# Part IV

# THE TIA GRANODIORITE

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## Chapter 17

### Introduction

This intrusion is located at the centre of the highest grade metamorphic rocks. Numerous pegmatite, aplite and quartz veins have been emplaced parallel and semi-parallel to a cataclastic foliation, some characters of which were outlined in Part II. The majority of these veins are planar, undeformed sheets, however several examples describe simple asymmetric folds that suggest movement of the granodiorite continued after solidification, or at least until after the granodiorite was solid enough to sustain the emplacement of sheet-like veins. From this it is inferred that in the final stages of emplacement, the granodiorite was in an advanced state of crystallization.

Binns (1966) reached a similar conclusion for the Abroi Gneiss, a comparable granodiorite intrusion in the Wongwibinda district about 70 miles to the north, in which the foliation was believed to be due initially to forceful emplacement parallel to the Wongwibinda Fault, which then produced later cataclasis within the granodiorite during episodes of transcurrent movement. In the case of the Tia Granodiorite movement of the Netherton Fault is believed to be responsible for the development of more strongly foliated granodiorite in narrow zones cutting the northern part of the intrusion. Throughout the remainder the foliation is much more uniform, and is more likely the result of emplacement into a differentially stressed, non-hydrostatic environment. The continuity of the youngest regional foliation of the envelope rocks with the granodiorite foliation suggests that emplacement coincided, at least in part, with the youngest regional deformation, denoted as F2 within the Brackendale Metamorphics and F3 within the Oxley Metamorphics.

### Xenoliths

An important characteristic is the overall rarity of xenolithic inclusions within the Tia granodiorite. This feature is emphasized here as it is important in the later discussion of its petrogenesis. Although these inclusions are rare, three varieties could be distinguished.

(a) Metasedimentary xenoliths, consisting of layered and veined schist containing mesoscopic folds of identical style to those of the highly folded envelope rocks, e.g. Plate 16A. These xenoliths range in size from several inches to over six feet in length, and are usually oriented with their longest axis parallel to the foliation of the enclosing granodiorite.

The preservation in these xenoliths of what are inferred to be F2 folds from the Brackendale Metamorphics or F3 folds from the Oxley Metamorphics suggests that incorporation of the xenoliths (and emplacement of the granodiorite) followed the metamorphism, development of veining and the formation of F2/F3 folds within the surrounding metasediments. Combined with the evidence that emplacement of the granodiorite must have been in part synchronous with the youngest regional deformation, it suggests that the granodiorite attained its present position during the latter stages of this deformation, after the generation of the mesoscopic folds in the envelope rocks, but before the complete relaxation of the differential stress responsible for the F2/F3 folds.

(b) Xenolithic inclusions of relatively pure quartz rock are scattered throughout, but are less common than (a). These are small (2" - 6"), often angular, homogeneous unlaminated inclusions which are arranged in one outcrop in a way that suggests they represent the remnants of earlier emplaced quartz veins which have been disrupted by later movement of the near-solid granodiorite. Other isolated inclusions of quartz-rock could represent metasedimentary quartzite xenoliths.

(c) Biotite-rich trondjhemitic and dioritic inclusions constitute the third variety. These are homogeneous, rounded to subrounded, and range in size from 6 to 12 inches. They are much rarer than (a) or (b), and are finer grained and of obviously more basic aspect than the enclosing granodiorite, e.g. Plate 16A. The overall character of these xenoliths suggests they may be of igneous derivation.

Contact Relationships (See Fig. 15)

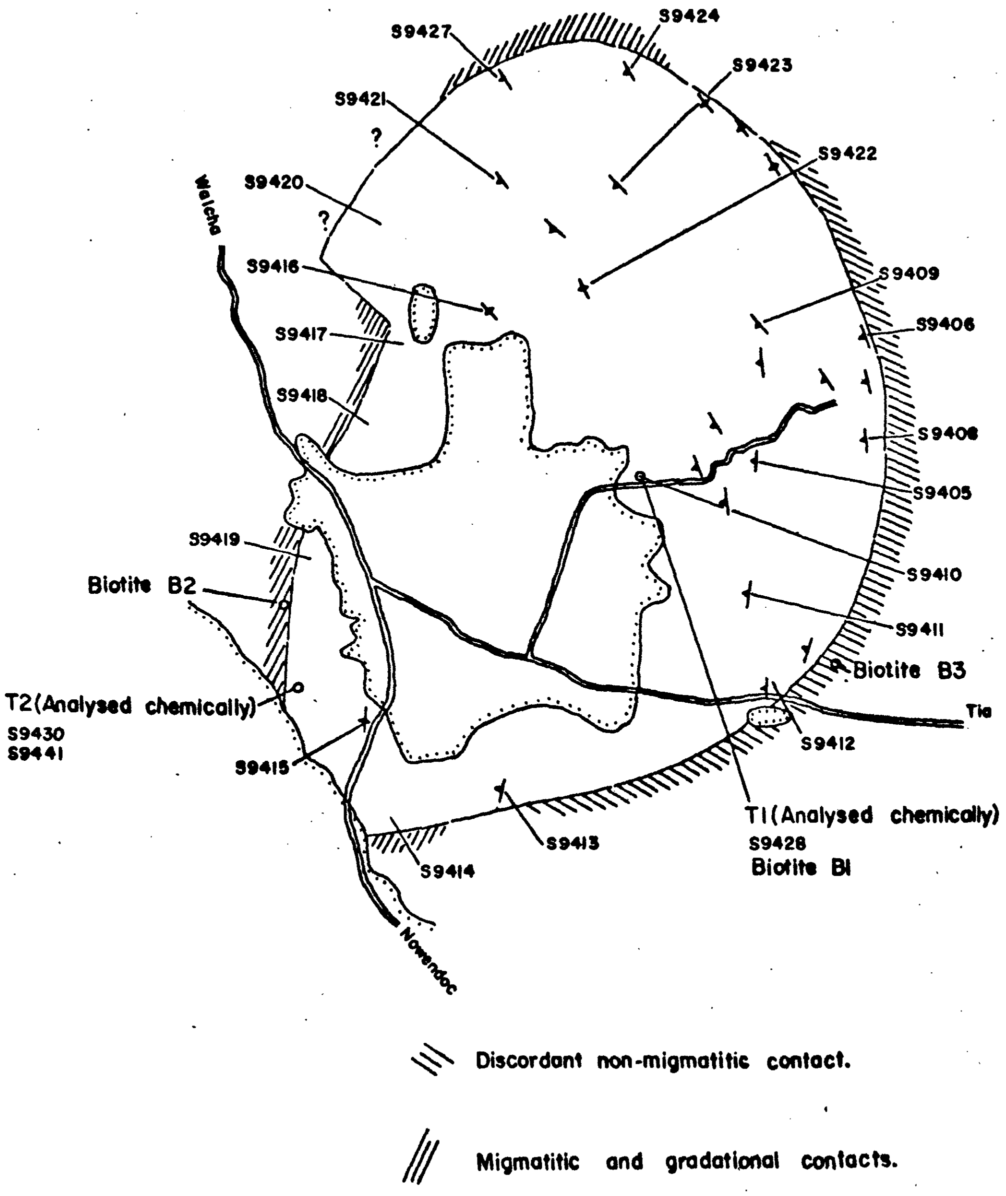
Locally discordant contact relationships characterise the southern to eastern contact, with a sharp transition from highly veined schist to granodiorite. At some localities along this boundary, veins and narrow sills of aplite and microgranodiorite intrude the granodiorite-schist boundary parallel to the foliation.

Toward the northern contact, a gradual change in character is apparent. Near "Fern Hill" homestead, (G.R. 1147750N, 476000E), over an interval of 20-30 yards, the laminated envelope schists coarsen and gradually change into granodiorite. Numerous sills of aplite and microgranodiorite parallel to the S2 foliation of the Brackendale Metamorphics and S of the granodiorite also cut across the contact. Along the western contact, localized migmatization is characteristic, and the typical contact rock

FIG. 15.

LOCALITIES OF MODALLY AND CHEMICALLY ANALYSED SAMPLES FROM THE TIA GRANODIORITE.

Scale 1 : 100000



consists of highly contorted migmatitic schist containing lenticles and patches of coarser grained "granitic" material.

## Petrography of the Granodiorite

The following description is based on 33 large thin sections, most of which were cut from samples collected on an approximate grid pattern, $\frac{3}{4}$ to 1 mile apart depending on outcrop. Localities of all these samples are shown on Fig 15. A further 14 large thin sections prepared in 1964 during the earlier project were also re-examined.

Inspection of the hand specimens suggests that the intrusion is homogeneous, with slight decrease in overall grain size in the narrow zones where granulation and mylonitization are most intense. In thin section, the granodiorite possesses a typical "granitic" or hypidiomorphic granular texture (Williams, Turner and Gilbert, 1954, p. 18) with evidence of substantial microtextural cataclasis. Quartz shows strong undulatory extinction as well as sutured grain boundaries and mortar textures. In some sections the quartz fabric shows considerable flattening and in others, cataclastically granulated quartz alternates with patches of coarser, granoblastic quartz. Plagioclase is euhedral to subhedral, strongly zoned, and possesses well developed Albite twinning. It shows less reaction to deformation than the accompanying quartz, however some Albite twin lamellae are bent, and there is minor fracturing and splitting of individual grains. Wart like intergrowths of sodic plagioclase and quartz (myremekite), are present in a small number of thin sections in accessory quantities. These small rounded bodies usually develop along the plagioclase-potassium feldspar grain boundaries and protrude into the latter, however they are also observed to originate from patches of finely granulated quartz + feldspar. Microperthitic potassium feldspar is present as subhedral to anhedral grains with inclusions of sodic feldspar ranging in size from highly oriented spindle shaped bodies, barely resolvable with the microscope, to coarser blebs and stringers showing little preferred orientation. The "tartan" or cross-hatched twinning characteristic of microcline is well developed. Apart from undulatory extinction, potassium feldspar shows little textural evidence of deformation.

The coarse, ragged biotite flakes show a moderate to strong preferred orientation and undulatory extinction. It is very strongly pleochroic, from deep red-brown to pale yellow-brown, and pleochroic haloes surrounding tiny inclusions are common. A fine grained colourless muscovite is clustered at the margins of the coarser biotite, e.g. Plate 16B, and this is often penetrated by a web of semiopaque brown material. The textural character of the muscovite suggests it is of secondary origin, however this will be further discussed in Chapter (20). Garnet is a rare accessory, occurring as isolated anhedral grains and as groups of small rounded grains associated with clots of biotite, e.g. Plate 16C. Other accessories identified include sphene, apatite, zircon, ilmenite and pyrrhotite.

### Aplites and Pegmatites

The aplites are found as sheets or veins parallel to the granodiorite foliation. They are fine grained leucocratic rocks and sectioning (S9434) revealed an equigranular hypidiomorphic texture consisting of twinned plagioclase and microcline in approximately equal proportions plus granular interlocking quartz amounting to approximately 30 modal percent. The only additional components are a small quantity ($\sim$ 1%) of chloritized biotite and a trace of garnet. In the sectioned sample collected at Brackendale in the southern part of the intrusion, quartz shows only slight undulatory extinction, suggesting little post-consolidation movement. In contrast, the enclosing granodiorite contains well developed cataclastic textural features.

The major constituents of the pegmatites are coarse (2" - 3") perthitic microcline and quartz which may be accompanied by smaller proportions of muscovite, prismatic tourmaline and garnet. An example (S5141) from the northern part of the intrusion adjacent to the Netherton Fault, reveals strong microtextural cataclasis which is thought to have arisen during movement along the nearby Netherton Fault.

## Dioritic and Trondjhemitic Xenoliths

These xenoliths are more basic than the granodiorite, containing up to 50% biotite visually estimated. The remainder is made up of plagioclase and quartz, which is unaccompanied by potassium feldspar. Plagioclase is unzoned. The biotite shows a high degree of preferred orientation, similarly oriented and continuous with the biotite fabric of the granodiorite. Biotite from the xenoliths shows identical pleochroism to that of the granodiorite and contains pleochroic haloes surrounding tiny inclusions. No obvious source of these xenoliths is exposed at the surface; their incorporation in the magma must therefore have taken place deeper in the crust prior to emplacement at its present site.

The above textural features of these xenoliths, together with their homogeneous appearance and absence of layering are consistent with two alternative hypotheses concerning their origin:

(1) These xenoliths have an essentially accidental igneous origin, included in the magma during its ascent.

(2) These xenoliths are essentially metamorphic consisting of fragments of high grade gneissic metamorphic rocks from the region of magma generation.

Discussion

According to Binns et al (1967), the New England region contains two suites of granitic intrusions. The major and most voluminous is known as the New England Batholith, while the name Hillgrove Plutonic Suite was proposed for the second. Several aspects clearly distinguish the two suites. The members of the Hillgrove Plutonic Suite are rich in quartz (usually 30%) which is a blue colour in handspecimens from unsheared bodies. They also contain a deep red-brown to pale yellow-brown pleochroic biotite, and where amphibole is present it is usually a very pale to colourless variety. Members are often sheared and foliated, with widespread cataclastic textural features. High grade regional metamorphism is associated with the Abroi Gneiss at Wongwibinda, (Binns, 1966), however around Hillgrove more limited contact metamorphic aureoles are typical.

In contrast, members of the New England Batholith are usually unsheared and normally contain less than 30% modal quartz, (Binns et al, 1967). Hornblende is common and is a deeply coloured variety. The biotite in Batholithic intrusions is typically a dark drab-brown, without the reddish tint typical of the biotites of the Hillgrove Plutonic Suite. Magnetite is the common opaque oxide phase of the Batholith but is absent or very rare in the Hillgrove Plutonic Suite.

Information concerning the age relationship of these two suites is limited, however present indications are that the Hillgrove Plutonic Suite is slightly older than the New England Batholith, (Evernden and Richards, 1962; Cooper, Richards and Webb, 1963; Binns and Richards, 1965).

It is clear from the above descriptions that the Tia Granodiorite is a typical member of the Hillgrove Plutonic Suite. The distinction between this suite and the New England Batholith is currently based largely on modal, mineralogical and structural characteristics. In Chapter (18) it is shown that significant chemical differences also exist.

## Chapter 16

# MODAL VARIATION AND CHEMISTRY OF THE TIA GRANODIORITE AND ASSOCIATED ROCKS.

## Modal Variation

A Swift point counter was used to determine the modal composition of 20 large thin sections, cut normal to the foliation, all of which were stained with cobalt-initrite to facilitate recognition of potassium feldspar, (Bailey and Stevens, 1960). Approximately 2000 points were counted on each section. The results are given in Table 13 and the modal variation illustrated using:

(1) Quartz-plagioclase-potassium feldspar Diagram, Fig 16a.

(2) Quartz-total feldspar-mafics (biotite) Diagram, Fig 16b.

These results in general confirm the visual impression of homogeneity throughout the granodiorite. The mode of most samples clearly plot in the granodiorite field of Nockolds' (1954) classification, with some specimens transitional to adamellite. The anomalous modal composition (S9418) which plotted in the middle of the adamellite field was collected at the western contact and is thought to be a marginal variant locally enriched in potassium feldspar.

The following modal properties characterise the Tia Granodiorite:

(1) A richness in quartz, ranging from 29.4 to 36.3 modal percent.

(2) An inverse relationship between the modal proportions of biotite and potassium feldspar, Fig 16c. There appeared to be no correlation of this variation with position within the intrusion.

(3) The widespread occurrence of minor or accessory muscovite, with textural characters suggesting it to be of secondary origin, clustered as fine flakes at the grain boundaries of coarser biotite.

(4) The occurrence of a trace of garnet.

(5) The rarity of a primary opaque mineral phase, which is either absent or amounts to only one or two small grains per thin section.

## Chemistry of the Granodiorite

The two analysed samples from the Tia Granodiorite were collected at the following localities:

T1 - from the centre of the intrusion, several hundred yards east of "Morah" homestead. (G.R. 1141400 N, 477300 E)

T2 - from close to the south-west contact, west of "The Lakes" homestead. (G.R. 1138400N, 472000 E)

These localities are also shown on Fig 15. The analyses, C.I.P.W. norms and modes of T1 and T2 are given

TABLE (13)

## Modal Analyses of the Tia Granodiorite

| Section No. | Quartz | Plagioclase | K-feldspar | Biotite | Mus-covite | Garnet |
|---|---|---|---|---|---|---|
| 9405 | 32.9 | 33.2 | 18.1 | 15.8 | - | - |
| 9406 | 33.7 | 35.2 | 13.2 | 17.6 | 0.3 | - |
| 9408 | 33.9 | 26.9 | 19.0 | 15.7 | 4.5 | Trace |
| 9409 | 31.0 | 36.6 | 14.5 | 15.5 | 2.4 | - |
| 9410 | 32.8 | 39.2 | 11.5 | 14.1 | 2.4 | - |
| 9411 | 31.3 | 36.8 | 12.2 | 19.7 | - | - |
| 9412 | 32.2 | 36.6 | 12.5 | 18.7 | - | - |
| 9413 | 32.9 | 32.7 | 21.0 | 12.8 | 0.6 | - |
| 9414 | 34.1 | 35.0 | 15.3 | 15.6 | - | - |
| 9415 | 36.3 | 31.2 | 20.1 | 12.0 | 0.4 | - |
| 9416 | 32.5 | 34.9 | 20.5 | 10.1 | 2.0 | - |
| 9417 | 33.0 | 36.7 | 15.2 | 14.2 | 1.1 | - |
| 9418 | 29.8 | 28.2 | 30.8 | 10.6 | 0.6 | Trace |
| 9419 | 34.7 | 33.2 | 22.8 | 8.5 | 0.8 | - |
| 9420 | 34.6 | 36.8 | 13.8 | 14.7 | 0.1 | - |
| 9421 | 34.6 | 31.1 | 17.3 | 16.0 | 1.0 | - |
| 9422 | 29.4 | 35.9 | 22.9 | 9.2 | 2.6 | - |
| 9423 | 30.4 | 34.6 | 18.9 | 15.1 | 1.0 | - |
| 9424 | 36.2 | 34.9 | 11.1 | 17.8 | - | - |
| 9426 | 30.5 | 35.3 | 16.1 | 17.9 | 0.2 | - |

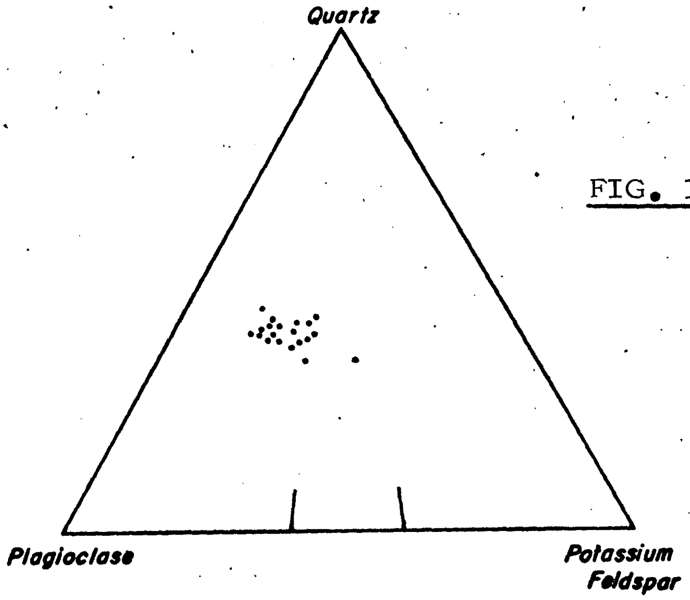


FIG. 16a.

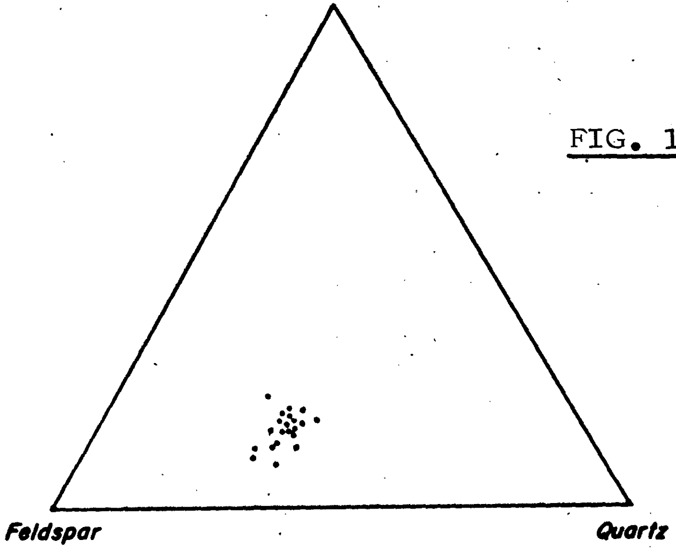


FIG. 16b.

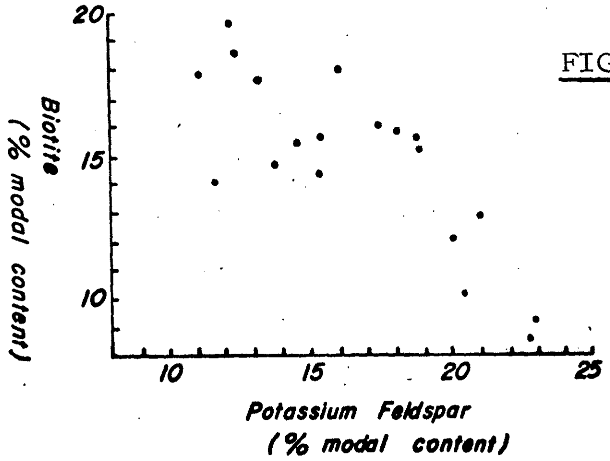


FIG. 16c.

in Table 14, and compared with two other representatives of the Hillgrove Plutonic Suite, the Abroi Gneiss and Hillgrove Adamellite, (analyses from Binns, 1968). A close chemical similarity of these representatives of the Hillgrove Plutonic Suite is obvious from these analyses.

## Chemistry of the Envelope Schist

Two petrographic features of the envelope schists surrounding the granodiorite are notable. They contain abundant potassium feldspar (Or88-Or92), and randomly oriented porphyroblasts of white mica which are shown in Chapter (15) to have rather an unusual composition. The abundance of orthoclase in the envelope schists suggests that potassium has been introduced into these rocks from the granodiorite.

To chemically verify this observation, the limited data given in Table 15 were gathered. The localities of the samples are given on Map 2, and further details in Table 15. The samples R1-R4 are arranged in order of increasing distance from the granodiorite, corresponding to decreasing metamorphic grade. It is clear from this limited data that a compositional gradient consisting of increasing $K_2O$ and decreasing $Na_2O$ exists with increasing metamorphic grade. It is believed that this shows that there has clearly been introduction of potassium into the

## TABLE (14)

## Chemistry of the Tia Granodiorite and Related Plutonic Rocks

| | Tia Granodiorite<br>T1 | T2 | Abroi Gneiss<br>Binns (1968) | Hillgrove Adamellite<br>Binns (1968) |
|---|---|---|---|---|
| $SiO_2$ | 69.28 | 69.43 | 67.14 | 69.55 |
| $TiO_2$ | 0.30 | 0.24 | 0.60 | 0.54 |
| $Al_2O_3$ | 15.52 | 14.78 | 14.82 | 14.16 |
| $Fe_2O_3$ | 0.18 | 0.24 | 0.48 | 0.60 |
| FeO | 3.14 | 3.09 | 4.14 | 3.33 |
| MnO | 0.05 | 0.07 | 0.10 | 0.23 |
| MgO | 1.39 | 1.51 | 1.82 | 1.45 |
| CaO | 2.07 | 2.51 | 2.60 | 2.20 |
| $Na_2O$ | 3.35 | 3.75 | 3.25 | 3.14 |
| $K_2O$ | 3.95 | 3.35 | 3.70 | 4.09 |
| $H_2O^+$ | 0.53 | 0.54 | 0.78 | 0.30 |
| $H_2O^-$ | 0.08 | 0.08 | 0.02 | 0.20 |
| $P_2O_5$ | 0.20 | 0.12 | 0.19 | 0.12 |
| | 100.04 | 99.71 | 99.77 | 99.91 |

### C.I.P.W. Norms

| | T1 | T2 | Abroi Gneiss | Hillgrove Adamellite |
|---|---|---|---|---|
| Qz | 26.1 | 24.8 | 23.3 | 26.6 |
| Or | 23.4 | 20.0 | 21.7 | 24.5 |
| Ab | 28.3 | 32.0 | 27.8 | 26.7 |
| An | 9.7 | 11.7 | 12.0 | 10.0 |
| C | 2.1 | 0.5 | 0.7 | 0.8 |
| Hyp | 8.7 | 9.1 | 10.8 | 8.6 |
| Mt | 0.2 | 0.2 | 0.7 | 0.9 |
| Ilm | 0.6 | 0.5 | 1.2 | 1.1 |
| Ap | 0.3 | 0.3 | 0.3 | 0.3 |

### Modes

| | T1 | T2 |
|---|---|---|
| Quartz | 34.6 | 31.6 |
| K-Feldspar | 15.5 | 18.8 |
| Plagioclase | 33.4 | 36.0 |
| Biotite | 13.6 | 12.5 |
| Muscovite | 2.4 | 0.4 |
| Accessory | 0.5 | 0.7 |

## TABLE (15)

### Chemistry of the Envelope Schists and Unmetamorphosed Greywackes.

| | R1 | R2 | R3 | R4 | GW1 | GW2 |
|---|---|---|---|---|---|---|
| $SiO_2$ | | 72.46 | | | | |
| $TiO_2$ | | 0.24 | | | | |
| $Al_2O_3$ | | 14.95 | | | | |
| $Fe_2O_3$ | | 0.69 | | | | |
| FeO | | 1.76 | | | | |
| MnO | | 0.06 | | | | |
| MgO | | 0.66 | | | | |
| CaO | | 0.77 | | | | |
| $Na_2O$ | 0.20 | 2.23 | 3.57 | 4.45 | 4.10 | 3.95 |
| $K_2O$ | 8.90 | 5.44 | 3.50 | 1.65 | 1.63 | 1.31 |
| $H_2O^+$ | | 0.74 | | | | |
| $H_2O^-$ | | 0.11 | | | | |
| $P_2O_5$ | | - | | | | |
| | | 100.11 | | | | |

Localities (see Map 2)

| | |
|---|---|
| R1 | Migmatitic schist from the south west contact from which biotite B2 was separated, (collected virtually at contact). |
| R2 | Envelope schist containing muscovite Mu1, biotite B3 and garnet G5 from 50 yards away from the south eastern contact. |
| R3 | High grade schist from south of the granodiorite from which muscovite Mu2 was separated. |
| R4 | Metamorphosed greywacke from Stage 1 within the low grade part of the Brackendale Metamorphics. |
| GW1, GW2 | Relatively unmetamorphosed Agnes Greywackes. |

higher grade metamorphic rocks associated with the granodiorite. The Tia Granodiorite is assumed to be the source of this potassium, and it is shown later (Chapter 20), that this migration resulted in the crystallization of muscovite within the intrusion.

## Comparison of the Chemistry of the Hillgrove Plutonic Suite and New England Batholith

On the diagrams of Fig 17, the Kia-Ora Adamellite[1] is separated from other members of the New England Batholith, of which it has previously been considered a member. The biotite of the Kia-Ora Adamellite shows the deep red-brown hues typical of that from the Hillgrove Plutonic Suite, and is also virtually identical chemically with that from the Tia Granodiorite, (see Chapter 19). The Kia-Ora Adamellite also contains a small percentage of modal muscovite with no hornblende, and a very minor opaque mineral phase consisting of a mixture of ilmenite and pyrrhotite, with no magnetite, (Chappell, 1966). These are also characteristic of the Hillgrove Plutonic Suite. The main difference between the two is the massive, unfoliated nature of the Kia-Ora Adamellite compared with the variously foliated Hillgrove Plutonic Suite, (although

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[1] The Kia-Ora Adamellite has since been subdivided into three separate bodies, (Chappell, *pers. comm.*)

this foliation is by no means diagnostic of the latter suite), and the slightly lower percentage of modal biotite, (3.2 - 9.7%).

Sufficient criteria of the Hillgrove Plutonic Suite are satisfied to suggest it more closely resembles this suite than the remainder of the Batholith. It is remarked by Chappell (1966) that the Kia-Ora Adamellite is unique in the southern part of the New England Batholith, possessing modal, chemical and mineralogic properties that clearly distinguish it from the other intrusives. It furthermore has a significantly higher initial $Sr^{87}/Sr^{86}$ ratio than the initial ratios of 0.704-0.705[1] of the other intrusives of the Moonbi district.

These similarities between the Kia-Ora Adamellite and the Hillgrove Plutonic Suite suggests that they arose by a similar petrogenetic process, differing in many respects to that which gave rise to the remainder of the Batholith. That the Kia-Ora Adamellite and the Hillgrove Plutonic Suite may be contemporaneous is not disputed by the available radiometric ages. Although undated, the Kia-Ora Adamellite is clearly older than 242 m. y., the

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[1] Chappell (1966) cites a personal comunication from P. Arriens as the source of these figures. The actual initial $Sr^{87}/Sr^{86}$ ratio of the Kia-Ora Adamellite is not given.

radiometric age of the crosscutting Bendemeer Adamellite, (Chappell, 1966). Ages of the Hillgrove Plutonic Suite are in the range 250-269 m. y., (Evernden and Richards, 1962; Binns and Richards, 1965).

The following variation diagrams are constructed using analyses of Wilkinson et al (1964), Chappell (1966), Phillips (1968) and Chapter (18) of this thesis.

Fig 17a $Na_2O$ - $K_2O$ - CaO

The data from the New England Batholith and the Hillgrove Plutonic Suite overlap to the extent that no distinction can be clearly made between these suites on the basis of these elements.

Fig 17b MgO - FeO - $Fe_2O_3$

This diagram shows that the Hillgrove Plutonic Suite has, in general, a higher $FeO/Fe_2O_3$ ratio than the New England Batholith. This chemical characteristic of the former is shared with the Kia-Ora Adamellite, and is further evidence of its consanguinity with the Hillgrove Plutonic Suite. The higher $FeO/Fe_2O_3$ ratios of these two is clearly reflected in similar $FeO/Fe_2O_3$ relationships in their biotites, (Chapter 19).

Fig 17c CaO - $Al_2O_3$ - (FeO+MnO+MgO)

This diagram shows that the New England Batholith and the Hillgrove Plutonic Suite (including the Kia-Ora

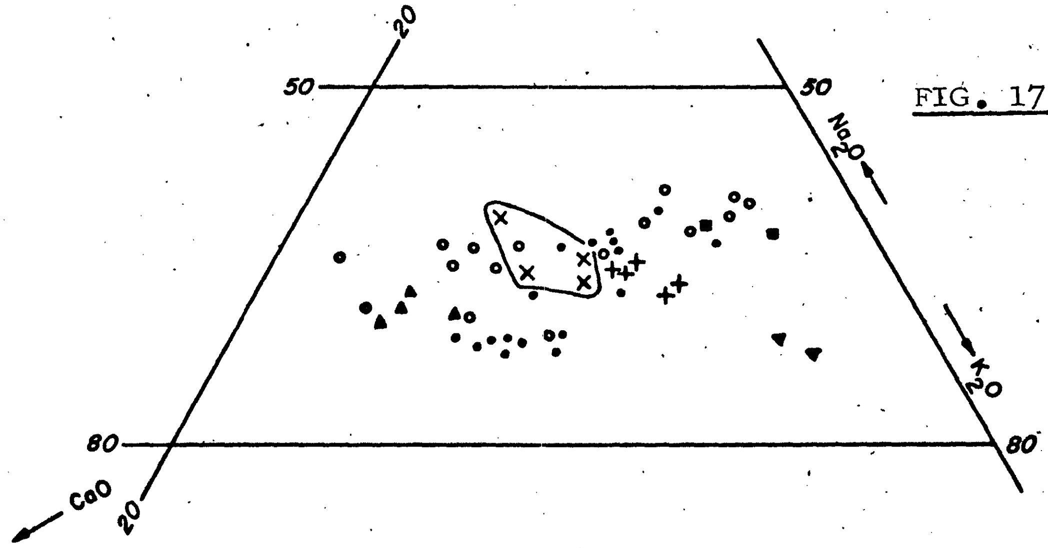


FIG. 17a.

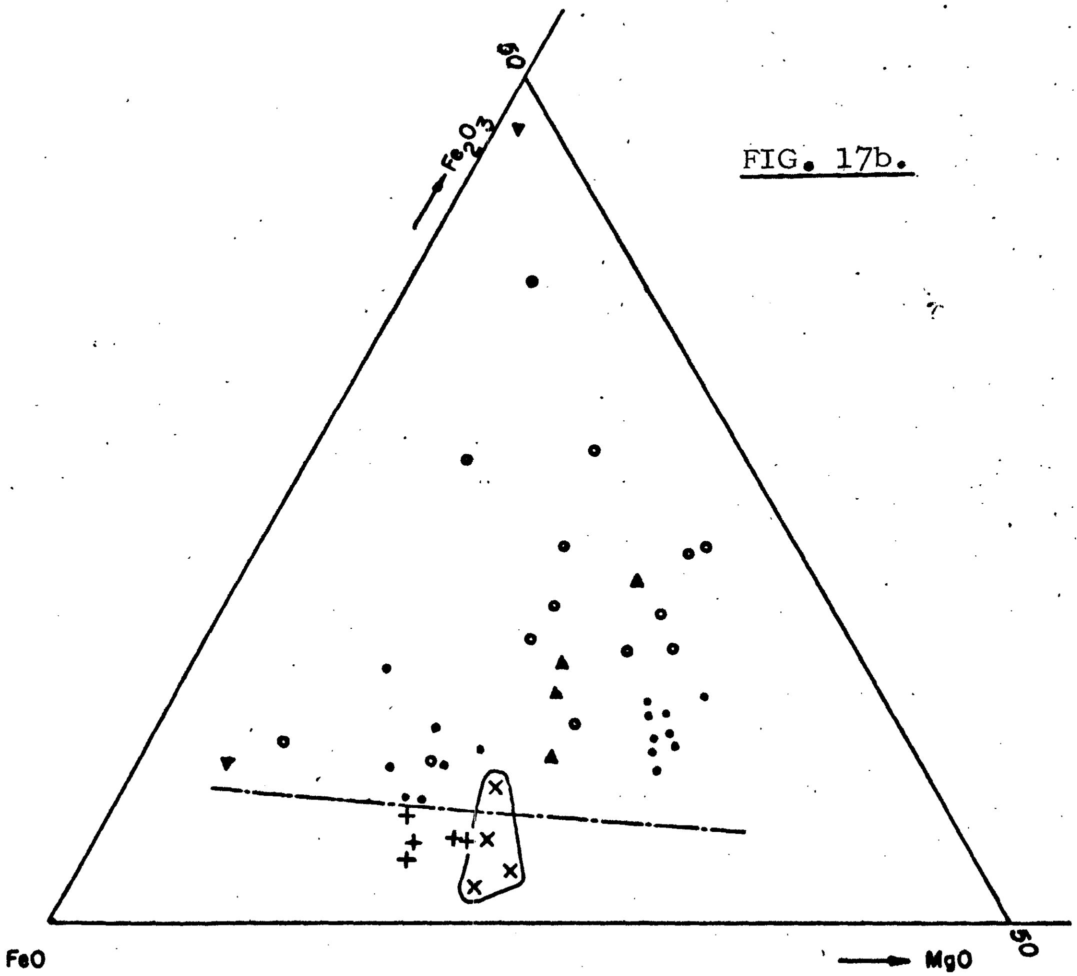
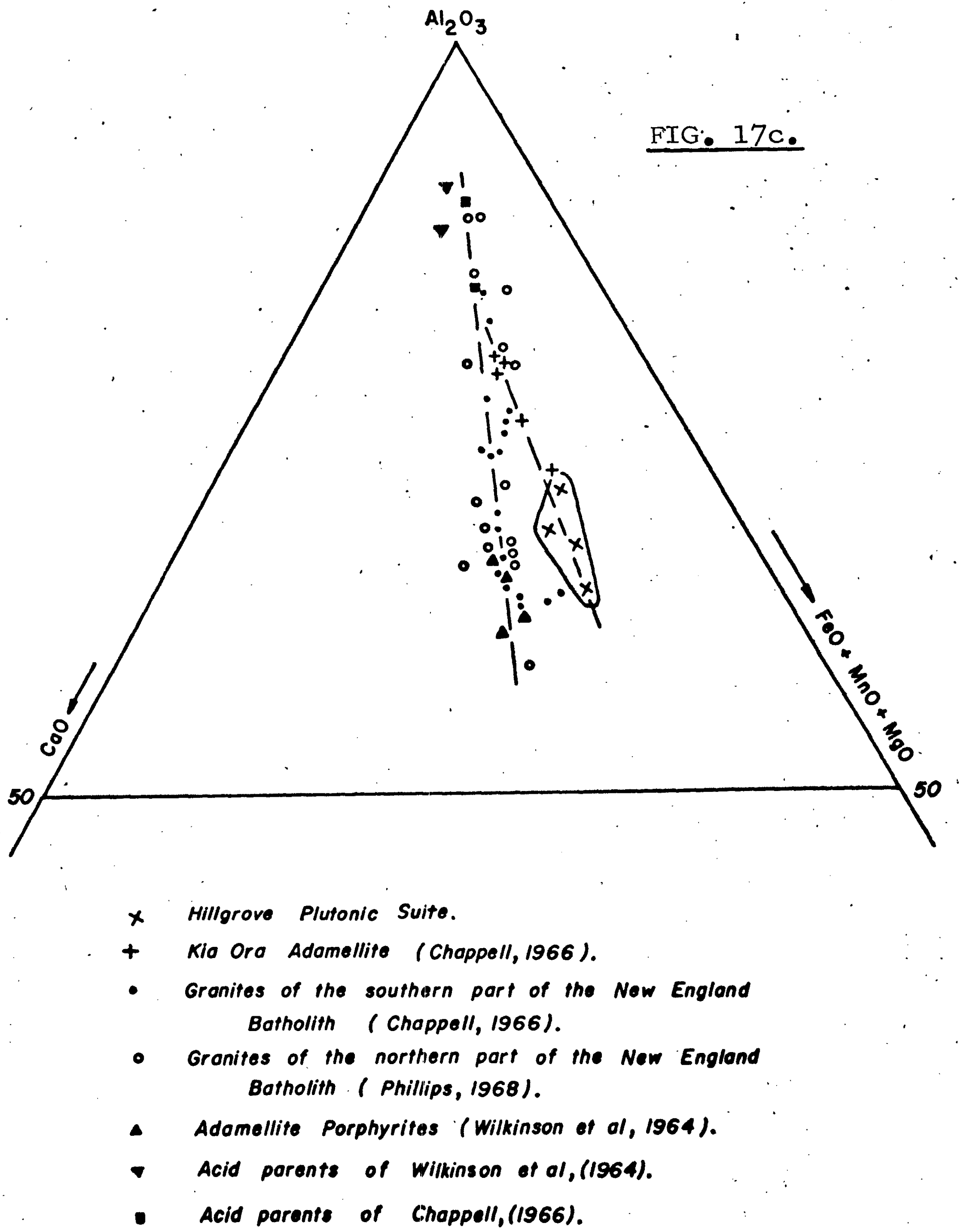


FIG. 17b.

FIG. 17c.


$Al_2O_3$
CaO
50
FeO + MnO + MgO
50
✗ Hillgrove Plutonic Suite.
+ Kia Ora Adamellite (Chappell, 1966).
• Granites of the southern part of the New England Batholith (Chappell, 1966).
○ Granites of the northern part of the New England Batholith (Phillips, 1968).
▲ Adamellite Porphyrites (Wilkinson et al, 1964).
▼ Acid parents of Wilkinson et al, (1964).
■ Acid parents of Chappell, (1966).

Adamellite) define two divergent trends in terms of these elements. The analyses plot on this diagram such that those nearest the $Al_2O_3$ vertex are the more acid members, with the trend away from this vertex toward more basic adamellites and granodiorites.

The trend defined by the Hillgrove Plutonic Suite shows that toward slightly more basic compositions, there is only minor enrichment in CaO with increasing (FeO+MnO+MgO). In contrast, with this same trend, the members of the New England Batholith show a significantly greater enrichment in CaO towards more basic compositions enriched in (FeO+MnO+MgO).

# CHAPTER 19

# MINERALOGY

## Potassium Feldspar

### Composition

A potassium feldspar from the analysed sample T1 was homogenized by dry heat treatment at 1050°C for 36 hours, and the proportion of orthoclase and albite estimated by the X-ray method of Orville (1958), using potassium bromate as an internal standard.

$\Delta 2\theta$ ($20\bar{1}$ K-feldspar - 101 $KBrO_3$) = 0.84

Using this value, the determinative graphs of Orville (1958) and (1963) give a composition, in mol. percent, of Or 88 Ab 12.

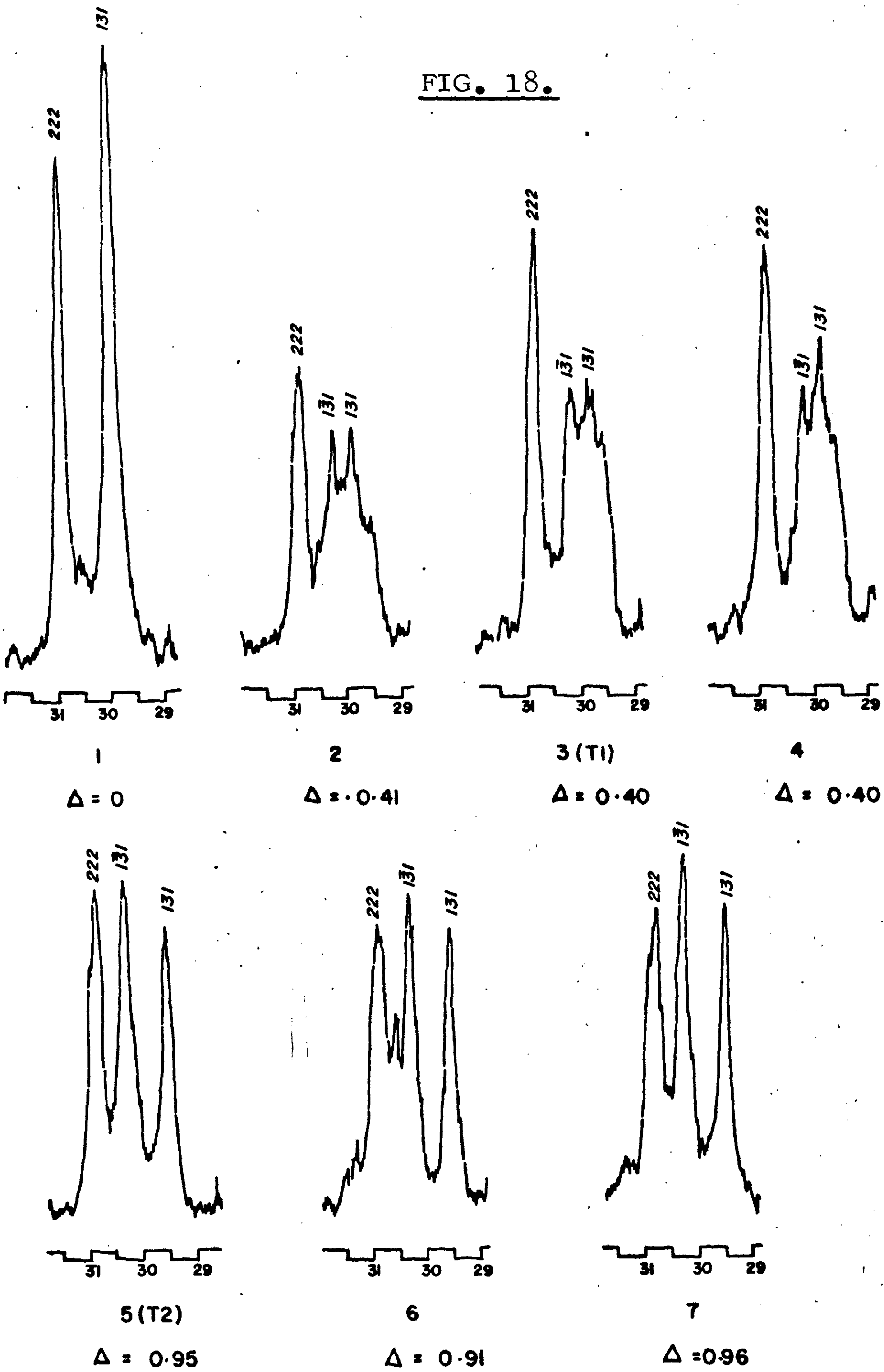
### Structural State

Diffractometer scans over the 131-$1\bar{3}1$ peaks of potassium feldspars from the granodiorite and associated rocks are illustrated in Fig 18.

The major aspects of the variation in structural state are summarised below:

(1) Non-migmatitic contact schist contains monoclinic orthoclase (Sample 1, Fig 18), with no sign of depression or broadening of the 131 peak.

FIG. 18.



1
Δ = 0

2
Δ = 0·41

3 (T1)
Δ = 0·40

4
Δ = 0·40

5 (T2)
Δ = 0·95

6
Δ = 0·91

7
Δ = 0·96

Variation of the structural state of Potassium Feldspar.

(2) The potassium feldspar from migmatitic contact schist (Sample 2, Fig 18) shows a distinctly triclinic character with clear separation of the 131 and $1\bar{3}1$ peaks. Using the measure of triclinicity proposed by Goldsmith and Laves (1954), where $\Delta = 12.5$ ($d131 - d1\bar{3}1$), this potassium feldspar has an intermediate triclinicity of $\Delta = 0.41$. This comes from a highly folded, layered migmatitic schist showing no sign of the microtextural cataclasis typical of the adjacent granodiorite.

(3) Potassium feldspars 3, 4 and 5 (Fig 18) were separated from samples of the Tia Granodiorite. There is clear separation of the 131 and $1\bar{3}1$ peaks in all three, with a variation in triclinicity from $\Delta = 0.40$ for samples 3 and 4, with 5 a distinctly triclinic variety close to maximum microcline, ($\Delta = 0.95$).

All are associated with well developed cataclastic textures, granulated quartz and bent and ragged biotites. All three show well developed cross-hatched twinning. Sample 4, with $\Delta = 0.40$, is from the north-east part of the intrusion and was selected because it has a very strong foliation.

(4) Potassium feldspar samples 6 and 7 come from an aplite and pegmatite respectively. These are

both close to maximum microcline, with samples 6 possessing $\Delta$ = 0.91 and 7 $\Delta$= 0.96.

Discussion

In the Wongwibinda district, about 70 miles north of the Tia Complex, Binns (1966) showed that cataclastic deformation due to movement along the Wongwibinda Fault is clearly associated with the inversion of orthoclase to microcline in the Abroi Gneiss and associated rocks adjacent to the fault. Throughout the remainder of the deformed intrusions and associated rocks of this district, this relationship is less clear, and resulted in the conclusion (Binns, 1966, p. 30) that "the exact time relationships between crystallization and deformation . . . . . . influence the triclinicity value assumed by the potassium feldspar".

Within the Tia Granodiorite and associated rocks there is no strong correlation between triclinicity and cataclastic deformation as described by Binns (1966) in the Wongwibinda district. The potassium feldspar from a highly sheared granodiorite sample (Sample 4, Fig 18) has an intermediate triclinicity of $\Delta$ = 0.40. Sample 5, by contrast, is from the less strongly foliated, less deformed southwest margin but contains a near maximum microcline with $\Delta$ = 0.95.

The potassium feldspar from the migmatitic contact rock (Sample 2, Fig 18), showing no microtextural cataclasis, is triclinic with $\Delta = 0.41$, while the non-migmatitic contact schist from the south-east contact (Sample 1, Fig 18) contains monoclinic orthoclase with $\Delta \sim 0$. This contrast between the structural states of the migmatitic and non-migmatitic feldspar samples suggests that the condition that promoted the inversion may also have been one of the conditions that encouraged the development of the migmatitic contact rock.

The experimental investigations of Goldsmith and Laves (1954) and Tomisaka (1962) show that water pressure is of great importance in determining the stability fields of monoclinic and triclinic potassium feldspars at any given temperature. Tomisaka (1962) found that microcline with a triclinicity of $\Delta = 0.945$ is stable under a water vapour pressure of 4000 atmospheres at about 470°C, $\Delta = 0.936$ under 2400 atmospheres at about 450°C and $\Delta = 0.910$ under 1500 atmospheres at about 450°C. At higher temperatures, the $\Delta$ values decrease as inversion to the monoclinic state commences. While deformation may assist the inversion, as illustrated by Binns (1966), the most important conditions appear to be temperature and water vapour pressure, assuming a slow rate of cooling under plutonic conditions. Within the Tia Granodiorite below about 460° or 470° (the upper stability limit of maximum microcline, Tomisaka, 1962; Steiger and Hart, 1967), slight lateral variation in the water vapour pressure during crystallization could result in significant variation in the structural state of the potassium feldspar throughout the granodiorite.

Partial inversion of the potassium feldspar in the migmatitic envelope schists is also ascribed to a higher water vapour pressure compared to that prevailing at the discordant non-migmatitic contacts during emplacement. From experimental work (eg. Tuttle and Bowen, 1958; von Platen, 1965; Winkler, 1967) partial melting of the contact rocks during emplacement to give patches and stringers of "granitic" material or migmatite would be expected to be enhanced by elevated water vapour pressure at any given temperature. The inversion of monoclinic orthoclase to triclinic microcline at the migmatitic contact is thus seen as a lower temperature manifestation of the migmatization process, and it is also significant that potassium feldspar from the adjacent granodiorite (Sample 5, Fig 18) is a near maximum microcline.

## Plagioclase

A study of the plagioclase of the Tia Granodiorite was reported earlier, (Gunthorpe, 1964). Compositions were determined by measuring the $\beta$ index in sodium light on grains plucked from thin sections. The average of 13 determinations was $An_{23}$. The most anorthite rich composition measured was in the core of a large zoned plagioclase which gave a composition of $An_{29}$. The more albitic rim of the same grain was found to have a composition of $An_{13}$.

## Biotite

### Optical Properties

The strongly pleochroic biotite of the granodiorite and migmatite showed the following absorption colours:

$\alpha$ = Deep red-brown
$\beta,\gamma$ = Pale yellow-brown

Six determinations of the $\beta,\gamma$ refractive index were in the range 1.649 - 1.653 (±.002). The metamorphic biotite (B3) from the contact schist has $\beta,\gamma$ deep brown, without the reddish tint, and a significantly lower refractive index ($\beta,\gamma$ = 1.646).

### Chemistry

Biotites from analysed granodiorite sample T1 (B1), a contact migmatite (B2) from the southwest boundary and non-migmatitic contact schist (B3) from the southeast boundary were chemically analysed, (for localities of samples see Fig 15). The analyses, together with structural formulae calculated on a 24(O, OH) basis are given in Table 16. A biotite of similar chemical composition and structural formula from the Kia-Ora Adamellite (Chappell, 1966) is included for comparison.

Trioctahedral biotite has the general formula (Deer, Howie and Zussman, V. 3, 1962, p. 7)

$$X_2\ Y_6\ Z_8\ O_{20}\ (OH, F)_4$$

where X is mainly K and Na, Y is mainly Al, Mg, $Fe^{2+}$, $Fe^{3+}$, Mn and Ti and Z is mainly Si and Al. The structural formulae of Table 16 are calculated on the assumption that the 8 Z sites are wholly occupied by Si and Al, with the excess Al being octahedrally co-ordinated in the Y site. The formulae are calculated on a 24(O, OH) basis as the analytically determined $H_2O^+$ almost fills the hydroxyl site to its maximum of 4. Fluorine was not determined and its possible effect on the structural formulae is therefore ignored. Calculation on a 22(O, OH) basis would have little effect on the structural formulae, very slightly lowering the octahedral Al and the total X and Y occupancies.

The small amount of Ca has been placed in the X site along with K and Na. According to Chappell (1966), Ca is, in general, absent from the biotite lattice, the

## TABLE (16)

Analysed Biotites from the Tia Granodiorite and Associated Rocks

| | Tl Grano-diorite B1 | Migmatite B2 | Non Migmatitic Contact Schist B3 | Kia-Ora Adamellite Chappell (1966) |
|---|---|---|---|---|
| $SiO_2$ | 35.09 | 36.29 | 38.94 | 35.13 |
| $TiO_2$ | 2.26 | 2.38 | 2.20 | 3.46 |
| $Al_2O_3$ | 19.39 | 17.05 | 18.78 | 16.75 |
| $Fe_2O_3$ | 0.84 | 2.04 | 2.38 | 0.94 |
| FeO | 20.83 | 19.94 | 16.45 | 22.39 |
| MnO | 0.46 | 0.54 | 0.72 | 0.37 |
| MgO | 8.71 | 8.02 | 7.47 | 6.05 |
| CaO | 0.35 | 0.14 | 0.21 | - |
| $Na_2O$ | 0.15 | 0.15 | 0.30 | 0.22 |
| $K_2O$ | 8.90 | 9.85 | 8.90 | 8.70 |
| $H_2O^+$ | 3.84 | 3.50 | 3.18 | 2.71 |
| $H_2O^-$ | 0.09 | 0.21 | 0.11 | BaO) $Rb_2O$) 0.13 |
| $P_2O_5$ | 0.00 | 0.02 | 0.02 | |
| | 99.89 | 100.13 | 99.76 | 96.85 |

Structural Formulae on the Basis of 24(O, OH)

| | B1 | | B2 | | B3 | | Kia-Ora | |
|---|---|---|---|---|---|---|---|---|
| Si | 5.31) | 8.00 | 5.58) | 8.00 | 5.87) | 8.00 | 5.52) | 8.00 |
| $Al^{iv}$ | 2.69) | | 2.42) | | 2.13) | | 2.48) | |
| $Al^{vi}$ | 0.77) | 5.79 | 0.67) | 5.67 | 1.20) | 5.56 | 0.62) | 5.55 |
| Ti | 0.26) | | 0.28) | | 0.25) | | 0.41) | |
| $Fe^{3+}$ | 0.10) | | 0.24) | | 0.27) | | 0.11) | |
| $Fe^{2+}$ | 2.64) | | 2.57) | | 2.07) | | 2.94) | |
| Mn | 0.06) | | 0.07) | | 0.09) | | 0.05) | |
| Mg | 1.96) | | 1.84) | | 1.68) | | 1.42) | |
| Ca | 0.06) | 1.82 | 0.02) | 1.99 | 0.02) | 1.81 | - ) | 1.83 |
| Na | 0.04) | | 0.04) | | 0.08) | | 0.07) | |
| K | 1.72) | | 1.93) | | 1.71) | | 1.75) | |
| Ba) Rb) | | | | | | | 0.01 | |
| OH | 3.88 | | 3.54 | | 3.20 | | 2.84 | |

Optical Properties

| | B1 | B2 | B3 | Kia-Ora |
|---|---|---|---|---|
| **Refractive Indices** | | | | |
| β, γ = (±.002) | 1.649 | 1.653 | 1.646 | 1.654 |
| **Absorption Colours** | | | | |
| β, γ = | Deep red brown | Deep red brown | Deep brown | Deep red brown |
| α = | Very pale brown | Very pale brown | Very pale brown | Very pale brown |

reported Ca of biotites throughout the literature being due to tiny inclusions of apatite. Failure to analyse for $P_2O_5$ and correct for this apatite has resulted in errors in determining the structural formulae. The biotites from the Tia Granodiorite and associated rocks were found to contain negligible $P_2O_5$, suggesting that no apatite impurity was present in the analysed mineral concentrates. Thus, unless analytical error is involved in the determination of either CaO or $P_2O_5$, they appear to contain a small Ca component occupying the X site.

The biotites B1, B2 and B3 conform fairly closely to the theoretical biotite formula given above. The X sites are almost filled in each case with slight deficiencies in B1 and B3. The Y site is deficient in each case, but all three are in the range 5.56 to 6.0.

## Discussion

### (1) Colour

From the work of Hall (1941), Hayama (1959) and Chinner (1960), the deep red-brown tints of biotites B1 and B2 are attributed to moderate titanium content (approximately 0.25 atoms/formula unit) combined with very low $Fe_2O_3/(FeO + Fe_2O_3)$ ratios and relatively high FeO/MgO ratios. The deep brown absorption colour without the reddish tint of biotite B3 is attributed to a significantly higher

$Fe_2O_3/(FeO + Fe_2O_3)$ ratio compared with B1 and B2, as the $TiO_2$ content and FeO/MgO ratio are virtually identical in all three biotites. The significantly greater MnO content of biotite B3 could also influence the colour assumed, (Chinner, 1960). Whether the octahedral aluminium content can influence the absorption colours is not known.

### (2) Octahedral Aluminium

Allowing for the analytical errors that may be involved, the octahedral aluminium contents of biotites B1 (0.77 atoms) and B2 (0.67 atoms) conform fairly closely to the value 0.6 atoms of octahedral aluminium/formula unit suggested by Chappell (1966) as characteristic of biotites co-existing with muscovite in granitic rocks. When biotite is the lone mafic mineral it contains less than 0.6 atoms octahedral aluminium/formula unit, and when biotite co-exists with hornblende in granitic rocks the octahedral aluminium content of the biotite is sensibly zero (Chappell, 1966). Biotite B3 from the non-migmatitic contact schist co-exists with muscovite and contains significantly more octahedral aluminium (1.2 atoms/formula unit) than B1 and B2.

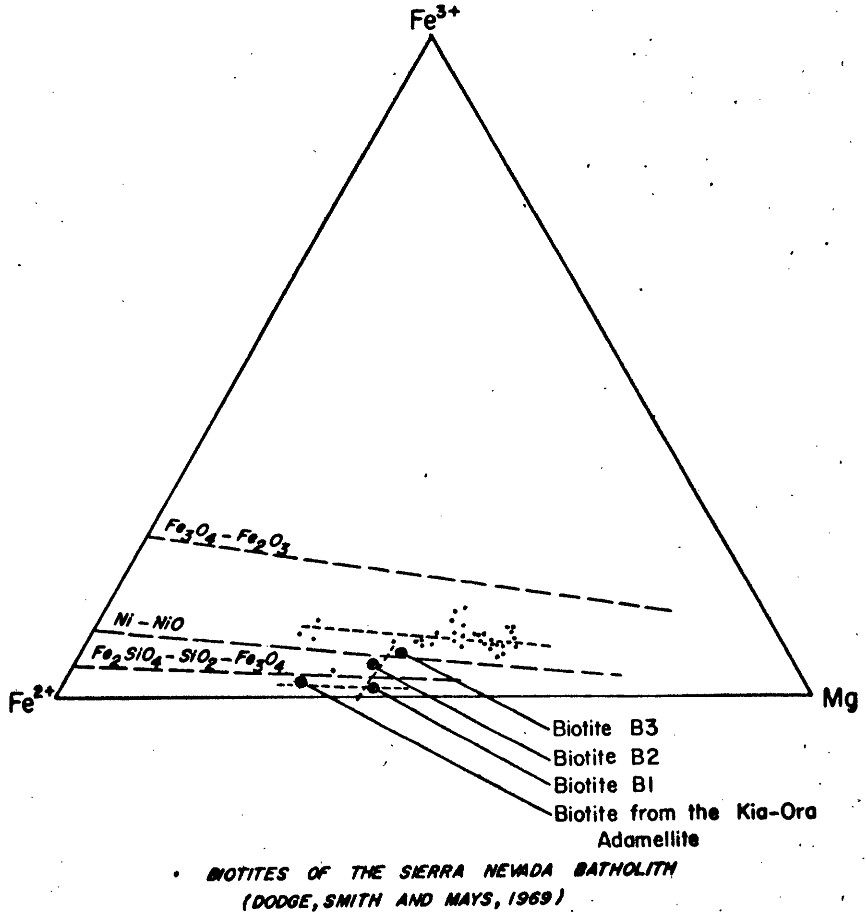
### (3) $Fe^{3+}/Fe^{2+} + Fe^{3+}$ Ratios

The experimental work of Eugster and Wones (1962) and Wones and Eugster (1965) is of limited value because the biotites do not have magnetite as a co-existing phase. Rough estimates of the oxidation-reduction conditions are however possible using the $Fe^{3+}/Fe^{2+} + Fe^{3+}$ ratios of the biotites, (Wones and Eugster, 1965, p.1264). The $Fe^{3+}/Fe^{2+} + Fe^{3+}$ ratio (= 0.035) of B1 suggests that this biotite crystallized when the oxygen fugacity throughout the granodiorite magma had assumed a value intermediate between the magnetite-wustite and quartz-fayalite-magnetite buffer conditions. Biotite B2 ($Fe^{3+}/Fe^{2+} + Fe^{3+} = 0.085$) crystallized at conditions between the quartz-fayalite-magnetite and nick-nickel oxide buffers, and biotite B3 ($Fe^{3+}/Fe^{2+} + Fe^{3+} = 0.115$) at conditions just to the higher oxygen fugacity side of the nickel-nickel oxide buffer.

There are also other possible complications in correlating their compositions with the experimental work. The possible alteration of the valency state of titanium with varying $PO_2$ is neglected, and the effect of this on the $Fe^{3+}/Fe^{2+} + Fe^{3+}$ ratio is unknown. The $PO_2$ conditions suggested by the $Fe^{3+}/Fe^{2+} + Fe^{3+}$ ratios could therefore be substantially in error, however these ratios indicate in a general way the lateral variation in oxidation-reduction conditions at the time of crystallization. It can be seen that there is a progressive reduction of the

## FIG. 19.

## CHEMICAL VARIATION OF THE BIOTITES.



(after Wones and Eugster, 1965).

biotites (i.e. decrease in $Fe^{3+}/Fe^{2+} + Fe^{3+}$) proceeding from the envelope schist, through the migmatite to the granodiorite, see Fig 19.

Muscovite

The refractive indices of muscovites from three different samples were virtually identical at β, γ = 1.599±.002. A basal spacing d(002) = 9.987±.004 Å was measured for the muscovite from T1 using silicon as an internal standard.

Chemistry

The analysis together with calculated structural formula for the muscovite from T1 is given below:

| | | | | |
|---|---|---|---|---|
| $SiO_2$ | 45.43 | Structural formulae on 22(O, OH) anhydrous basis | | |
| $TiO_2$ | 0.67 | | | |
| $Al_2O_3$ | 33.50 | Si | 6.12) | 8.00 |
| $Fe_2O_3$ | 0.10 | $Al^{iv}$ | 1.88) | |
| FeO | 1.93 | $Al^{vi}$ | 3.44) | 4.13 |
| MnO | 0.01 | Ti | 0.07) | |
| MgO | 1.48 | $Fe^{3+}$ | 0.10) | |
| CaO | 0.39 | $Fe^{2+}$ | 0.22) | |
| $Na_2O$ | 0.51 | Mg | 0.30) | |
| $K_2O$ | 10.14 | Ca | 0.04) | 1.91 |
| $H_2O^+$ | 3.35 | Na | 0.13) | |
| $H_2O^-$ | 0.13 | K | 1.74) | |
| $P_2O_5$ | 0.10 | | | |
| | 97.74 | | | |

Analytical errors are believed to be responsible for the low total, as the whole analysis was performed on slightly less than 1.5 grams of mineral concentrate. If it is assumed that this error is evenly distributed, the analysis is a valid indication of the chemistry of the muscovite. Before calculating the structural formula, the CaO value of the analysis was corrected for apatite by assuming that the $P_2O_5$ of the analysis was the result of this impurity.

The calculated structural formula suggests that the analysed muscovite conforms fairly closely to the ideal formula, given by Deer, Howie and Zussman, V. 3, 1962, p. 11 as:

$$K_2Al_4(Al_2Si_6O_{20})(OH, F)_4$$

The X site of the analysed muscovite is almost filled to its maximum of 2, with a small proportion of Na representing a minor paragonite component, and a trace of Ca. The Y site has a small excess but is very close to the ideal occupancy of 4. All the Ti and some of the Fe assigned to this site are probably derived from minute inclusions of opaque material in the muscovite of the analysed concentrate. The Z site, with 1.88 Al and 6.12 Si is also very close to the ideal occupancies of 2 and 6 respectively.

Taking the above into consideration, it is evident that muscovite is a relatively pure variety, with minor amounts of Na, Fe, Mg and possible Ti causing a slight departure from the ideal formula.

## Garnet

Although a rare constituent, sufficient garnet was concentrated from one granodiorite sample to allow a partial analysis for MnO, (the garnet thus analysed is that illustrated in Plate 16C). This is compared with a garnet from a pegmatite within the granodiorite. Cell dimensions were determined in each case by X-ray powder photograph and refractive indices were measured in sodium light on a portion of each concentrate.

| | Granodiorite | Pegmatite |
|---|---|---|
| $a\mathring{A}$ | 11.559 | 11.562 |
| $n_d$ | 1.813 | 1.819 |
| MnO (wt%) | 10.20 | 13.77 |

Using determinative charts modified from Winchell (1958), the following approximate compositions were determined.

| | Almandine | Spessartine | Grossular | Pyrope (Mol. %) |
|---|---|---|---|---|
| Granodiorite | 66 | 25 | 4 | 5 |
| Pegmatite | 59 | 33 | 8 | - |

## Opaque Mineral Phases

An X-ray powder photograph of a concentrate of the opaque mineral phase showed it to be a mixture of two phases, pyrrhotite and ilmenite, (see Appendix 2).

# Chapter 20

# PETROGENESIS

## Introduction

The information contained in the previous chapters is now used to examine the various theories of granite petrogenesis, with the aim of explaining the origin and evolution of the Tia Granodiorite.

## Previous work on Granite Petrogenesis in Northern N.S.W.

The mineralogic and modal characteristics that define two suites of granitic intrusions in northern N.S.W. have already been mentioned. Previous workers (eg. Vernon, 1961; Wilkinson, Vernon and Shaw, 1964; Chappell, 1966; Wilkinson, 1966; Phillips, 1968) have developed the theory that hybridism, i.e. the mixing of acid liquids with basic igneous rock material, has been the dominant process in the evolution of the various granitic rock types of the New England Batholith.

In the Tenterfield district, Wilkinson et al (1964) show that a number of adamellite-porphyrite intrusions have arisen by a process of large scale hybridism involving a low melting, silicic, alkalic liquid and near solid biotite diorite. Dioritic microxenoliths are common, and their mineralogy is similar to equivalent minerals occurring as individual phenocrysts. There is also textural evidence of mixing, with micro-brecciation and cataclasis of phenocrysts derived by progressive fragmentation of the dioritic microxenoliths. Wilkinson et al (1964) believe that the silicic, alkalic low melting liquid was introduced into the diorite from an external source, with the liquid in contact with the disrupted dioritic material for only a short period prior to final crystallization. The Bungulla Porphyritic Adamellite, a later, major intrusion of the Batholith, is of similar composition to the adamellite porphyrites, and it is suggested that slow crystallization at depth of the latter would give rise to more "normal" granitoid adamellites.

At the southern end of the Batholith in the Moonbi district, Chappell (1966) also demonstrated that, with the exception of the Kia-Ora Adamellite, the generation of the granite magmas involved processes of large scale hybridism. These granites are believed by Chappell to have originated by partial melting of basic rocks of shoshonitic composition near the base of the crust. The acid liquid fraction thus derived is believed to have included cognate xenolithic material of the basaltic parent during partial melting. The final composition of the granites is considered to have resulted from the dispersion of this xenolithic material throughout, giving a strong chemical coherence of the mafic silicates of the cognate xenoliths and those of the remainder of the intrusion.

In the northern part of the Batholith near the Queensland border, Phillips (1968) showed again the processes of hybridism were important in the genesis of the granites. It is suggested that the porphyritic adamellites are the product of reaction between dolerite (or equivalent rock) and a magma close to the Stanthorpe Adamellite in composition.

On petrographic grounds, Vernon (1961) believed that contamination was important in the development of the adamellite-granodiorite of the Uralla area. As evidence he cited the progressive reconstitution and disintegration of abundant basic xenoliths resulting in a release of mafic silicates into the magma. The gradation from marginal granodiorite to a core of adamellite in this intrusion is attributed to this process rather than crystal fractionation.

The hypothesis that the various members of the New England Batholith have hybrid origins relies very heavily on the existence of abundant basic igneous xenoliths and microxenoliths within the various intrusions. The rarity of these basic xenoliths within the members of the Hillgrove Plutonic Suite suggests that a comparable process of hybridism has not been important in the generation of these latter magmas.

It was this feature, among others, that resulted in the proposal by Binns (1966) of a different hypothesis to explain the origin of the Abroi Gneiss. In the Wongwibinda district, an intrusive sequence was established within the Zone of Migmatites surrounding the Abroi Gneiss, commencing with leucocratic adamellite veins and continuing through a series of biotite enriched sills, dykes and small intrusions, (Binns, 1966). The abundance of schistose xenoliths with diffuse margins in the later members of the sequence was believed to point to increasing assimilation of metasedimentary material by an initially siliceous, ferromagnesian-free magma. The Abroi Gneiss was thought therefore to have developed by contamination of a siliceous, low melting liquid, similar in composition to leucocratic adamellite from the Zone of Migmatites, with the common metasedimentary rocks of the area, consisting of quartzose greywacke and slate.

## Petrogenesis of the Tia Granodiorite

### Introduction

A widely accepted theory of granite petrogenesis holds that these magmas may arise from straight-forward partial fusion of pre-existing solid rocks, (Eskola, 1932; Tuttle and Bowen, 1958; Kranck and Oja, 1960; Turner and Verhoogen, 1960; Wyllie and Tuttle, 1960, 1961; Luth, Jahns and Tuttle, 1964; Barth, 1965; Kleeman, 1965; von Platen, 1965; Winkler, 1967; James and Hamilton, 1969).

The source of such magmas is commonly believed to be the lower levels of the crust, and the intrusion of this magma to different levels is thus likely to result in granites occurring in a series of different geologic enviroments, (cf. the "granite series" of Read, 1949, 1955; and the zonal classification of Buddington, 1959).

As a first approximation it is this hypothesis that most adequately explains the homogeneity, rarity of xenoliths and association with regional metamorphism that characterises the Tia Granodiorite.

In the framework of this partial melting hypothesis of granite petrogenesis, the following specific questions concerning the Tia Granodiorite offer themselves for explanation:

1. At what T, P and $PH_2O$ conditions did partial melting take place and what was the nature of the pre-existing solid rock that underwent partial melting?

2. Did the magma thus generated subsequently undergo any chemical or mineralogic changes by, for example, contamination with other rock material, or metasomatic transfer of elements into the envelope schists.

Further questions of a more general aspect concern the significance of the chemical differences between the New England Batholith and the Hillgrove Plutonic Suite and the relationship between the metamorphic evolution of the

Tia Complex and the Tia Granodiorite.

During the production of granitic magmas, the chemical composition of the liquid phase depends on the physical conditions prevailing and on the composition of the rocks being melted, (Tuttle and Bowen, 1958; von Platen, 1965; Winkler, 1967; James and Hamilton, 1969). Of the two questions posed above, the second must be answered first, as any change in composition during evolution of the magma would invalidate its subsequent correlation with the experimental work on the granite system.

## Compositional Change During the Evolution of the Tia Granodiorite

### 1. Contamination

Scattered metasedimentary xenoliths throughout the granodiorite possess very sharp contacts and show no evidence of any reaction with the surrounding rock. Trondjhemitic and dioritic xenoliths, also with sharp contacts, show no sign of fragmentation and dispersion of their constituents throughout the granodiorite, as described for example by Vernon (1961), Wilkinson *et al* (1964) and Chappell (1966).

It is concluded that during the later stages of evolution of the Tia Granodiorite, represented by the present level of exposure, there is little evidence that the composition of the magma has been substantially modified by contamination with other rock material. Contamination could still have taken place, however, at lower levels where partial melting and magma generation occurred.

## 2. Metasomatism

In Chapter (18) it is shown that layered schist and migmatite contact rocks are considerably enriched in potassium. It is believed that this is the result of migration of potassium from the granodiorite into cooler envelope rocks during emplacement. Orville (1963) demonstrated this transfer experimentally and also showed that migration of sodium ions should take place in the opposite direction. This process would deplete the granodiorite in potassium feldspar, and increase the modal plagioclase, which overall should become more sodic. The modal study reported in Chapter (18) is insufficiently detailed to detect any variation attributable to this migration, however it is interesting to note that the granodiorite T1 from the centre of the intrusion has a $K_2O/Na_2O$ ratio of 1.18, while T2 from near the contact has $K_2O/Na_2O$ of 0.89.

The capability of metasomatic transfer of certain elements to significantly alter the composition of the granodiorite should therefore be examined more closely. Some possible effects of this transfer are discussed below.

## (a) Myrmekite

Myrmekite is clearly replacing the potassium feldspar, however it is a minor constituent of the granodiorite, present in no more than accessory quantities in some thin sections. As a source of potassium for metasomatic transfer, its formation is clearly inadequate to detectably change the overall composition of the granodiorite or provide for the potassium metasomatism of the contact schists.

## (b) Muscovite

Muscovite is of sufficient abundance and widespread occurrence in the Tia Granodiorite for its crystallization to provide substantial potassium for introduction into the envelope rocks. Migration of potassium increases the normative corundum of the granodiorite, resulting in the crystallization of muscovite by the following reaction, (Billings, 1938; Hemley, 1959; Burnham and Shade, 1968).

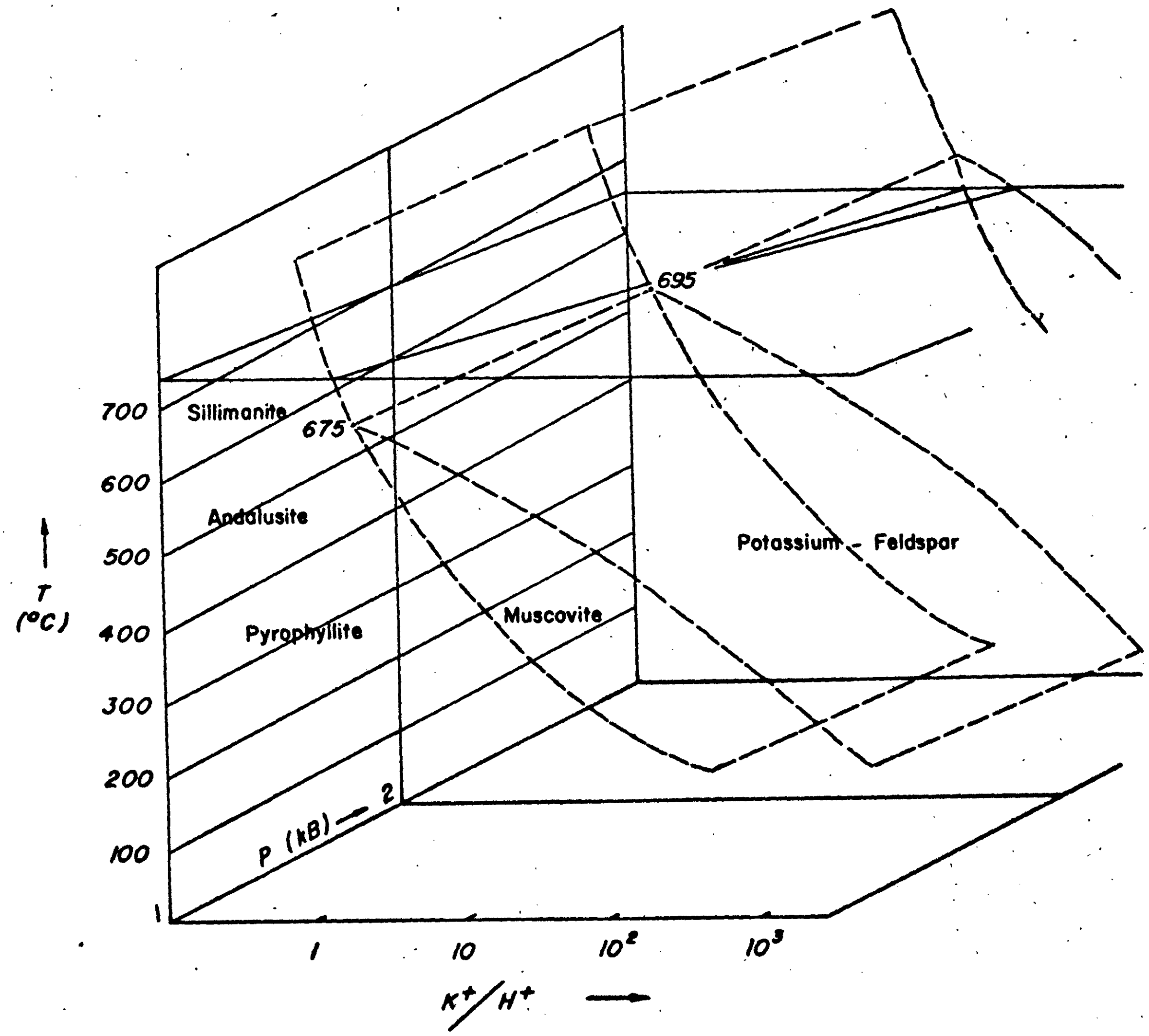
$$\underset{\text{Potassium Feldspar}}{3KAlSi_3O_8} + 2H^+ \rightleftharpoons \underset{\text{Muscovite}}{KAl_3Si_3O_{10}(OH)_2} + 6SiO_2 + 2K^+$$

At a likely fluid pressure (eg. $< 2$kB) in a cooling granitic melt, the experimental work suggests that the temperature of crystallization of muscovite is controlled by the $K^+/H^+$ ratio, of the fluid phase. The inferred relationships of the relevant phases of the system

$K_2O$ - $Al_2O_3$ - $SiO_2$ - $H_2O$ in Fig 20 are constructed from the data of Hemley (1959) and Burnham and Shade (1968). This shows that the lower the $K^+/H^+$ ratio during crystallization, the higher the temperature at which the muscovite stability field is intersected. If in addition potassium migrates along a temperature gradient into the envelope rocks, as shown by Orville (1963), then the above reaction is displaced in the direction of crystallization of muscovite. Low temperature, post-consolidation "deuteric" alteration and sericitization of feldspars of granites is usually explained by reactions of the above type, however if the $K^+/H^+$ ratio is sufficiently low, the muscovite stability field may be entered while the melt is still largely liquid, and muscovite crystallizes as a mineral phase of apparently primary origin.

The $Fe^{2+}/Fe^{3+}$ ratio of the granodiorite implies that the magma crystallized at conditions of low oxygen fugacity. The chemistry of the biotite suggests that $PO_2$ conditions in the melt were between those defined by the magnetite-wüstite and quartz-fayalite-magnetite buffers. Under isobaric conditions, a decrease in the partial pressure of oxygen results in an increase in the equilibrated hydrogen pressure, (Miyashiro, 1964, p. 722), and by dissociation, an increase in the $H^+$ of the melt. The $K^+/H^+$ ratio may therefore be decreased at conditions of low oxygen

FIG. 20.



Schematic representation of the system $K_2O$-$Al_2O_3$-$SiO_2$-$H_2O$ at varying $K^+$ $H^+$ ratios, from the data of Hemley(1959) and Burnham and Shade,(1968).

fugacity, permitting the crystallization of muscovite at progressively higher temperatures according to Fig. 20.

The textural character of the muscovite supports the above hypothesis. It occurs as clusters bordering larger biotites, suggesting it crystallized after the biotite, and as stringers and lenticles of small flakes parallel to the cataclastic foliation. The octahedral aluminium content of the biotite indicates that it is in equilibrium with muscovite, and this is explained by equilibration of the biotite with the melt during crystallization, whereby the octahedral aluminium of the biotite effectively represents solid solution of muscovite in the biotite lattice. Once approximately 0.6 atoms/formula unit of octahedral aluminium is surpassed, muscovite crystallizes, nucleating at the margins of the coarser grained, muscovite-saturated biotites. Flexing and undulatory extinction of these muscovites show they have also participated in the cataclastic deformation.

There is no textural evidence of the breakdown and removal of potassium feldspar by the above reaction, and this agrees with the conclusion that crystallization of muscovite took place at a relatively high temperature while the granodiorite was still mobile and largely fluid. In addition, to make the melt corundum normative, the migration of sodium from the wall rocks into the melt, as predicted by Orville (1963), must have been relatively insignificant compared with that of potassium outwards.

In summary, it has been shown that the crystallization of muscovite in the Tia Granodiorite coincided with the depletion of the partly fluid magma in potassium, which entered the fluid phase and underwent metasomatic transfer into the envelope rocks. This depletion in potassium must be considered when correlating the bulk chemistry of the granodiorite with experimental studies of synthetic granite systems.

## The Nature of the Rock Material inferred to have undergone Partial Melting

The following evidence is available:

(1) The granodiorite is significantly reduced, i.e. with a high $Fe^{2+}/Fe^{3+}$ ratio, and it is reasonable to infer that this was also a chemical characteristic of the source rocks that underwent partial melting.

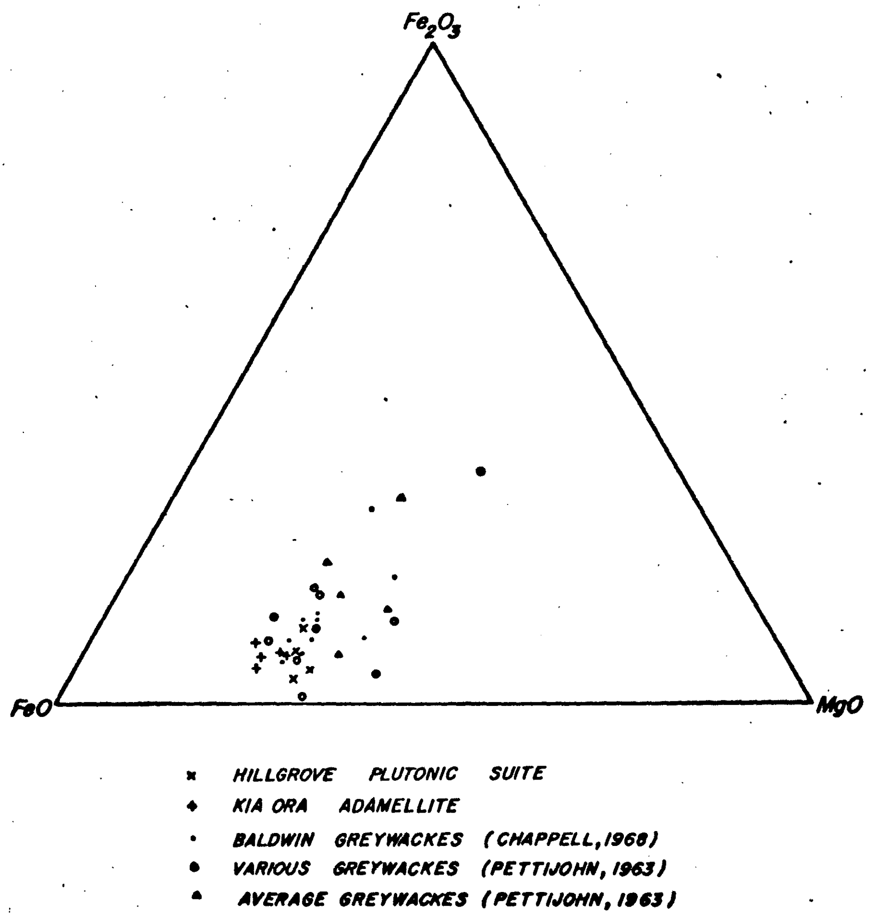
(2) The higher initial $Sr^{86}/Sr^{87}$ ratio of the Kia-Ora Adamellite mentioned earlier suggests that it was derived by partial melting of sialic crustal rocks, perhaps originally sedimentary. While not conclusive, the fact that the Kia-Ora Adamellite and the Tia Granodiorite have so many features in common supports the possibility that they arose by a similar process.

(3) The Tia Granodiorite is intimately associated with widespread regional metamorphism, and has localized migmatitic envelope rocks inferred to have developed by partial melting. The biotite of these migmatitic envelope rocks has almost identical chemistry to that of the Tia Granodiorite, (see Chapter 19).

These features are consistent with the generation of the granodiorite magma by partial melting within a geosynclinal pile originally composed of mainly greywackes with black shales and minor basic volcanics. Geosynclinal greywackes are characterized by a high $Fe^{2+}/Fe^{3+}$ ratio. This is illustrated in Fig 21 in which the close correspondence of the Tia Granodiorite and the Kia-Ora Adamellite with various typical greywackes is apparent. If carbonaceous black shales were a significant component of the pile, regional metamorphism and partial melting would lead to a further increase in the $Fe^{2+}/Fe^{3+}$ ratio of the melt because of the reduction of the iron by reaction with the carbonaceous material (mainly graphite) of the shale, (Miyashiro, 1964, p.726). Original sedimentary differences in oxidation-reduction conditions would disappear once melting has occurred and the magma has acquired some degree of mobility.

The chemical differences outlined earlier between the Hillgrove Plutonic Suite and the New England Batholith

FIG. 21.


$Fe_2O_3$
FeO
MgO
× HILLGROVE PLUTONIC SUITE
+ KIA ORA ADAMELLITE
· BALDWIN GREYWACKES (CHAPPELL, 1968)
● VARIOUS GREYWACKES (PETTIJOHN, 1963)
▲ AVERAGE GREYWACKES (PETTIJOHN, 1963)

are now explicable in terms of their differing petrogenesis. The wide range of $FeO/Fe_2O_3$ ratios of the plutons of the New England Batholith is seen as the result of the addition of varying amounts of basic igneous rock material, containing significant magnetite and possessing a wide range of $FeO/Fe_2O_3$ ratios, to an acid low melting liquid, (or acid parent of Wilkinson et al, 1964; Chappell, 1966). The uniformly high $FeO/Fe_2O_3$ ratio of the Hillgrove Plutonic Suite is interpreted to mean that little or no such addition of basic igneous rock material took place during the evolution of the members of this suite.

Hybridism involving basic igneous rock and an acid liquid again accounts for the enrichment in CaO with increasing FeO+Mn+MgO that characterizes the New England Batholith. The trend followed by the Hillgrove Plutonic Suite in Fig 17c shows much less enrichment in CaO with increasing FeO+MnO+MgO. This latter behaviour is also explicable by partial melting of metasedimentary material of mixed greywacke - shale composition alone.

## Origin of the Dioritic and Trondjhemitic Xenoliths

Two alternatives concerning the origin of these rare inclusions have been stated in Chapter ( 17). In view of the evidence of lack of basic rock-acid liquid hybridism within the Hillgrove Plutonic Suite, it is thought that these are unlikely to be xenoliths of pre-existing basic or intermediate igneous rock.

Chemical inhomogeneities within the source rocks wherein partial melting and magma generation occurred would be expected to result in differing degrees of partial melting, depending on the composition of the rock undergoing melting. The biotite of the granodiorite is envisaged as entering the melt as suspended material within the regions of more complete melting (see below). This then achieves the same composition throughout by equilibration via the melt. The rare dioritic and trondjhemitic xenoliths are believed to represent material from areas in which, because of differing original composition, melting was less complete. These xenoliths are thereby envisaged as fragments of potassium feldspar-free paragneiss that remained after partial melting of the source rocks.

## The T, P and $PH_2O$ conditions of Magma Generation

To make any worthwhile estimate of these conditions the following must be taken into account:

(1) There is no reliable way of estimating the proportion of the inferred metamorphosed greywacke-shale source rocks that were melted to give the granodiorite magma.

(2) It has been shown that the granodiorite has been depleted in potassium, which has migrated into the envelope rocks.

(3) Von Platen (1965) and Knabe (1966) (in Winkler, 1967, p. 213) showed that during partial melting, biotite does not enter the fluid phase to any extent. The potassium of the biotite must therefore be extracted from the CIPW normative felsic constituents before comparing the Tia Granodiorite with bulk compositions produced experimentally.

(4) Anorthite added to the granite system drastically changes the composition of the initial liquids formed, i.e. the more anorthite rich the rock undergoing melting, the more orthoclase rich the early melting fraction becomes, (Von Platen, 1965; Winkler, 1967; James and Hamilton, 1969).

Fig 22a is constructed from the data of Tuttle and Bowen (1958), Luth et al (1964) and Winkler (1967). The analyses of the Hillgrove Plutonic Suite plot very close to the cotectic minima of 2-3 kilobars at 660-670°C. on the Or side of the line joining the cotectic minima. This position corresponds very closely to the field of maximum concentration of granitic rocks compiled by Tuttle and Bowen (1958).

After subtracting the potassium of the biotite in each the analyses T1 and T2 plot well away from the cotectic minima, toward the Qz-Ab sideline ($T1^1$ and $T2^1$ of Fig 22a). It has also been shown, however, that the granodiorite is depleted in potassium, so at its time of generation it would have plotted closer to the cotectic minima of Fig 22a,

FIG. 22a.

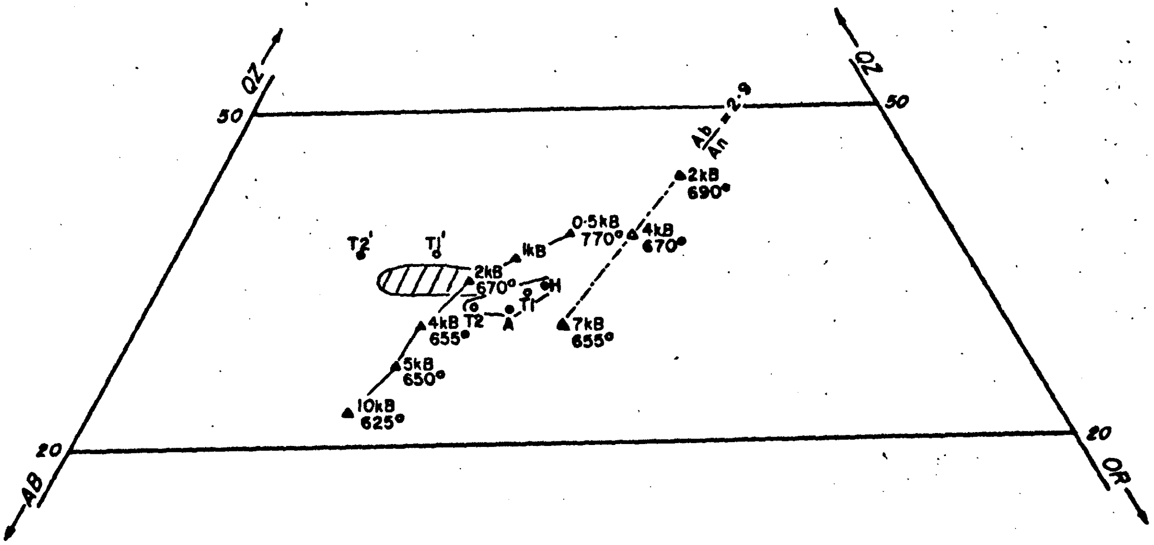
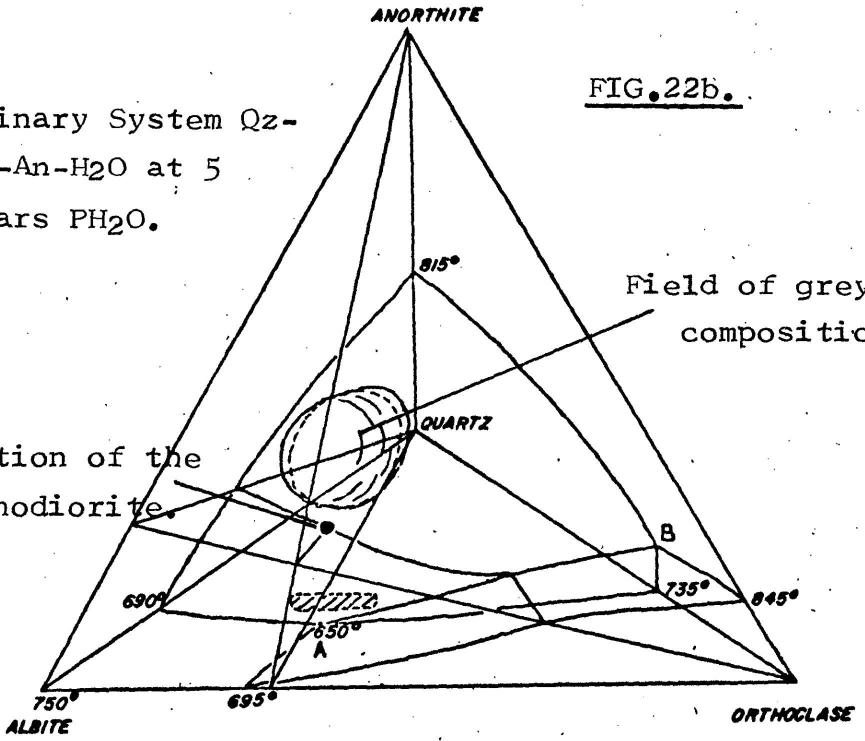


FIG.22b.

The Quinary System Qz-Or-Ab-An-H2O at 5 kilobars PH2O.



Field of greywacke composition.

Composition of the Tia Granodiorite.

somewhere along the lines connecting T1 and $T1^1$ and T2 and $T2^1$. The original composition of the felsic constituents of the melt is thus difficult to estimate accurately, although the region of likely composition in the Qz-Ab-Or triangle is known, (outlined in Fig 22a).

The Tia Granodiorite also contains substantial normative anorthite, so it actually belongs to the quinary system Qz-Or-Ab-An-$H_2O$, and the analyses of Fig 22a plot above the Qz-Ab-Or face of the Qz-Or-Ab-An tetrahedron (Fig 22b). At pressures less than about 5 kilobars, the analyses plot in the plagioclase space, and at higher pressures in the quartz space.

Isobaric partial melting of rocks of approximate greywacke composition in the quinary system (Fig 22b) starts with a tiny proportion of melt of composition A which increases in proportion and changes in composition along the isobaric univariant line A-B as the temperature rises. The composition of the fluid phase follows A-B until all the potassium of the parent has entered the fluid phase, when the composition of the melt leaves the isobaric univariant line and progresses toward the composition of the parent by traversing the divariant surface separating the quartz and plagioclase space. Once this takes place the Ab/An ratio of the melt falls rapidly, and the Ab/An ratios such as those of T1 (= 3.3) and T2 (= 2.9) may be acquired.

Two arguments suggest that the composition of the melt did not leave the divariant surface during magma generation, i.e. neither all the quartz nor all the plagioclase entered the melt phase.

(1) Most typical greywackes contain a lower Ab/An ratio than that of the Tia Granodiorite, (Pettijohn, 1963).

(2) The trondjhemitic and dioritic xenoliths, inferred to represent residual source material, contain both quartz and plagioclase.

This suggests that partial melting to produce the Tia Granodiorite magma took place at about 5 kilobars water vapour pressure.

The generation of a granodiorite magma also depends on the Or/Ab ratio of the melt. At higher water vapour pressures, the granite minimum is known to shift toward the Ab vertex, and it has also been shown that the univariant line in the quinary system exhibits the same trend, (Winkler, 1967, p. 206), see Fig 22a. It follows that compositions capable of generating granitic melts with Ab/Or equal to or less than unity (granitic liquids sensu stricto) at 1 kilobar $PH_2O$ may form melts with Ab/Or greater than unity (granodioritic liquids) at 5 kilobars $PH_2O$, (James and Hamilton, 1969, p. 135). This estimate of pressure is in close agreement with that deduced above.

The temperature reached during partial melting is more difficult to estimate. At a water vapour pressure of 5 kilobars, melting would have commenced at about 650°C, (see Fig22b), and a maximum temperature reached of the order of 720°C. A temperature such as this, significantly greater than the granite minima, is necessary if the granodiorite magma is to undergo emplacement into higher levels of the overlying deformed and metamorphosed geosynclinal rocks. As the magma undergoes upward emplacement, the temperature and water vapour pressure decrease and the melt undergoes progressive crystallization following a path opposite to that described above for partial melting, but at a progressively lowering water vapour pressure. At the very latest stages of crystallization, a minor quartz, potassium feldspar-rich fraction separated from the remainder of the near solid magma and underwent separate emplacement as aplite and pegmatite sheets.

## Summary of Petrogenesis

It is suggested that the Tia Granodiorite originated by partial melting of geosynclinal sedimentary rocks of predominantly greywacke composition with probable minor black shales. Partial melting is believed to have taken place at about 5 kilobars $PH_2O$ over a temperature interval of 650-720°C. During emplacement the granodiorite became depleted in potassium which underwent metasomatic transfer into the envelope rocks. The melt thus became corundum normative and muscovite crystallized as a pseudo-primary phase.

The two suites of granitic intrusives found in north-eastern N.S.W. show significant chemical differences. These differences are explicable as consequences of their differing petrogeneses. The intrusives of the New England Batholith have been shown by various workers to have arisen by processes of basic igneous rock-acid low melting liquid hybridism. In contrast, the plutons of the Hillgrove Plutonic Suite are more likely the result of partial melting of metasedimentary rocks, with basic igneous rock-acid liquid hybridism playing an insignificant part. The Kia-Ora Adamellite, previously considered to be a member of the New England Batholith, is shown to be related to the Hillgrove Plutonic Suite.