	0.2069
FeO	12.8376	Fe	9.9789
Na2O	0.0000	Na	0.0000
K2O	0.0042	K	0.0035
total	97.5775		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 100.00

garnet

			Wt.%
SiO2	36.9399	Si	17.2674
TiO2	0.6563	Ti	0.3934
Al2O3	9.4523	Al	5.0028
Cr2O3	0.0597	Cr	0.0408
MgO	0.0000	Mg	0.0000
CaO	33.3157	Ca	23.8109
MnO	0.5892	Mn	0.4563
FeO	16.4740	Fe	12.8055
Na2O	0.0142	Na	0.0105
K2O	0.0000	K	0.0000
total	97.5012		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 100.00

K-feldspar

			Wt.%
SiO2	63.9252	Si	29.8815
TiO2	0.0286	Ti	0.0172
Al2O3	17.7277	Al	9.3826
Cr2O3	0.0000	Cr	0.0000
MgO	0.0017	Mg	0.0010
CaO	0.1407	Ca	0.1006
MnO	0.0161	Mn	0.0124
FeO	0.1630	Fe	0.1267
Na2O	0.4932	Na	0.3659
K2O	16.1016	K	13.3670
total	98.5978		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 98.38

amphibole

			Wt.%
SiO2	37.3803	Si	17.4732
TiO2	0.6628	Ti	0.3974
Al2O3	13.7007	Al	7.2512
Cr2O3	0.0729	Cr	0.0499
MgO	8.0256	Mg	4.8404
CaO	11.5490	Ca	8.2541
MnO	0.3168	Mn	0.2454
FeO	19.8932	Fe	15.4633
Na2O	1.0288	Na	0.7632
K2O	2.6197	K	2.1748
total	95.2498		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 58.56

fine diopside

			Wt.%
SiO2	48.8279	Si	22.8244
TiO2	0.3247	Ti	0.1947
Al2O3	2.5686	Al	1.3595
Cr2O3	0.0264	Cr	0.0181
MgO	8.1378	Mg	4.9080
CaO	23.1989	Ca	16.5804
MnO	0.4779	Mn	0.3701
FeO	14.2015	Fe	11.0391
Na2O	0.3715	Na	0.2756
K2O	0.0497	K	0.0412
total	98.1849		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 50.31

coarse diopside

			Wt.%
SiO2	52.1194	Si	24.3630
TiO2	0.0692	Ti	0.0415
Al2O3	1.3823	Al	0.7316
Cr2O3	0.0155	Cr	0.0106
MgO	13.3541	Mg	8.0540
CaO	24.4404	Ca	17.4677
MnO	0.3059	Mn	0.2369
FeO	7.3179	Fe	5.6883
Na2O	0.2979	Na	0.2210
K2O	0.0167	K	0.0139
total	99.3194		

Tw 120

amphibole

			Wt.%
SiO2	45.2308	Si	21.1429
TiO2	1.1229	Ti	0.6732
Al2O3	7.0492	Al	3.7309
Cr2O3	0.0000	Cr	0.0000
MgO	9.1694	Mg	5.5302
CaO	10.9730	Ca	7.8424
MnO	0.4279	Mn	0.3314
FeO	20.4922	Fe	15.9289
Na2O	0.7502	Na	0.5566
K2O	0.4921	K	0.4085
total	95.7077		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 56.15

plagioclase An 54

			Wt.%
SiO2	55.6875	Si	26.0309
TiO2	0.0047	Ti	0.0028
Al2O3	26.6707	Al	14.1158
Cr2O3	0.0000	Cr	0.0000
MgO	0.0000	Mg	0.0000
CaO	9.7704	Ca	6.9829
MnO	0.0000	Mn	0.0000
FeO	0.1655	Fe	0.1286
Na2O	4.4424	Na	3.2957
K2O	0.1170	K	0.0971
total	96.8582		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 100.00

plagioclase An 47

			Wt.%
SiO2	57.5897	Si	26.9200
TiO2	0.0000	Ti	0.0000
Al2O3	25.4329	Al	13.4607
Cr2O3	0.0039	Cr	0.0027
MgO	0.0000	Mg	0.0000
CaO	8.2297	Ca	5.8818
MnO	0.0000	Mn	0.0000
FeO	0.2603	Fe	0.2023
Na2O	5.0449	Na	3.7427
K2O	0.1220	K	0.1013
total	96.6835		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 100.00

plagioclase An 36

			Wt.%
SiO2	60.1228	Si	28.1041
TiO2	0.0047	Ti	0.0028
Al2O3	23.6813	Al	12.5336
Cr2O3	0.0000	Cr	0.0000
MgO	0.0000	Mg	0.0000
CaO	6.1901	Ca	4.4241
MnO	0.0352	Mn	0.0272
FeO	0.1270	Fe	0.0987
Na2O	5.9833	Na	4.4388
K2O	0.1095	K	0.0909
total	96.2540		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 100.00

Tw 142

epidote

			Wt.%
SiO2	37.4356	Si	17.4991
TiO2	0.1402	Ti	0.0840
Al2O3	22.8558	Al	12.0967
Cr2O3	0.0380	Cr	0.0260
Fe2O3	0.0000	Fe	0.0000
MgO	0.0000	Mg	0.0000
CaO	22.5160	Ca	16.0923
MnO	0.5926	Mn	0.4590
FeO	11.6811	Fe	9.0799
Na2O	0.0195	Na	0.0145
K2O	0.0201	K	0.0167
total	95.2989		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 100.00

white mica

			Wt.%
SiO2	47.3166	Si	22.1179
TiO2	0.0432	Ti	0.0259
Al2O3	24.3203	Al	12.8718
Cr2O3	0.0000	Cr	0.0000
Fe2O3	0.0000	Fe	0.0000
MgO	3.8927	Mg	2.3477
CaO	0.0921	Ca	0.0659
MnO	0.0766	Mn	0.0593
FeO	5.8059	Fe	4.5130
Na2O	0.0626	Na	0.0464
K2O	9.8889	K	8.2094
total	91.4990		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 45.89

magnetite

			Wt.%
SiO2	0.1090	Si	0.0510
TiO2	3.4148	Ti	2.0472
Al2O3	0.0437	Al	0.0231
Cr2O3	0.0386	Cr	0.0264
Fe2O3	63.2421	Fe	44.2339
MgO	0.0000	Mg	0.0000
CaO	0.0290	Ca	0.0207
MnO	0.0215	Mn	0.0167
FeO	34.6217	Fe	26.9120
Na2O	0.0000	Na	0.0000
K2O	0.0000	K	0.0000
total	101.5205		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 100.00

chlorite

			Wt.%
SiO2	25.6421	Si	11.9863
TiO2	0.0091	Ti	0.0055
Al2O3	18.4582	Al	9.7692
Cr2O3	0.0547	Cr	0.0374
Fe2O3	29.1210	Fe	20.3684
MgO	17.8829	Mg	10.7854
CaO	0.0495	Ca	0.0354
MnO	0.5310	Mn	0.4112
FeO	0.0000	Fe	0.0000
Na2O	0.0014	Na	0.0010
K2O	0.1784	K	0.1481
total	91.9283		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 1.66

plagioclase An 47

			Wt.%
SiO2	55.9718	Si	26.1638
TiO2	0.0047	Ti	0.0028
Al2O3	26.1123	Al	13.8202
Cr2O3	0.0313	Cr	0.0214
Fe2O3	0.0000	Fe	0.0000
MgO	0.0000	Mg	0.0000
CaO	9.4783	Ca	6.7742
MnO	0.0416	Mn	0.0322
FeO	0.4790	Fe	0.3724
Na2O	5.9660	Na	4.4259
K2O	0.1123	K	0.0933
total	98.1973		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 100.00

plagioclase An 41

			Wt.%
SiO2	57.6022	Si	26.9259
TiO2	0.0558	Ti	0.0334
Al2O3	25.2619	Al	13.3701
Cr2O3	0.0391	Cr	0.0267
Fe2O3	0.0000	Fe	0.0000
MgO	0.0000	Mg	0.0000
CaO	8.4202	Ca	6.0180
MnO	0.0192	Mn	0.0149
FeO	0.6237	Fe	0.4848
Na2O	6.5805	Na	4.8818
K2O	0.1025	K	0.0851
total	98.7051		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 100.00

plagioclase An 1

			Wt.%
SiO2	68.1342	Si	31.8490
TiO2	0.0179	Ti	0.0107
Al2O3	19.1759	Al	10.1491
Cr2O3	0.0000	Cr	0.0000
Fe2O3	0.0000	Fe	0.0000
MgO	0.0070	Mg	0.0042
CaO	0.2461	Ca	0.1759
MnO	0.0000	Mn	0.0000
FeO	0.1629	Fe	0.1266
Na2O	11.3187	Na	8.3969
K2O	0.2762	K	0.2293
total	99.3389		

Ratio (Fe+Mn)/(Fe+Mn+Mg) = 92.87

plagioclase An 2·5

			Wt.%
SiO2	67.3599	Si	31.4871
TiO2	0.0000	Ti	0.0000
B2O3	2.2373	B	0.6948
Al2O3	19.3169	Al	10.2237
Cr2O3	0.0039	Cr	0.0027
MgO	0.0180	Mg	0.0109
CaO	0.4122	Ca	0.2946
MnO	0.0000	Mn	0.0000
FeO	0.5482	Fe	0.4261
Na2O	8.5677	Na	6.3561
K2O	0.1386	K	0.1151
H2O	1.7795		
total	100.3824		

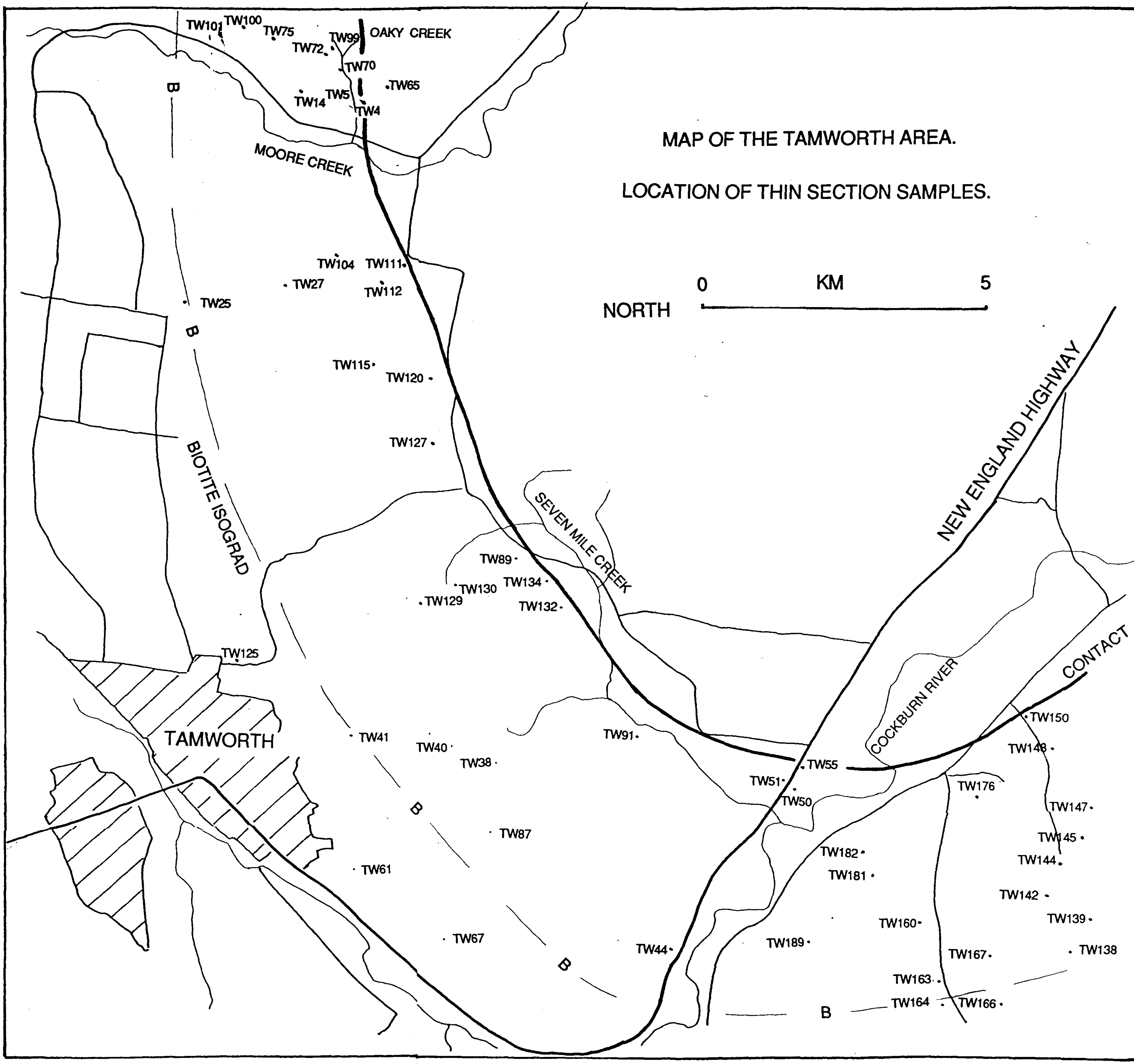
Ratio (Fe+Mn)/(Fe+Mn+Mg) = 94.46

Location of Rock Samples

Tw	MU	Grid Ref.	Map	Rock Type	Tw	MU	Grid Ref.	Map	Rock Type
1		046 689	A		100	52869	025 696	A	breccia
2		046 688	A		101	52860	019 703	A	conglomerate
3		046 689	A		102	52933	025 690	A	limestone
4		046 689	A		103	52927	024 683	A	limestone
5	52918	046 092	A	andesite	104	52858	043 645	T	limestone
6	52916	046 092	A	calc-silicate	105	52871	044 643	T	argillite
7	52905	045 092	A	calc-silicate	106		044 643	T	
8		045 091	A		107		046 643	T	
9	52895	044 093	A	calc-silicate	108		046 643	T	
10		044 092	AA		109		049 648	T	
11		044 092	A		110		049 648	T	
12		044 091	A		111	52859	047 655	T	lith-arenite
13	52896	042 091	A	lith-arenite	112	52941	051 653	T	lith-arenite
14		042 092	A		113		050 653	T	
15		042 092	A		114		049 652	T	
16		041 092	A		115	52870	048 652	T	argillite
17		039 692	A		116		048 652	T	
18		039 690	A		117		053 645	T	
19		022 679	T		118		062 639	T	
20		028 651	T		119		062 639	T	
21	52905	028 651	T	lith-arenite	120	52861	063 624	T	argillite
22		034 650	T		121		063 624	T	
23		034 649	T		122		053 622	T	
24		034 648	T		123		053 621	T	
25	52899	036 652	T	chert	124		042 614	T	
26	52921	036 652	T	argillite	125	52873	035 605	T	laminated argillite
27	52903	038 657	T	conglomerate	126		055 641	T	
28	52845	038 656	T	arenite	127	52851	055 642	T	laminated argillite
29	52913	038 656	T	arenite	128	52934	057 642	T	calc-silicate

30		025 645	T		129	52935	059 628	T	calc-silicate
31		022 667	T		130		060 628	T	
32	52883	022 667	T	limestone	131	52915	060 628	T	lith-arenite
33	52929	013 678	T	limestone	132	52867	071 609	T	limestone
34	52908	063 624	T	argillite	133	52864	073 607	T	limestone
35	52901	063 624	T	arenite	134		074 607	T	
36		063 623	T		135		074 607	T	
37	52862	059 589	T	calc-silicate	136		067 605	T	
38		055 589	T		137		071 611	T	
39		055 588	T		138		148 560	M	
40	52865	055 589	T	conglomerate	139		146 560	M	
41	52937	052 588	T	lith-arenite	140		147 563	M	
42		052 588	T		141		143 568	M	
43		050 589	T		142	52910	143 568	M	lith-arenite
44	52876	093 566	T	limestone	143	52891	142 570	M	chert
45	52866	088 560	T	conglomerate	144		148 573	M	
46	52909	110 585	T	argillite	145	52917	144 577	M	argillite
47	52919	110 585	T	arenite	146	52914	144 577	M	argillite
48	52902	110 583	T	argillite	147	52911	144 584	M	arenite
49	52893	110 583	T	argillite	148		144 583		
50	52878	104 583	T	calc-silicate vein	149	52872	139 589	M	
51	52907	104 584	T	argillite	150		147 585	M	
52	52932	104 585	T	argillite	151		147 585	M	
53	52906	104 585	T	arenite	152		133 581		
54	52925	106 587	T	laminated argillite	153		132 584	M	
57	52894	115 571	T	argillite	154	52852	129 582	M	calc-silicate
58	52830	115 571	T	arenite	155		128 582	M	
59	52923	116 572	T	argillite	156		118 582	M	
60	52931	116 573	T	laminated argillite	157		117 570	M	
61	52868	045 570	T	argillite	158		117 567	M	
62	52926	045 571	T	arenite	159		117 571	M	
63	52898	046 689	T	arenite	160		117 571	M	

64		046 689	T		161		116 575	M	
65		046 690	A		162	52886	114 576	M	conglomerate
66	52900	045 687	A	laminated argillite	163	52889	123 557	M	conglomerate
67		045 686	A		164	52846	124 567	M	limestone
68		044 689	A		165		124 557	M	
69	52887	044 689	A	laminated argillite	166	52874	126 557	M	conglomerate
70		044 686	A		167	52940	124 562	M	conglomerate
71	52853	039 695	A	argillite	168		124 562	M	
72		038 695	A		169	52890	126 566	M	spilite
73	52924	037 695	A	argillite	170	52939	122 567	M	lith-arenite
74	52936	037 695	A	volc-arenite	171	52882	123 564	M	argillite
75	52928	037 695	A	laminated argillite	172	52930	125 569	M	argillite
76		036 695			173	52885	127 570	M	limestone
77	52922	036 695	A	argillite	174		124 591	M	
78	52892	036 699	A	volc-arenite	175		128 576	M	
79		036 696	A		176	52856	129 576	M	spilite
80		036 695	T		177		132 576	M	
81		034 695	T		178		124 578	M	
82	52881	034 696	T	argillite	179		101 555	M	
85	52879	069 588	T	laminted argillite	180	52888	105 554	M	laminated argillite
86	52897	069 588	T	argillite	181		105 553	M	
87	52877	069 591	T	lith-arenite	182	52854	104 552	M	calc-silicate
88	52863	069 591	T	laminated argillite	183		110 568	M	
89	52880	071 594	T	argillite	184		112 567	M	
90	52938	074 595	T	calc-silicate	185		112 565	M	
91	52847	074 606	T	conglomerate	186		109 564	M	
92	52845	074 606	T	argillite	187		109 563	M	
93	52890	070 605	T	quartzite	188		109 562	M	
95		060 618	T		189	52855	108 562	M	lith-arenite
96		060 619	T		190	52849	108 560	M	argillite
99	52875	035 695	A	andesite	200		683 176		


MAP OF THE TAMWORTH AREA.
LOCATION OF THIN SECTION SAMPLES.
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KM
5
NORTH
OAKY CREEK
MOORE CREEK
SEVEN MILE CREEK
NEW ENGLAND HIGHWAY
COCKBURN RIVER
CONTACT
BIOTITE ISOGRAD
TAMWORTH
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TW100
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TW72
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