Part VI

PETROGENESIS OF THE METAMORPHIC ROCKS AND GEOLOGICAL HISTORY

PETROGENESIS OF THE METAMORPHIC ROCKS AND GEOLOGICAL HISTORY

Introduction

In this Part, integration of all the structural, petrographic, mineralogical and geochemical data is attempted and an overall geological history for the region is proposed.

Chapter 25

METAMORPHIC HISTORY OF THE TIA COMPLEX

Introduction

It is shown that the rocks of the Tia Complex have undergone a complicated structural and metamorphic history. This contrasts with the regional metamorphism and deformation of the "Moona Plains style" which has affected the remainder of the subdivisions described in Part I. These two areas of contrasting metamorphic and structural style are separated by faults along which substantial movement must have occurred in order to juxtapose the contrasted regions.

The rocks of the Tia Complex have been studied more closely than the remainder of this region and this discussion applies to the Tia Complex only, unless otherwise indicated.

Metamorphic History of the Tia Complex

It is shown that in general, the extent of metamorphic recrystallization and structural deformation undergoes progressive contraction with time towards the Tia Granodiorite. This change in the distribution of metamorphic and structural activity is seen as defining a major cycle of metamorphism in which the generation and uprise of the granodiorite magma played an important part. In contrast, the recrystallization of minerals infilling veins throughout the Zone A metabasalts is spatially associated with the Nowendoc Ultrabasic belt.

The details of the metamorphic history of these rocks are deduced from the relationship of the metamorphic minerals to the successive structural elements, and the textural relationship and chemistry of the coexisting minerals.

Using these features, a succession of metamorphic episodes have been recognized throughout the Tia Complex. These are not necessarily viewed as discrete periods of metamorphism, as the majority belong to a large scale cycle of metamorphism associated with the Tia Granodiorite. These episodes are denoted respectively as M1, M2, M3 etc. and are described in more detail below:

M1

The existence of the F2 folds in an earlier quartz and mica-rich layering throughout the Oxley and Wybeena Metamorphics defines a pre-F2 metamorphic episode M1. This episode is inferred to have coincided with F1 during which the S1 layering developed as a metamorphically differentiated planar surface. Evidence of the M1 episode is absent from the Brackendale Metamorphics.

The metamorphic grade and its distribution during M1 is not known as S1 has undergone widespread transposition into S2 and it appears that the M1 fabrics and assemblages have been completely obliterated by overprinting. It is stated in Part II, Chapter (4) that the possibility of Pre-F1 deformation could not be eliminated and likewise earlier episodes of metamorphism may also have existed, the evidence of which has also been obliterated.

It is problematical whether the M1 episode strictly belongs to the metamorphic cycle associated with the Tia Granodiorite. There is no evidence of M1 in the Brackendale Metamorphics and it is shown in Part I that this subdivision is probably younger than the Oxley and Wybeena Metamorphics, which may be viewed as basement successions. It is therefore possible that M1 belongs to an earlier metamorphic cycle and orogenic period. Confirmation of this must await a much more detailed structural analysis of the relationship of the inferred basement and the Brackendale Metamorphics.

M2

This is the first major episode that clearly belongs to the cycle of metamorphism associated with the Tia Granodiorite and is recognizable within all three subdivisions of the Tia Complex. Within the Brackendale Metamorphics, this episode coincided F1 and the development of the metamorphic S1 lamination and schistosity. Within the basement successions, this episode coincided with F2 and the transposition of the S1 metamorphic layering and schistosity into S2.

Within the Brackendale Metamorphics this episode of metamorphism was of biotite grade or above. The progressive development of the S1 veining toward the granodiorite in this subdivision is evidence that the direction of the increasing metamorphic grade during M2 was towards the area now occupied by the Tia Granodiorite. The metamorphism of the basement successions reached biotite grade or above throughout the Transition Zone and Zone 2, in which a biotite schistosity developed parallel to the transposed S1 layering.

The M2 episode coincided with a large-scale regional deformation, however the association of the higher metamorphic grades of M2 with the granodiorite suggests that this is the first episode of a metamorphic cycle clearly associated with the Tia Granodiorite. The granodiorite was not emplaced until after M2 However its future site was indicated by the distribution of metamorphic activity during this episode.

M3

This episode is also recognizable in all three subdivisions of the Tia Complex, in which it coincided with the F2 folding of the Brackendale Metamorphics and F3 folding of the basement. The M3 episode corresponds to the development of a penetrative mica schistosity parallel to the axial planes of the abundant F2 and F3 mesoscopic folds. Rocks with evidence of the M3 episode are found in Stage 2 of the Brackendale Metamorphics and within the lower part of Zone 2, the transition Zone and Zone 1 of the Oxley and Wybeena Metamorphics. Rocks preserving the M3 episode are also found scattered throughout the area closer to the granodiorite. Between M2 and M3, biotite grade conditions contracted toward the granodiorite such that the M3 episode gave rise to the Transition Zone containing biotite grade M2 schists retrogressed to lower metamorphic grade.

<u>M4</u>

This episode involves the metasomatic introduction of potassium from the granodiorite into the envelope rocks. The abundance of orthoclase in these envelope schists has already been mentioned. Some limited chemical data supports the hypothesis that introduction of potassium has occurred. It is shown in Part IV, Chapter (20) that this migration of potassium resulted in the crystallization of muscovite in the granodiorite.

<u>M5</u>

This episode refers to the post-tectonic crystallization of micas in the vicinity of the granodiorite. This is much more strongly exhibited by the white micas than the biotite and is a characteristic of Stage 3 of the Brackendale Metamorphics and the upper Zone 2 schists of the Oxley Metamorphics. In Chapter (15) it is shown that the white mica that crystallizes as coarse cross-cutting porphyroblasts has an unusual composition which is interpreted as solid solution of muscovite and pyrophyllite.

Substantial overlap of M3, M4 and M5 is apparent throughout. In some cases the white mica porphyroblasts show a weak preferred orientation parallel to the M3 fabrics. This suggests that M3 to M5 refer to events recognizable within a continuous process involving declining structural activity combined with the nucleation and growth of porphyroblastic white mica and randomly oriented biotite.

It is shown in Part IV, Chapter (17) that the granodiorite was emplaced toward the close of the F2/F3 deformation of the envelope, and that the muscovite within the granodiorite is strung out parallel to the granodiorite foliation. In Part IV Chapter (20) it is shown that this muscovite crystallized as a consequence of the metasomatic introduction of potassium into the envelope schists. This suggests that M4 occurred towards the end of M3, with perhaps some overlap with M5..

M6

The episodes described above are both spatially and temporally associated with the generation and emplacement of the Tia Granodiorite. The M6 episode is spatially associated with the serpentinites of the

Nowendoc ultrabasic belt and although a temporal association cannot be proved, serpentinite emplacement is the only event with which this episode can be correlated and a relationship of M6 with this event seems likely.

It is shown in Chapter (10) that Zone A and some lower Zone B metabasalts have evidence of low grade regional dynamic metamorphism (i.e. M1, M2, M3) followed by static metamorphic recrystallization. This latter episode M6 is marked by the superposition on the M1, M2 and M3 assemblages of a later M6 assemblage consisting of:

Quartz-albite-pumpellyite-actinolite-crossite-chlorite-stilpnomelane.

The relationship between these two assmeblages is clearly seen in the post tectonic veins cutting these metabasalts. These veins contain metastable relics of epidote partially replaced by epidote and the mineral fabrics show that M6 was unaccompanied by deformation. As crossite has also been shown to be a late crystallizing phase in these metabasalts, it is also included in the M6 assemblage.

There is no clear imprint of M6 in the interlaminated siliceous schists except for some stilpnomelane in one sample of a Transition Zone schist from north west of Nowendoc.

Summary.

Six episodes of metamorphism have been recognized within the Tia Complex and it is shown that episodes M2, M3, M4 and M5 are closely related to the generation and emplacement of the Tia Granodiorite. Episode M1 may be a survivor from an earlier orogenic period, however further work is needed to determine its status. The last episode M6 is spatially related to the Nowendoc ultrabasic belt, and appears to be connected with the emplacement of serpentinites within the Nowendoc Fault zone.

This relatively complicated scheme of metamorphic evolution contrasts strongly with the "Moona Plains style" of metamorphism that characterizes the other subdivisions. Their metamorphic history consists of a single episode of recrystallization apparently unaccompanied by strong deformation.

Chapter 26

METAMORPHIC FACIES AND MINERAL REACTIONS

Introduction

The metamorphic episodes described in the previous chapter may now be discussed in terms of the metamorphic facies, and the possible metamorphic reactions that occurred. The M1 assemblages cannot be discussed as they have apparently been completely overprinted by later episodes. This discussion will therefore concentrate on M2-M6.

The scheme of metamorphic facies adopted herein is essentially that of Turner (1968).

Metamorphic Facies within the Metabasic Rocks

Zone A

Within this zone, and the lower grade part of Zone B, the assemblages developed during the M2-M5 episodes have been overprinted by assemblages of the M6 episode. The ACF diagram for the M2-M5 episodes is shown in Fig. 27a. The mineral assemblages of the M2-M5 episodes in this zone and the lower grade part of Zone B are typical of the Greenschist Facies of Turner (1968).

During the M6 episode, new mineral phases crystallized and minerals earlier stable were wholly or partially replaced. The ACF diagram for the M6 episode is shown in Fig. 27b. The glaucophanic amphibole crossite is an additional mineral phase of the M6 episode, and cannot be satisfactorily represented on

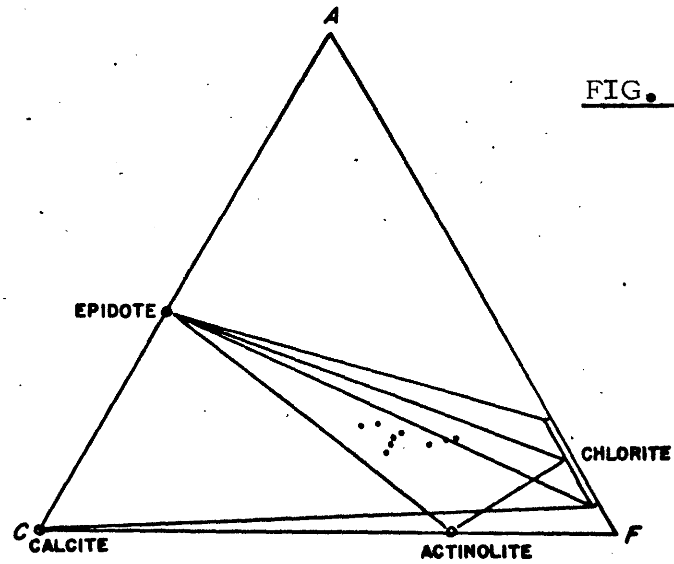

FIG. 27a.

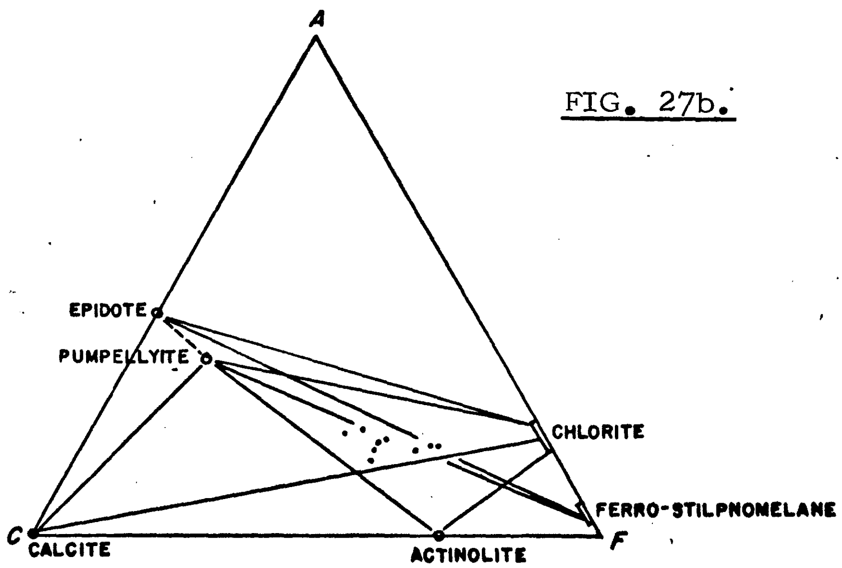

FIG. 27b.

the ACF diagram.

The abundance of pumpellyite in the M6 assemblages suggests they belong to the Prehnite-Pumpellyite-Metagreywacke Facies of Turner (1968). The presence of crossite indicates a transition to the Glaucophane-Lawsonite Facies of Turner (1968). Other phases characteristic of the latter facies, such as lawsonite, jadeite and aragonite are not found in these rocks.

It could not be shown that epidote and pumpellyite co-existed stably during M6, however epidote co-exists with crossite and stilpnomelane in some assemblages in which pumpellyite is absent. The possibility that epidote and pumpellyite were stable together is indicated on the ACF diagram by a broken tie-line.

Zone B

The lower part of this zone is similar to Zone A, and the dominant assemblages are those of the Greenschist Facies. The M6 episode has also affected some rocks of the lower part of this zone adjacent to the Nowendoc Ultrabasic Belt. The transition from actinolite to aluminous hornblende is inferred to take place at about the middle of this zone, above which albite-epidote amphibolites containing pale coloured hornblendes and minor biotite are typical. The ACF diagram for these assemblages is shown in Fig. 28a. The broken lines on this diagram indicate that chlorite may be

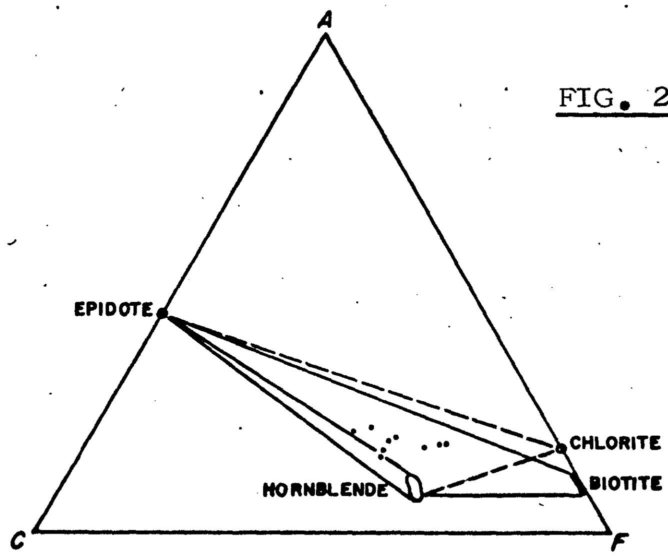

FIG. 28a.

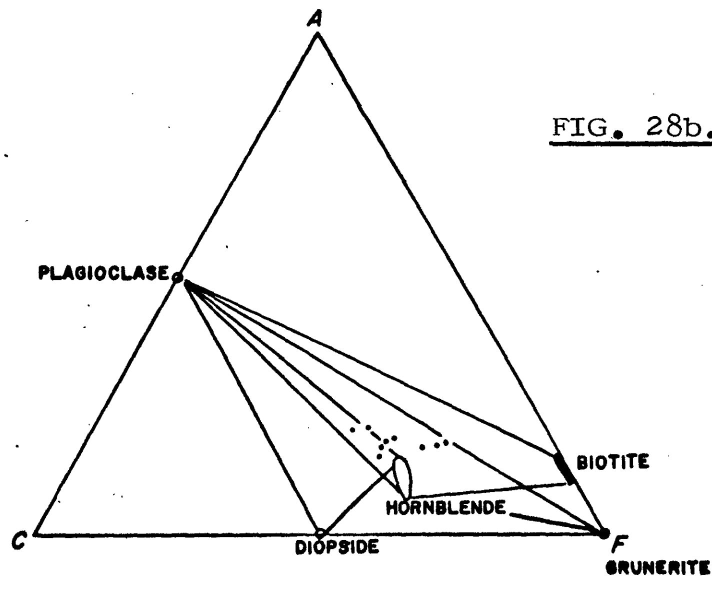

FIG. 28b.

a stable phase in some of the transitional rocks. These assemblages are characteristic of the Greenschist-amphibolite Transition Facies of Turner (1968), formerly known as the epidote-amphibolite facies.

Zones C and D

In both these zones the metabasic rocks have assemblages typical of the Amphibolite Facies of Turner (1968). The ACF diagram for these zones is shown in Fig. 28b. The majority of the amphibolites contain hornblende, plagioclase and quartz, with minor amounts of biotite. The hornblende has been shown to exhibit some grade dependent chemical variation. Diopside is an additional mineral phase at the highest metamorphic grade and grunerite is also found in one Zone D horizon.

Mineral Reactions

Reactions in the Low Grade Zones

In the low grade rocks, the original igneous assemblage can be seen to have undergone a series of complex reactions to give the observed metamorphic assemblage. Without more chemical data, precise reactions cannot be suggested but their overall nature can be inferred. During M1-M5, the original igneous clinopyroxene has been partially or completely replaced to yield actinolite, chlorite and epidote, and the original calcic plagioclase has given albite, epidote and possibly calcite. Original titaniferous opaque oxides have reacted to give sphene and iron oxide, and any olivine that may originally have been present has been replaced by chlorite.

During the M6 episode, the following mineral reactions took place:

(1) Epidote was replaced by pumpellyite. Banno (1964) p.281 showed that the pumpellyite bearing rocks of the Sanbagawa area have higher FeO/Fe_2O_3 values than those without. It is also known that the iron of epidotes is predominantly ferric, whereas pumpellyite is more enriched in ferrous iron, (Ernst, 1963). The crystallization of pumpellyite would therefore be expected at lower oxygen partial pressures.

It is shown in Chapter (16) that the analysed metabasalts have relatively high FeO/Fe_2O_3 ratios, but this data, although limited, does not indicate that the Zone A metabasalts are more reduced than those of higher metamorphic grade. This chemical data, in fact, suggests that there has been no significant change in the FeO/Fe_2O_3 ratio and this reaction is not therefore a result of a simple change in PO_2 during M6.

Replacement probably therefore occurred either as a result of a decrease in T or an increase in P (or both) during M6, as pumpellyite is known to be stable at lower T at a given P and at higher P at a given T than epidote, (Coombs, 1961, p.347).

(2) Stilpnomelane crystallized as a new mineral phase during M6, usually as radiating blades at the surface of chlorite grains. The crystallization of ferro-stilpnomelane rather than ferri-stilpnomelane also indicates a high Fe^{2t}/Fe^{3t} ratio and relatively low PO_2 conditions. The reaction by which stilpnomelane arose is probably similar to that proposed by Brown (1967), p.281, essentially as follows:

$$\text{Chlorite} + 0.1K_2O + 0.2MnO + 11SiO_2 + 1.6\ \text{Magnetite} + 2.5H_2O \rightleftharpoons 1.7\ \text{Ferro-stilpnomelane} + O_2$$

(3) Actinolite and chlorite were also stable during M6, crystallizing in the veins along with pumpellyite and stilpnomelane. These are not newly generated phases, but are present in the original M1-M5 assemblage. They have apparently transferred via the fluid phase and undergone growth in the veins. A change in their composition is probable, but no chemical data is available.

(4) Crossite is also inferred to have crystallized during the M6 episode. Texturally, it appears to have crystallized directly from the original clinopyroxene of the host basalt, (see Chapter 10). It appears that during M6, crossite rather than actinolite crystallized at the grain boundaries of the clinopyroxene, however actinolite was still stable and is found within veins along with other M6 minerals.

Without knowing the chemical composition of the crossites it is difficult to determine likely mineral reactions. The generalized reaction:

(1) Clinopyroxene (+H_2O) $\rightarrow$ Actinolitic amphibole took place during M1-M5, whereas during M6, the generalized reaction:

(2) Clinopyroxene (+ Albite + H_2O) $\rightarrow$ Crossite (+ Epidote ?) appears to have taken place in preference to (1). Diffusion of Na and Al to the sites of crossite nucleation is necessary for reaction (2), and these may have diffused from albite sited possibly only millimetres away from the crossite. The generalized reaction:

Actinolite (+ Albite) $\rightarrow$ Crossite (+ Epidote ?) has not taken place, and crossite and actinolite stably co-exist, with the actinolite rimming the crossite to form zoned amphibole plates.

It has been shown that glaucophane bearing metabasic rocks of the Sanbagawa area in Japan have much higher Fe^{3t} than those lacking glaucophane, (Iwasaki, 1963, p.32; Banno, 1964, p.283). The metabasic rocks of the Tia Complex all have relatively low Fe^{3t} (see Chapter 16 , Fig. 11), and have FeO/Fe_2O_3 ratios much more like those of the Franciscan metabasic rocks. Ernst (1963) suggests that glaucophanic amphiboles are stable outside the Glaucophane-Lawsonite Facies in rocks deficient in CaO and rich in Na_2O and MgO relative to Al_2O_3. Of the two metabasalts containing crossite that were analysed, one is deficient (MB6) and one enriched (MB8) in CaO and neither are enriched in Na_2O and MgO relative to Al_2O_3. Although the data is limited, unusual host rock composition does not appear to be an adequate explanation for crystallization of crossite in these metabasalts.

It is known that crystallization of glaucophane in rocks of normal composition is favoured by higher pressures, (Ernst, 1963). In view of the discussion above, an increase in pressure is believed to be an important factor in promoting the crystallization of crossite in the low grade metabasic rocks of the Tia Complex.

Actinolite-Hornblende Transition

This transition is inferred to take place where there is a rapid decrease and disappearance of chlorite. Again lack of chemical data limits discussion of possible reactions. There appears to be little decrease in the quantity of epidote where the inferred transition takes place, so the reaction is probably essentially as follows:

Actinolite + Albite + Chlorite $\rightarrow$ Hornblende + Quartz + H_2O.

Disappearance of Epidote

Epidote decreases rapidly and disappears at the Zone B - Zone C boundary, coinciding with the crystallization of calcic plagioclase. The composition of the epidote is unknown but it probably contained some iron. The reaction therefore probably took the following form:

Albite + Epidote $\rightarrow$ Calcic Plagioclase + Quartz with excess Ca, Al and Fe from the epidote being accommodated in the co-existing hornblende.

Reactions in Zones C and D

It has been shown that the hornblendes of these zones vary in chemical composition. This is partly in response to the composition of the host rock, however some grade dependent chemical variation was also found. The higher grade hornblendes are enriched in Na, resulting in the crystallization of a more calcic plagioclase as an accompanying phase.

The crystallization of grunerite in Zone D appears to result from replacement of earlier hornblende. This has taken place at the contact between the grunerite-garnet quartzite and the amphibolite. The crystallization of grunerite suggests an increase in Fe^{2t} and depletion of Ca and Al within the host rock. A strong chemical gradient between these two lithologies may have resulted in the transfer of these elements, but again lack of chemical data limits discussion.

In the highest grade amphibolite horizon, diopside is present and is believed to be derived by a breakdown reaction of hornblende.

Metamorphic Facies within the Siliceous Metasedimentary Rocks

Zone 1 (Oxley Metamorphics)

The assemblages of this zone belong to the Greenschist Facies of Turner (1968). The AKF diagram of these assemblages is given in Fig. 29a, showing the inferred wide compositional field of the white micas of this grade, ranging from muscovite proper to phengitic varieties. The assemblages recorded are all ascribed to the M1-M5 metamorphic episodes, and, in contrast to the metabasic rocks, there is little mineralogic evidence of the M6 episode in these rocks.

Transition Zone (Oxley Metamorphics)

The assemblages are again characteristic of the Greenschist Facies. The assemblages of this zone are shown in Fig. 29b. It has been shown that the assemblages of this zone are derived by retrogressive metamorphism of a biotite grade assemblage to give phengite rich schists. The inferred original assemblages are shown by dotted lines in Fig. 29b, and the final assemblage by solid lines.

Ferri-stilpnomelane found in the schists of the Transition Zone northwest of Nowendoc is believed to be the only mineralogic evidence of M6 in these rocks.

Zone 2 of the Oxley Metamorphics, and the Brackendale Metamorphics

Biotite is a characteristic mineral in all assemblages herein discussed. The lower grade portion of these rocks

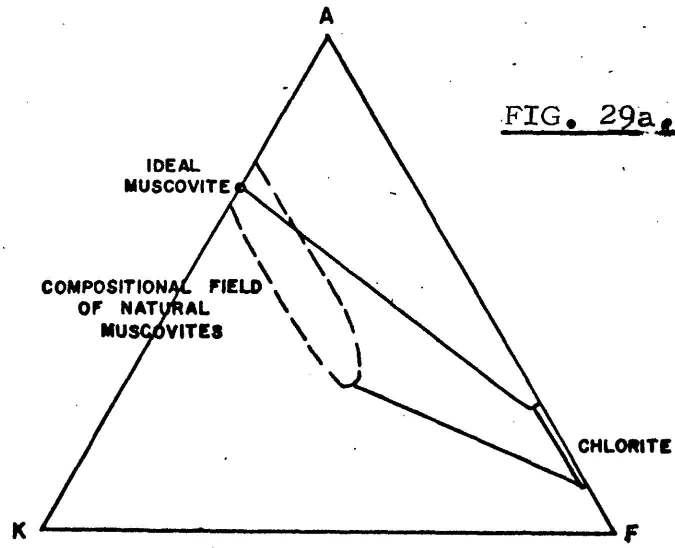

FIG. 29a.

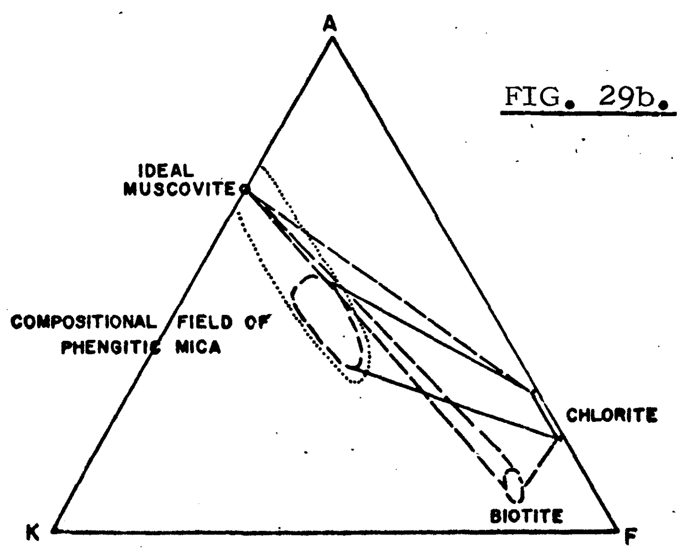

FIG. 29b.

probably recrystallized in the Greenschist Facies and Greenschist-amphibolite Transition Facies, but the assemblages of the interbedded metabasic rocks suggest the majority belong to the Amphibolite Facies of Turner (1968).

These rocks have been shown to have a complex metamorphic history. An AKF diagram to illustrate the possible assemblages before the emplacement of the granodiorite and introduction of potassium is shown in Fig. 30a. The ties for the lower grade assemblages are shown as broken lines. At higher metamorphic grade the ties shown as solid lines are believed to be valid, indicating that during M3 orthoclase and an aluminosilicate, probably sillimanite, crystallized.

The AKF diagram of Fig. 30b shows the assemblages that crystallized during M4 and M5, following the emplacement of the granodiorite and the introduction of potassium into the envelope rocks. The analysed envelope schist and its biotite (B3) and muscovite (MU1) are plotted on Fig. 30b, showing the potassium enriched bulk composition of the envelope schist and the aluminium enriched compositions of the muscovite and biotite.

Metamorphic Reactions

Transition Zone

The reaction by which biotite was replaced by a phengitic white mica was probably similar to that proposed

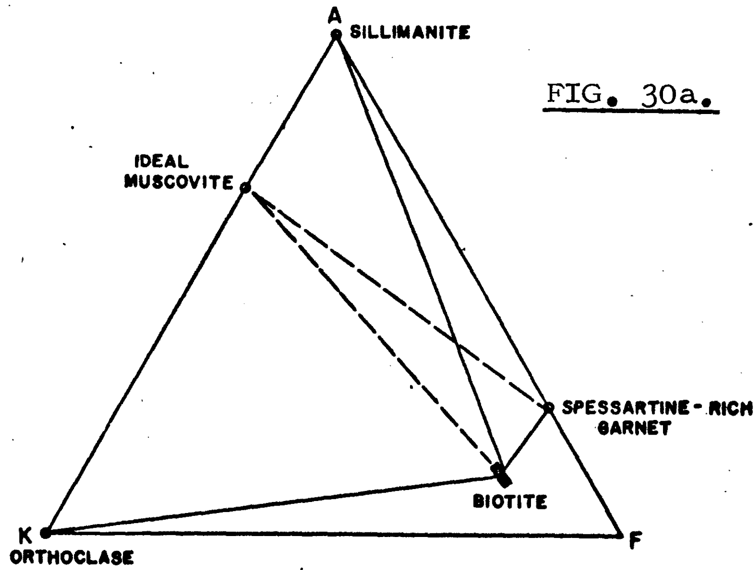

FIG. 30a.

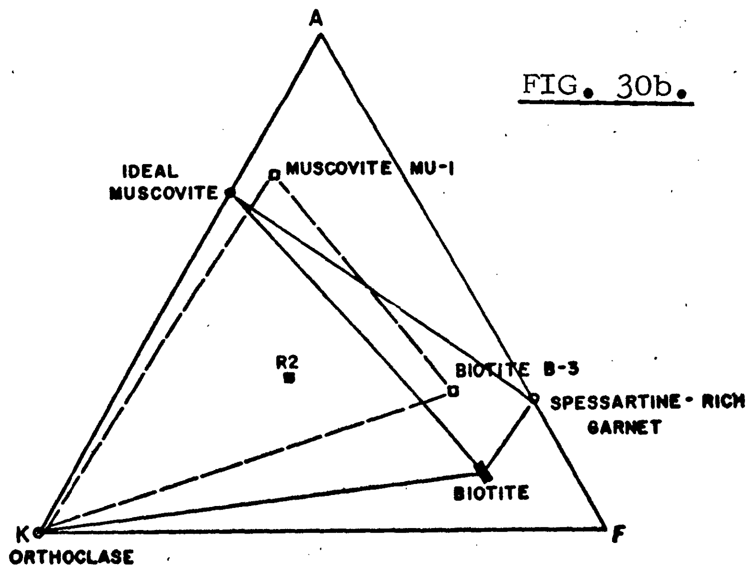

FIG. 30b.

by Ernst (1963) as follows:

5 Muscovite + 3 Biotite + 7 Quartz + $4H_2O \rightleftharpoons$ 8 Phengite + Chlorite.

For rocks slightly richer in K_2O, the following reaction was proposed by Van der Plas (1959) for the crystallization of phengitic mica:

3 Muscovite + Biotite + 2 Microcline + 3 Quartz + $2H_2O$ $\rightleftharpoons$ = 6 Phengite.

The production of phengitic mica by these reactions is favoured by higher PH_2O, but if the system was effectively saturated with H_2O, slightly lower grade P-T conditions can explain the development of the observed assemblages.

Reactions at Higher Grades

The chemical composition of the hornblendes of the interbedded metabasic rocks suggest that adjacent to the granodiorite upper Amphibolite Facies conditions prevailed. At these conditions, an aluminosilicate such as sillimanite would be generated from the muscovite of the accompanying schists by the following reaction:

Muscovite Quartz $\rightleftharpoons$ Orthoclase Sillimanite

$KAl_3Si_3O_{10}(OH)_2 + SiO_2 \quad KAlSi_3O_8 + Al_2SiO_5 + H_2O.$

It is believed that this reaction took place in the highest metamorphic grade schists during the M3 episode prior to the emplacement of the granodiorite. Following this reaction, the granodiorite was emplaced, and it has been shown that the envelope rocks became enriched in potassium, (this latter event being designated M4). Partially coincident with and following these events, porphyroblastic muscovites crystallized, and it has been shown that these are enriched in aluminium relative to ideal muscovite. Biotite B3, co-existing with this muscovite (see Fig. 30b), is also enriched in aluminium in its octahedral site. It is believed that the compositions of these micas indicate that they were not derived from a simple prograde reaction, but from a later reaction involving the aluminosilicate developed during M3.

It is reasonable to infer that the emplacement of the granodiorite coincided with the attainment of the highest P-T conditions of metamorphism, and that migration of potassium was a relatively continuous process during and following this emplacement. This migration of potassium is not likely to have been a rapid geologic process, but is viewed as a slow diffusion along a temperature gradient from the granodiorite into the envelope, (Orville, 1963). It is also reasonable to infer that the granodiorite magma was enriched in water and other volatile fluids relative to the envelope rocks, and that migration of these fluids took place along a gradient in PH_2O between the granodiorite and the envelope. The PH_2O in equilibrium with the M3 assemblage may therefore have been substantially increased by migration of fluid from the slowly crystallizing granodiorite.

While the P-T conditions within the envelope rocks remained above the upper P-T limits of muscovite stability, the introduction of potassium would result in the crystallization of orthoclase according to the following reaction:

$$\underset{\text{Sillimanite}}{Al_2SiO_5} + \underset{\text{Introduced Potassium}}{K_2O} + \underset{\text{Quartz}}{5\ SiO_2} \rightleftharpoons \underset{\text{Orthoclase}}{2KAlSi_3O_8}$$

A proportion of the orthoclase of some of the higher grade schists is inferred to have crystallized according to this reaction, especially that of the schists at the granodiorite contact in which there is abundant orthoclase and little muscovite.

As the temperature gradually decreased in the envelope to cross the upper boundary of the muscovite stability field, and slow migration of potassium from the granodiorite continued, the following reaction is believed to have occurred:

$$\underset{\text{Sillimanite}}{3Al_2SiO_5} + \underset{\text{Introduced Potassium}}{K_2O} + \underset{\text{Quartz}}{3SiO_2} + 2H_2O \rightleftharpoons \underset{\text{Muscovite}}{2KAl_3Si_3O(OH)_2}$$

The muscovites are interpreted to contain an unusually high pyrophyllite component, for which the following reaction may be written:

$$\underset{\text{Sillimanite}}{2Al_2SiO_5} + \underset{\text{Quartz}}{6SiO_2} + 2H_2O \rightleftharpoons \underset{\text{Pyrophyllite}}{Al_4Si_8O_{20}(OH)_4}$$

Both these reactions are favoured by high water pressures, an increase in which is attributed to its migration from the granodiorite into the slightly "drier" envelope rocks.

It is the combination of the above two reactions operating under conditions of high PH_2O that is believed to give rise to the aluminium enriched composition of the white mica porphyroblasts. An analogous reaction involving a change in the composition of the biotite can explain its enrichment in octahedral aluminium.

It is believed that initially the increase in PH_2O was in equilibrium with sillimanite and orthoclase, but that as the temperature decreased and the muscovite stability field was entered, sillimanite was no longer stable. PH_2O was then sufficiently high for the nucleation of relatively large muscovite porphyroblasts with pyrophyllite - type substitution made possible by enlargement of the pyrophyllite stability field at high PH_2O.

Similar muscovite porphyroblasts described by Guidotti (1968) were interpreted as the result of a prograde reaction during which staurolite was replaced by muscovite. These were shown to belong to an equilibrium mineral assemblage. Likewise the muscovite porphyroblasts of the schists of the Tia Complex occur in equilibrium assemblages, which are viewed as having developed in response to changing PH_2O conditions at a relatively high metamorphic grade.

Conditions of Metamorphism

The probable conditions at which the assemblages crystallized can be discussed in only general terms. The rocks have undergone a complex metamorphic history, and minerals useful as indicators of probable conditions are absent. Estimates of the probable conditions can however be derived from a consideration of the metamorphic facies recognized, within the limits imposed by the conditions under which the Tia Granodiorite was generated.

The Tia Granodiorite is believed to have been generated by partial melting at approximately 5 kilobars, thereby providing an upper pressure limit for the high grade rocks. The melting interval is estimated at 650° - 720°C, suggesting a maximum temperature of metamorphism between these values. The slight migmatization and partial melting of the granodiorite suggests a maximum temperature of 660 - 670°C. at less than 5 kilobars. These conditions correspond to the lower pressure-higher temperature part of the Amphibolite Facies, (Turner, 1968, p.366), in general agreement with the mineral assemblages developed during metamorphism.

The existence of a late low temperature - higher pressure episode in Zone A is based on the occurrence of minerals such as crossite in rocks of normal composition, pumpellyite, and stilpnomelane. It is believed that these minerals indicate conditions of metamorphism intermediate between the Prehnite-Pumpellyite Metagreywacke and Glaucophane-Lawsonite Schist Facies. On this basis, the conditions of metamorphism can be tentatively estimated at approximately 5 kilobars and 200-250°C, (Turner, 1968). This episode of higher pressure metamorphism is shown to have been a relatively static recrystallization following earlier periods of lower pressure metamorphism.

Chapter (27)

CONCLUSION AND GEOLOGICAL HISTORY

In this thesis a major structural unit, the Tia Complex, has been defined within the Central Complex of the New England region. This unit contains rocks showing a complex structural and metamorphic history, culminating in part with emplacement of the Tia Granodiorite into the highest metamorphic grade rocks. It is bounded by major fault zones, one of which has been the site of emplacement of the Nowendoc Ultrabasic Belt.

Outside the Tia Complex, the rocks exhibit evidence of a much simpler structural history, and where they have been metamorphosed to any extent, the style of metamorphism is quite different to that of the Tia Complex. This has been termed the "Moona Plains" style of metamorphism, and is typified by the regional metamorphic rocks associated with the granitic intrusions at Moona Plains.

Within the Tia Complex, two distinct lithological associations have been recognized, and have been tentatively correlated with the lithological associations of Binns et al (1967). It is suggested on this basis that the Oxley and Wybeena Metamorphics are of Middle Palaeozoic age, whereas the Brackendale Metamorphics are considered to be Upper Palaeozoic, possibly Permian. The latter have been infolded and infaulted and have undergone regional metamorphism along with the inferred Middle Palaeozoic basement successions. Support for the above correlation comes from a comparison of the structural succession within the inferred basement and the younger rocks. Episodes of earlier folding (and metamorphism) which are recognizable within the inferred basement are absent in the inferred Upper Palaeozoic rocks.

Within the Tia Complex much of the regional metamorphism has been shown to be related to the uprise and emplacement of the Tia Granodiorite. This metamorphism ranged from lower Greenschist Facies to upper Amphibolite Facies immediately surrounding the Tia Granodiorite, and four metamorphic zones based on the mineral assemblages in metabasic rocks of the succession have been erected. The hornblendes of the metabasic rocks have also been shown to exhibit a systematic variation in composition with metamorphic grade.

The metamorphism of the siliceous schists surrounding the granodiorite shows local additional complexity resulting from emplacement of the granodiorite and introduction of potassium into the envelope schists under conditions of higher PH_2O. This resulted in the crystallization of muscovite porphyroblasts whose composition suggests they developed in part from an aluminosilicate such as sillimanite produced by metamorphism preceding emplacement of the granodiorite.

The petrogenesis of the Tia Granodiorite is believed to have involved partial melting at about 5 kilobars of geosynclinal rocks approximating to greywacke composition. Partial melting of these rocks has given a magma that is relatively reduced, and this is reflected in the chemistry of the biotite which has an extremely high FeO/Fe_2O_3 ratio. A high FeO/Fe_2O_3 ratio is shown to be characteristic of the Hillgrove Plutonic Suite (including the Kia-Ora Adamellite). This and other chemical differences between the Hillgrove Plutonic Suite and the New England Batholith suggests differences in their petrogenesis. The former is believed to have originated by partial melting of metasediments, while the latter has been shown by many workers to have originated by processes of hybridism involving the mixing of basic igneous rock and an acid liquid.

During emplacement, potassium underwent migration from the granodiorite into the envelope schists. This is shown to have taken place while the granodiorite was still largely molten, and resulted in the crystallization of muscovite as an apparently primary phase within the granodiorite.

The Nowendoc Serpentinite contains a relatively large body of relatively unserpentinised harzburgite. This is deformed and mylonitised throughout and it is believed that emplacement of this peridotite took place by essentially solid flow prior to serpentinisation.

The structures within the harzburgite and within the completely serpentinised surrounding peridotite are interpreted to mean that serpentinisation was accompanied by a substantial volume increase. This resulted in the formation of the composite rock and serpentine breccias, and the volume increase was accommodated by a self-generated tectonic emplacement upwards within the Nowendoc Fault zone.

In the low grade rocks adjacent to the serpentinites, it has been shown that a late, essentially post-tectonic episode of metamorphism has taken place. The phases developed during this episode suggest it took place as the result of an increase in pressure (to approximately 5 kilobars) at relatively low temperatures. It is now suggested that recrystallization during this phase was coincident with serpentinisation of the peridotite. The pressure increment required to generate the phases developed during the M6 episode is thus seen as being supplied by pressure gradients generated during volume increase during serpentinisation and consequent tectonic emplacement upwards within the fault zone.

Geological History

The data and interpretations given throughout this thesis are now used to construct an overall geological history for this region, (Table 19).

TABLE. 19.

Geological History of the Walcha-Nowendoc-Yarrowitch District.

MIDDLE PALAEOZOIC.

(1) Deposition of a sequence of alternating greywackes, shales, cherts, jaspers and basic lavas.

(2) This underwent subsequent deformation (eg. F1) probably accompanied by low to medium grade metamorphism, (eg. M1).

UPPER PALAEOZOIC.

(3) Deposition of succession of greywackes, shales, conglomerates, and pebbly mudstones, presumably on Middle Palaeozoic basement.

(4) Both the basement and younger rocks then underwent concurrent regional deformation and metamorphism. Two contrasted styles of metamorphism and deformation have been recognised in the region.

(5) This cycle of metamorphism is thought to have coincided with partial melting at depth and the generation of the Tia Granodiorite magma, which underwent emplacement to higher levels towards the end of this cycle.

(6) Following this cycle, there was considerable faulting of the region. A peridotite intrusion, the precursor of the Nowendoc Serpentinite, was emplaced into the roots of the Nowendoc Fault. On serpentinisation and volume expansion, this underwent tectonic self-emplacement upwards within the fault zone.

(7) It is believed that serpentinite emplacement coincided with the appearance in the low grade metabasalts of mineral phases indicating a late, post-tectonic episode of slightly higher pressure metamorphism, (M6).

(8) Subsequent generations of faulting have effectively divided the rocks of the region into a number of fault bounded blocks.

(9) Extrusion of a thick basaltic lava pile during the Tertiary constitutes the last major geological event of the region.