ORIGIN OF CERTAIN GRANITIC ROCKS

THE ORIGIN OF CERTAIN GRANITIC ROCKS OCCURRING

IN

GLAMORGAN TOWNSHIP, SOUTHEASTERN ONTARIO

By

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TITLE: The origin of certain granitic rocks occurring in Glamorgan township, Southeastern Ontario.

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SCOPE AND CONTENTS:

A detailed geological and petrochemical study of granite, migmatite and paragneiss led to the conclusion that partial melting of the latter explains many characteristics of the rocks of Glamorgan township.

The partial melting accompanied high grade metamorphism and conditions were probably within the limits 550 - 650°C and 3.5 to 6 kilobars total pressure.

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ABSTRACT

Glamorgan township in southeastern Ontario, is underlain by Precambrian rocks of the Grenville province. Prominent amongst these are migmatite, paragneiss, and granite gneiss, which collectively form a series of rocks (the Glamorgan gneiss series).

Field work revealed that this series is completely gradational from a geological aspect, and that the geological gradation is complemented by a geochemical gradation.

An explanation of these gradational relationships constitutes the main contribution of this study. The conclusions reached are that partial melting of paragneiss produced migmatite and a trondhjemitic melt, which later produced granitic (in the strict sense) derivatives.

In developing the main conclusions, a number of subsidiary problems are discussed, chief of which are the possible metavolcanic or metasedimentary origin of the paragneiss and the possible origin of so-called diorite as a differentiate of an alkaline gabbro. Metamorphism was concluded to be of Miyashiro's low pressure intermediate type.

By the use of experimentally determined reactions and stability fields a metamorphic grid was devised, which led to the following upper limits of metamorphic conditions: 550 to 650°C and 3 to 6.5 kilobars total pressure. These estimates in turn lead to the following limiting geothermal gradients: 25 to 55°C per kilometre.

The Glamorgan occurrence was found to share three characteristics with many other Precambrian terrains: 1. migmatisation and emplacement of granite accompanied high grade metamorphism; 2. an early sodium-rich granite was followed by a more potassic one; and 3. the more sodic granite is associated with a small amount of basic igneous rock. These three generalisations were used to formulate a possible model for deep crustal petrogenesis.

1. INTRODUCTION

1.1 SCOPE OF STUDY

The purpose of this study is initially to describe certain granitoid rocks of Glamorgan township, southeastern Ontario, in terms of their geology and petrochemistry. A petrogenetic scheme consistent with the descriptions is then developed.

Specific problems of this kind have general implications bearing on one of the most controversial topics of deep-crustal petrogenesis, namely the origin of granite and migmatite. This being so, it is pertinent to review current ideas concerning the nature and origin of such rocks.

1.2 DEFINITIONS OF GRANITE AND MIGMATITE

Granites in the broad sense are

> "holocrystalline coarse grained rocks of plutonic aspect (but not necessarily of igneous origin) composed essentially of quartz, potash feldspar and/or sodic plagioclase, and subordinate biotite, hornblende or pyroxene," (Turner and Verhoogen, 1960, p. 330).

So defined, granite includes

> "the family of granitoids such as quartz-diorite or tonalite and trondjhemite, granodiorite, quartz-monzonite or adamellite and granite [in the restricted sense] or leuco-granite and alaskite," (Buddington, 1959).

In the narrow sense granite is a rock with a normative composition similar to that of first formed melts in the haplogranitic system, (Tuttle and Bowen, 1958) It may also be called "ideal granite"[1] (Mehnert, 1959), or "normgranite" (Tuttle, unpublished).

Texture is generally said to be hypidiomorphic, but

> "the textures of these rocks are more varied than that of any group of plutonic rocks," (Moorhouse, 1959, p. 269).

The term migmatite is used here to denote a rock comprising two components of contrasted compositions, one of which is broadly granitic. This is equivalent to Jung and Roques' (1948) term "epibolite". Following Mehnert (1962) the granitic component will be called leucosome and the non-granitic melanosome.

In Section Two the terms granite and migmatite are used descriptively, without genetic conotations.

1.3 THE ORIGIN OF GRANITE

Granite bodies are either conformable to, or disruptive of, the surrounding rock. According to Buddington (1959) the conformable relationship is typical of katazonal emplacement, the disruptive of epizonal emplacement, while meszonal plutons exhibit either or both characteristics. This general dichotomy of form has led to two dominant

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[1] Not to be confused with Eskola's (1948) ideal granite, since called "kaligranite," Eskola (1963).

ideas concerning the origin of granite. One theory holds that granite is an igneous rock, the product of crystallization of a silicate melt. The second states that granite forms by metasomatism of pre-existing rocks, without the intervention of a melt.

Comprehensive histories of both schools of thought already exist in a great number, and in varying degrees of objectivity, (e.g., Backlund, 1946, Eskola, 1948, Gilluly, 1948, Perrin and Roubault, 1939, Read, 1957, Reynolds, 1946, Tuttle and Bowen, 1958, Sederholm, 1907, and Walton, 1960). Consequently the topic will not be entered here. Neither will a detailed account of field evidence, cited in support of favoured hypotheses, be presented, since most evidence of this kind is equivocal and directly responsible for the "Granite Controversy" in the first place. Instead, experimental work pertinent to the problem is reviewed in the hope that physical limitations can be suggested for genetic processes envisioned by field geologists.

1.3.1 Magmatic granites

Fractional crystallization of a haplobasaltic melt can lead to simple analogues of many other igneous rock types, (Bowen, 1928). Final liquids from this process tend towards "petrogeny's residua system", of which the haplogranitic system is a part, (Bowen, 1937). Natural granites could therefore develop from more basic melts by silica enrichment. Later work shows that in iron bearing systems, silica enrichment requires a constant or increasing fugacity of oxygen, (Roedder and Osborne, 1966).

The earth's crust may originally have formed in this way (Bowen, 1948), but the continued emplacement of granitic rocks in the crust throughout geological time would require much more attendant basic rock than there is observational evidence for, (see, for example, Turner and Verhoogen, 1960, p. 283).

Granitic melts not only represent part of a "residua system", they also represent the first melting fraction of solid rocks of an appropriate composition. This forms the basis of the anatectic model for the production of granite, (Wyllie and Tuttle, 1960), for which complementary evidence is provided by Winkler's (1961) experimental melting of natural rocks. Important determinants of the temperature and pressure at which anatexis can be expected are initial composition (von Platen, 1964) and presence or absence of such fluxing agents as HF and Li_2O in the "vapour" phase, (Tuttle and Wyllie, 1964).

With excess H_2O and a linear geothermal gradient of 30°C anatexis could be expected at depths from 20 to 25 kilometers in the earths crust, (Wyllie, 1963). One weight per cent H_2O may be sufficient under these conditions to melt 10 to 15 per cent of arkose, shale or granite. First formed liquids will be saturated with respect to water, though large bodies of water saturated melt are unlikely at great depth, (Burnham, in press).

1.3.2 Metasomatic granites

Two contrasting hypotheses (involving respectively "dry" and "wet" diffusion) have been formulated by metasomatists. Data concerning intercrystalline diffusion of elements in silicates is scarce, but suggests that this "dry" process is too slow to account for long range geological phenomena. Coefficients of diffusion of Ra, Pb, Li, Na, and K ions in alkali feldspar range from 10^{-8} to 10^{-12} cm^2 per second. At this rate movement of only a centimetre to a metre would take a million years, (Mehnert, 1959). The presence of an intergranular film increases diffusion rates about 10^6 times, (Rosenquist, 1952), thereby providing feasibility for the "wet" diffusion model. Mass transport can also be affected by direct percolation, if pore space allows, (Korzhinskii, 1964).

An analogue of a possible agent of metasomatism is the aqueous rich phase produced in the laboratory, in equilibrium with subsolidus and hypersolidus granite, (Burnham, in press). Starting material was Spruce Pine pegmatite, which has a composition close to the five kilobar eutectic in the synthetic granite system, (Luth, Jahns and Tuttle, 1964). At high temperatures and pressures the vapour phase has a solid content equivalent to an albite-rich ideal granite, (see figure 7.2). Tuttle and Luth found a similar vapour in equilibrium with the Westerly granite at 10 kilobars total pressure. In nature, a fluid of this kind could be produced either by saturation of a granitic melt, with respect to H_2O, or by heating (but not melting) a rock of granitoid composition containing connate water, for example greywacke, to a temperature close to its solidus.

Given the presence of such a fluid, ion exchange along a temperature gradient, between fluid and solid phases, is a possible mechanism of differentiation, of an originally homogeneous system. (Orville, 1960).

1.3.3 Conclusion

The anatectic model for the formation of some granites is well supported by experimental work. Some support is also provided for the "wet" metasomatic viewpoint in that a possible granitising agent can form at high pressures, as a water rich phase in equilibrium with a granitoid rock or melt close to the solidus.

1.4 THE ORIGIN OF MIGMATITE

Migmatites are found in regions of high grade metamorphism, associated with granitic rocks of the conformable kind. All that has been said concerning the origin of granite is applicable to the origin of migmatite leucosome, though the intimate association of the latter with melanosome introduces special problems.

Migmatite was originally defined genetically, as a rock of which there are

> "two elements of different genetic value, one a schistose sediment or foliated eruptive, the other formed by the resolution of material like the first or by injection from without," (Sederholm, 1907).[1]

By "resolution", Sederholm implied partial melting or anatexis, a process explicitly preferred by Holmquist (1920). A later definition (Sederholm, 1926) added metasomatism as a further possible genetic process to be considered. The metasomatic agent was called "ichor" and was described as a fluid intermediate between a water rich melt and an aqueous silicate solution. This fluid differed from "colonnes filtrantes" (Termier, 1912) in being ultimately derived from granitic magma, (c.f.,Burnham's measurements of the composition of the granitic vapour phase).

Wegman doubted that granitic melt played any part in migmatite formation, (1935). He claimed that diffusion of ions in an intergranular film was the genetic process. Likewise Ramberg (1952) writes of "sub-magmatic metamorphic-metasomatic processes" being involved in the genesis of migmatites.

White, (1966) has summarised the various hypotheses under the following headings:

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[1]Translated by Loberg (1963).

1. Bodily injection of granitic magma,
2. Production of the granitic portion by metasomatism,
3. Partial melting,
4. Segregation without melting.

He points out that 1 and 2 involve the introduction of granitic material into the system, while the last two

> "imply redistribution without major changes of bulk chemistry."

1.5 PREVIOUS WORK IN GLAMORGAN AND NEIGHBOURING TOWNSHIPS

Adams and Barlow (1910) produced the first comprehensive geological account of the region of which Glamorgan township forms a part. Armstrong, (1958) published a preliminary map of the township itself, and this has been used here[1] as a basis for mapping that body of rock designated Glamorgan batholith by Adams and Barlow (1910), the Glamorgan stromatolith by Foye (1916) and the Glamorgan granite gneiss by Hewitt and Satterly (1957).

The controversy surrounding the origin of granite is reflected in the geneses proposed for granitic rocks found in and around Glamorgan township. Early accounts stress the magmatist viewpoint. Ells (1902) for example, writes of the granite gneisses of eastern Ontario as being "apparently of igneous origin". Later writers, while accepting the presence of granitic magmas, also ascribe a significant role to metasomatism. Adams and Barlow (1913) state that "the granite gneiss is undoubtedly of igneous origin," though elsewhere (1910, p. 123) they suggest that the "grey granite gneiss" might be derived from marble, through amphibolite,

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[1]See Appendix 1.

under the metasomatic influence of the melt that formed the "red granite gneiss". Reynolds (1946) quotes this judgement with approval.

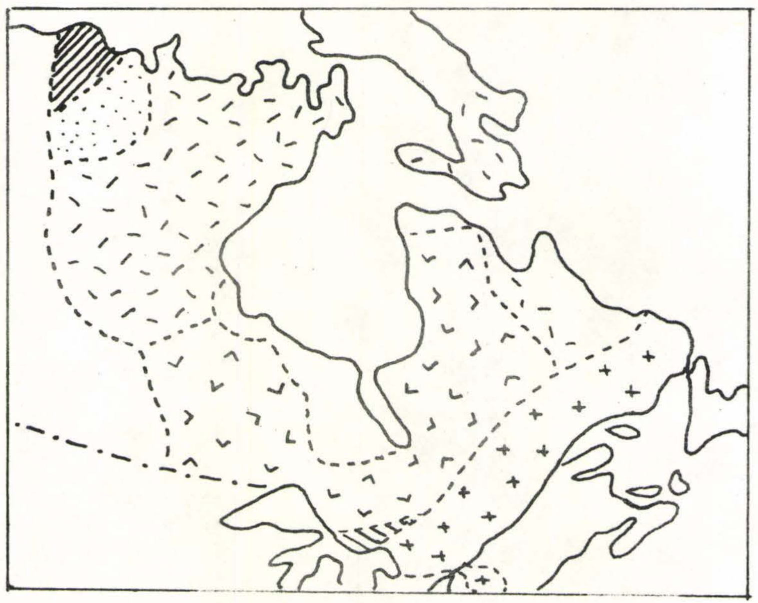
Migmatites in the region were thought to result from the forcible intrusion of magma between layers of country rock, thereby forming a stromatolith (Foye, 1916b, or an "interlayered xenolithic dome," Buddington, 1959). Recently Satterly (1943, 1944) and Hewitt (1956, 1957) have described "hybrid gneisses" supposed to have formed by lit-par-lit injection of granitic magma and by "granitisation."

1.6 THE REGIONAL SETTING

Underlying the area mapped, are Precambrian rocks of the Grenville province. In this study the phrase Grenville province is used to mean the part of the Candian Shield that underwent metamorphism about 1.2 to 0.9 billion years ago. The event may have been an orogeny (Wilson, 1949), and it may have occurred as a continuous event (Wynne-Edwards, 1964), or in two (Walton and de Waard, 1964) or several (Appleyard, 1965) pulses. The resulting metasediments and metavolcanics are referred to as the Grenville Series.

Figure 1.1 indicates the location of what will be called the contiguous Grenville province of Ontario, Quebec and New York state. Inliers of equivalent rock may exist elsewhere on the continent but methods of correlation are questionable, (Engel, 1956, and Gilluly, 1966). Age relations in the Precambrian Shield as a whole are given in Table 1.1, and of the Grenville province in Ontario, in Table 1.2. Table 1.3 shows lithological types and their proportions in the Grenville province as a whole, and Figure 1.2 (Lumbers, 1964) shows the metamorphic grade and distribution of rocks in the region surrounding Glamorgan township.

FIGURE 1.1 MAIN STRUCTURAL DIVISIONS OF THE CANADIAN SHIELD, (STOCKWELL, 1962).



Grenville province

Churchill province

Bear province

Slave province

Superior province

Penokean subprovince

TABLE 1.1 Chronology of the Canadian Shield

GROUT et al (1951)	GOLDICH et al. (1961)				STOCKWELL (1964)			
	ERA	SYSTEM	OROGENY	AGE (10^6 yrs age)	EON	ERA	OROGENY	AGE (10^6 yrs age)
Paleozoic	Paleozoic	Cambrian		600	Paleozoic	Cambrian		600
Later pre-cambrian	Late pre-cambrian	Keewenawan	Grenville	1,000	Proter-zoic	Hadrynian		880
						Helikian	Grenville	1,280
			Penokean	1,700			Elsonian	1,640
	Middle pre-cambrian	Huronian				Aphebian	Hudsonian	2,390
Middle Precambrian	Early pre-cambrian	Timiskamian	Algoman	-2,500	Archaen		Kenoran	
Earlier pre-cambrian		Ontarian	Laurentian	- ?				

TABLE 1.2 GENERALISED AGE RELATIONS IN THE GRENVILLE PROVINCE OF S.E. ONTARIO

Post Meta-morphic	Late Pegmatites and Diabases	(c.0.9. b.y.)
	Younger Pink Granites and Syenites	(c.1.0. b.y.)
Pre Meta-morphic	Older Grey Granites	
	Nepheline Syenites	(e.g. Blue Mt. 1.2 b.y.)
	Gabbro-Diorite group	
	Grenville Series deposited	(c. 1.4 b.y.)

Sources: Hewitt (1956), Grant (1959), Lumbers and Silver (1964) Krogh (1964)

TABLE 1.3 LITHOLOGICAL PROPORTIONS IN THE GRENVILLE PROVINCE (Engel, 1963)

Basic Volcanics	3 %
Felsic Volcanics	4
Sedimentary Rock	20
Peridotite	trace
Diorite and quartz diorite	.01
Granitic rock*	66
Other	6

*Includes quartz monzonite, granodiorite, quartz porphyry and gneisses pervasively veined by granite.

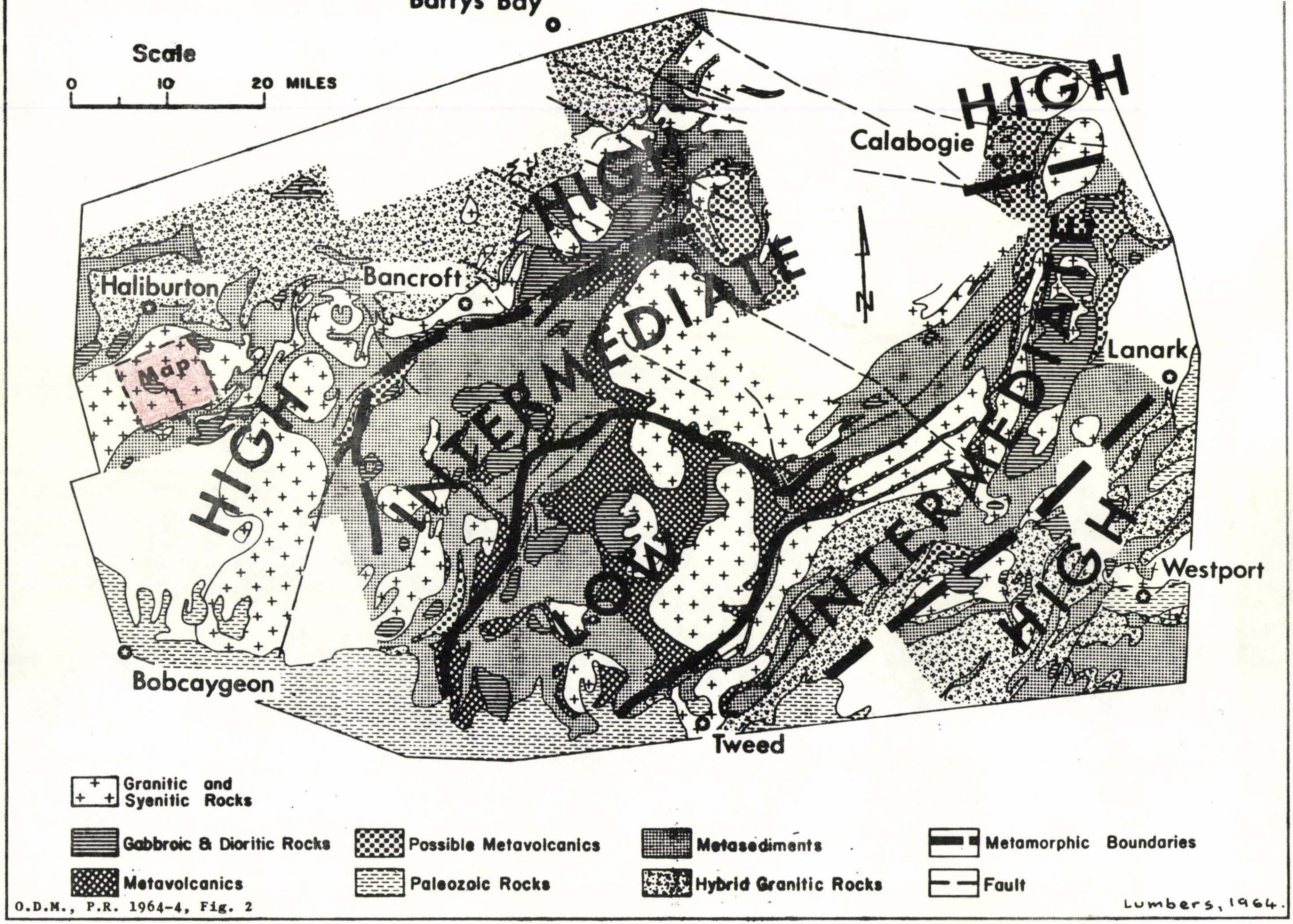


FIGURE 1.2. METAMORPHIC GRADE AND ROCK DISTRIBUTION IN S.E.ONTARIO.

FIGURE 2.1. FRAGMENTED CALC-SILICATE BAND IN TREMOLITE BEARING MARBLE, ONE MILE EAST OF CONTAU LAKE.

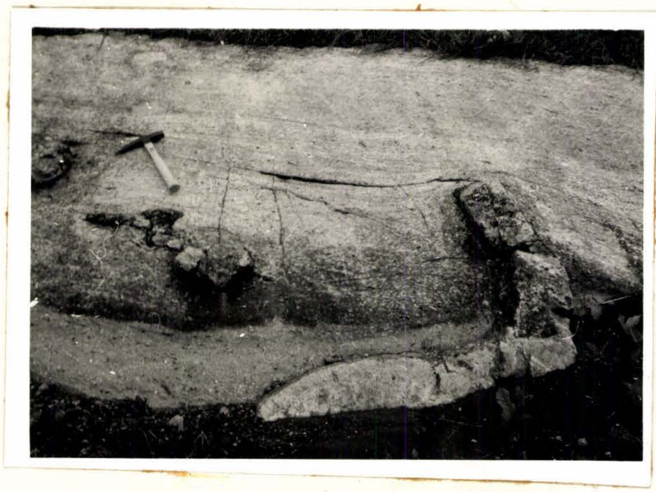
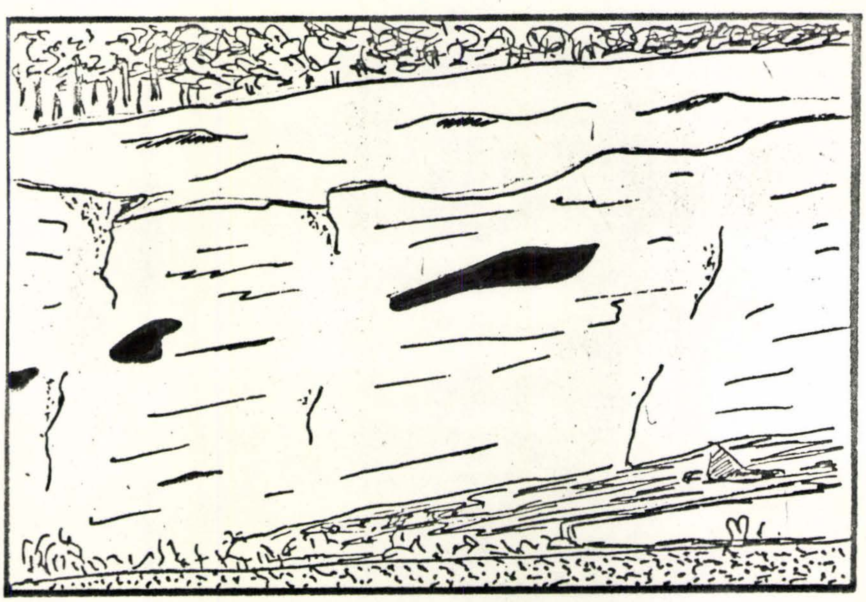


FIGURE 2.2. FRAGMENTED AMPHIBOLITE BAND IN MIGMATITE, FOUR MILES WEST OF GOODERHAM ON HIGHWAY 500.



Some believe that the Grenville province results from the metamorphism of older rocks, and would therefore call it a sub-province. Wynne-Edwards provides a recent statement of this view (1964). Close to the Grenville front a gradual transition into the Superior province may take place and Krogh (1966) has detected ages intermediate between Superior and Grenville ages up to 100 miles south of the front in Ontario. He relates this to the classic problem of "the disappearance of the Huronian," (Quirke and Collins, 1937). Further from the front however there is no direct evidence that the Grenville rocks result from metamorphic reworking of older ones (Krogh, 1964). Indeed, there is evidence of volcanic-sedimentary deposition in the Hastings lowlands about 1.4 billion years ago (Lumbers and Silver, 1965).

2. GEOLOGY OF THE BEDROCK IN GLAMORGAN TOWNSHIP

2.1 INTRODUCTION

The region mapped is the approximately 50 square miles of Glamorgan township, north of concession V. This area is part of an extensive peneplain, (Adams and Barlow 1910, pp. 1-10). Average height is about 1250 feet above sea level, with Green's Mountain (1460 feet) the highest point in the township.

In the west, where forest fire was followed by stripping of soil cover, exposure is as high as 70 per cent. In the east, bedrock is obscured by drift, swamp and forest, exposure being generally less than 20 per cent.

Map 1 (in pocket) shows the distribution of rock types in the township, and Table 2.1 their relative proportions. A comparison of the latter with Table 1.2 reveals that this region is proportionately richer in granitic rocks than the Grenville province as a whole.

2.2 THE GRENVILLE SERIES

Two major rock types in this area are assignable to the Grenville series - marble and paragneiss. Amphibolite and quartzite are not common though both, and particularly amphibolite, constitute prominent units in other parts of the Grenville province, (see for example Engel and Engel, 1962).

2.2.1 Marble or metamorphosed calcareous rock

Impure (or silicated) marble is found on three sides of the

TABLE 2.1

LITHOLOGICAL PROPORTIONS IN THE MAP AREA

				Engel's (1963) proportions for comparison (Table 1.3)	
Granitoid Rocks	Pink granite gneiss (includes graphic granite)	10			
	Grey granite gneiss	17	90%	Granitic Rock	66%
	Migmatite	62			
	Pegmatite	1			
	Diorite	2		Diorite and Quartz Diorite	.01
Grenville Series	Marble	5		Basic Volcanics	
	Paragneiss	2	8%	Felsic Volcanics	27
	Other*	1		Sedimentary Rock	
				Peridotite	trace
				Other	6

*Amphibolite and quartzite

Glamorgan gneiss complex, and close to the latter a marble-granite migmatite is encountered. Within the marble and migmatite zones, irregular bodies of skarn occur.

The greatest development of metamorphosed calcareous rocks is in the south of Glamorgan township, where

> "A great development of nearly pure marble is found," (Adams and Barlow, 1910, p. 195).

Bruce and Russell (1939) deny that "pure marble" occurs anywhere in the Grenville province.

In the township, all varieties of marble are coarsely crystalline with grain sizes of 2 to 10 mm. White, yellow, grey, and greenish types occur, all of which appear grey on a weathered surface. Most of the rock appears to have undergone flowage giving rise to marble tectonic breccias. In the example shown in Figure 2.1, the brecciated band is a diopside-rich rock, with a post-brecciation rim of phlogopite (a tenth of an inch thick) round each block. In the surrounding marble, discrete grains of tremolite are found fragmented and pulled apart.

Calcite content grades from generally about 90 per cent to 0 in calcite-free calc silicate rock. On the south shore of Contau Lake dolomite occurs in the marble, (Adams and Barlow, 1910, p. 202).

In thin section mosaic texture is common, and at least two silicates accompany calcite. Predominant assemblages are calcite-tremolite-diopside[1] and calcite-phlogopite-diopside. Tremolite marble contains patches of calcite free diopside-tremolite rock with accessory

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[1]This method of designating an assemblage is explained in Section 6.1.3.

phlogopite. At Maxwell's Crossing a calcite-scapolite-diopside rock is found in association with a scapolite-diopside gneiss.

Graphite is ubiquitous in these rocks and small euhedral grains of dark green hornblende and of red sphene are seen in some thin sections. At Gooderham a spinel and diopside-bearing marble is found together with a marble containing phlogopite, tremolite, diopside, and yellow-brown chondrodite.

The skarn bodies are isolated, irregular and very coarsely crystalline. The largest is in concession VII, lot 35, where white and pink calcite are accompanied by dark green pyroxene and hornblende, and greenish-grey scapolite. Granite outcrops on the east of this exposure.

On the south side of highway 500 in concession VII, lot 2, a pod of skarn is exposed in migmatite. The following minerals occur - white, pink, and grey calcite, dark green pyroxene and amphibole, light green apatite, purple fluorite, red sphene and garnet, pyrite, and molybdenite.

Other examples of garnetiferous skarn occur along the Buckhorn road at the Glamor Lake turnoff, and in concession VI lots 8-9. A specimen from the latter was sectioned and revealed the following mineral proportions:

Saussuritized plagioclase	30% (Composition, An_{24})
Diopsidic-augite	30%
Grossularitic garnet	20%
Epidote	10%

Calcite and scapolite are present in small amounts, and the garnet and plagioclase are intergrown. Epidote is present as discrete grains.

A 10 foot square outcrop of massive tremolite was found in concession V, lot 21. Within it were segregations of pyrrhotite up to an inch across, with marcasite and limonite as alteration products.

The wide variability in chemical composition of these metamorphosed calcareous rocks is shown in Table 2.2. The more silica rich examples are in close proximity to granite gneiss. The less silica rich are found further from granite.

In Section 8, calcite bearing assemblages are tabulated.

2.2.2 Paragneiss

Fine grained grey gneiss outcrops along concessions V and VI interbedded with marble, west of Stormy Lake surrounded by migmatite, and south of Bluehawk Lake also associated with migmatite.

The predominant minerals are biotite, plagioclase and quartz, a characteristic paragenesis of the Grenville province and one that is conventionally regarded as paragneiss, (e.g., Engel and Engel, 1953; Armstrong, 1958; and Buddington and Leonard, 1962). In fact, the main macroscopic evidence for an ultimately sedimentary origin for this highly metamorphosed rock is its occurrence interbedded with marble. Some so-called paragneisses of the Adirondacks are reported by Silver (1964) to be metavolcanics.

In thin section the Glamorgan biotite-quartz-plagioclase rock displays some evidence that the name paragneiss may be appropriate. In specimen E12, for example, the following accessory minerals were found - microcline, pyrite, magnetite, apatite, calcite, and graphite. The last two, at least, suggest a sedimentary origin and are typical of paragneisses from the Haliburton - Bancroft region.

TABLE 2.2

CHEMICAL ANALYSES OF METAMORPHOSED CALCAREOUS ROCKS

A. Comparatively pure marble, (from Satterly, 1942).

	Lot 19 Con. V		Lot 25
	S. side of ridge	N. side of ridge	Con.IV
SiO_2	1.34	2.10	4.22
Fe_2O_3	.24	.25	.47
Al_2O_3	.12	.25	.26
$Ca_3(PO_4)_2$	.04	.02	.02
$CaCO_3$	90.56	89.07	90.36
$MgCO_3$	7.34	9.33	4.81
	99.65	101.02	100.14
			Includes .11% S

B. Silicated marble.

	"Altered" Marble[1]	N13[2]	N14[3]
SiO_2	32.88	42.5	61.13
TiO_2	.49	.05	.17
Al_2O_3	9.04	9.3	14.99
Fe_2O_3	.77	.07	.42
FeO	3.48	.22	1.37
MnO	—	.02	.06
MgO	4.18	1.6	2.73
CaO	30.90	21.9	6.79
Na_2O	1.17	1.99	2.77
K_2O	0.85	4.59	7.37
P_2O_5	—	.03	.13

TABLE 2.2

(Continued)

	"Altered"Marble[1]	N13	N14
H_2O+	1.08	.69	.27
H_2O-		.07	.13
CO_2	15.20	17.66	.98
Sum	100.04	100.1	99.31

Analyses N13 and N14 by John Muysson

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[1]Adams and Barlow, 1910, p. 104.

[2]In this and succeeding tables, samples analysed for this thesis are numbered in accordance with their occurrence on the sampling design, (Figure 4.1). N13 contains approximately 30% calcite, 60% diopside, 8% hornblende, and 2% phlogopite.

[3]Marble migmatite - alternating bands of diopside rich rock (with a little calcite) and pegmatite rich in potash feldspar.

Biotite (pleochroic in straw-yellow and brown) occurs in clusters, with individual flakes lying in the plane of foliation. Quartz is invariably strained and oligoclase is twinned mainly on the albite law though combined carlsbad-albite twins are found as also are pericline twines. Some untwinned plagioclase is also present.[1] Porphyroblastic aggregates of plagioclase and quartz occur in Sample GII.

The paragneiss just described is found without any granitoid bands, furthest from granite and migmatite. Closer to the latter, a different mineralogy prevails, so that it is reasonable to consider the quartz-biotite-plagioclase rock as being the least altered variety. Engel and Engel (1953) used this same field criterion for their own "least-altered paragneiss" from the northwest Adirondacks. Their paragneiss, though more silicic, had the same major mineralogy as the Glamorgan examples.

The more altered paragneiss is a variety in which hornblende and microcline are prominent. Sphene is an additional accessory mineral in this case, both as discrete grains and as a rim to magnetite. In the field, this rock is found with sparse conformable granitic veins, and appears intermediate between paragneiss and migmatite.

In a single outcrop between Glamorgan town line and Bluehawk Lake, an almandine-bearing variety of paragneiss was found. In it, epidote (birefringence - .045)[2] co-exists with quartz. Similar rock was picked up as float on the northeast side of Stormy Lake. Analyses given in Table 2.3.

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[1] Staining was attempted in the belief that this might prove to be potash feldspar. The test was negative.

[2] This is indicative of a composition close to 30% of the iron end member, (Deer, Howie, & Zussman, 1962, v. 1, p. 203.

TABLE 2.3 CHEMICAL ANALYSES OF PARAGNEISS

(with whole rock migmatite for comparison)

	C3[1]	E12[2]	G11[2]	H5[1]	I6[1]	J8[3]
SiO_2	65.5	64.8	66.86	65.4	65.14	67.9
TiO_2	.94	.95	.70	.53	.70	.49
Al_2O_3	15.2	16.1	15.09	15.3	16.37	14.8
Fe_2O_3	3.01	2.30	1.97	1.21	1.93	1.69
FeO	2.77	3.03	2.69	2.71	2.61	2.55
MnO	.15	.07	.08	.06	.10	.09
MgO	1.5	1.75	1.72	2.43	1.46	1.70
CaO	3.8	3.40	3.92	3.03	3.96	3.02
Na_2O	4.93	4.92	4.43	4.38	5.33	4.71
K_2O	1.42	1.74	1.36	3.36	1.48	1.75
P_2O_5	.29	.29	.16	.09	.18	.10
H_2O+	.29	.64	.69	.56	.51	.51
H_2O-	.02	.06	.18	.08	.12	.07
CO_2	.02	.22	.16	.31	.02	.17
Sum.	99.8	100.3	100.01	99.5	99.91	99.6

[1] Amphibolitic paragneiss relicts in migmatite. H5 is contaminated by a little micropegmatite, occuring in a fine veinlet in the rock.

[2] Least altered paragneiss.

[3] Whole rock migmatite.

Analyses by John Muysson

2.3 NORMS

	C3	E12	G11	H5	I6	J8
Quartz	21.6	20.0	24.6	16.6	17.6	22.7
Orthoclase	8.4	10.7	8.0	19.9	8.8	10.4
Albite	41.7	41.4	37.4	37.0	45.0	39.8
Anorthite	15.1	13.6	17.2	12.1	16.3	13.9
Diopside	1.6	----	1.0	.8	2.7	----
Hypersthene	4.3	6.6	6.1	8.9	4.6	9.9
Magnetite	4.4	3.3	2.9	1.8	2.8	2.5
Ilmenite	1.8	1.8	1.3	1.0	1.3	.9
Apatite	0.6	0.6	----	----	----	----
Calcite	----	0.5	.4	.7	----	.4
Corundum	----	1.1	----	----	----	----

MODES

						Leucosome (a)	Melanosome (b)
Microcline	8.0	____	tr	11.4	10.3	19.3	2.2
Plagioclase	55.8	46.8	53.1	45.6	44.2	45.8	44.7
Quartz	22.1	32.3	27.6	25.7	25.6	30.1	15.4
Biotite	4.6	18.6	19.0	5.2	9.0	4.0	9.7
Hornblende	8.9	----	----	11.0	10.3	----	26.7
Accessories	0.6	1.3	0.3	1.1	0.6	0.8	1.3
Plag. Comp.	An_{25}	An_{22}	An_{24}	An_{22}	An_{26}	An_{25}	An_{25}

2.2.3 Amphibolite and quartzite

Dark grey, quartz-free amphibolite is common in the Grenville province as a whole, though scarce in Glamorgan township. Bands, lenses, and dikes are found, however, and the conformable amphibolites usually, but not invariably, have a fine banding.

On the basis of occurrence and petrography, three kinds of amphibolite can be distinguished in Glamorgan township. In the migmatite (9c on the map), all gradations are found between marble and a conformable variety of amphibolite made up of hornblende (x = yellowish-green, Y = green, Z = deep green) and plagioclase (An_{25} to An_{33}), in a mosaic aggregate, with the hornblende having a prevailing alignment in one direction and imparting to the rock a distinct foliation. Accessory diopsidic augite ($C \wedge Z = 45°$) and calcite are present in some examples, (Plate XVI, Adams and Barlow, 1910).

A second type is found as cross-cutting dikes outside the Glamorgan granite gneiss complex. One such dike rock from Stone Quarry has an amphibole-plagioclase-biotite-magnetite assemblage in a fine-grained mosaic.

The last variety is found as isolated and disconnected blocks within granite gneiss and migmatite, and for reasons that will become apparent later, is described in Section 2.3.1 below.

Analyses of amphibolite are given in Table 2.4.

Grey impure quartzite outcrops west of Contau Lake. It contains biotite and, in places, a green pyroxene. The most extensive development of quartzite in the Haliburton Highlands is found in adjacent Monmouth township.

TABLE 2.4 CHEMICAL ANALYSES OF AMPHIBOLITES

	1	2	3
SiO_2	45.46	50.00	50.83
TiO_2	2.10	0.82	1.10
Al_2O_3	16.10	18.84	18.64
Fe_2O_3	3.42	2.57	2.84
FeO	8.63	5.51	5.97
MnO	0.14	0.08	0.10
CaO	10.80	10.65	7.50
MgO	7.30	4.63	4.90
K_2O	0.70	1.18	1.83
Na_2O	2.71	4.46	4.22
Co_2	1.13	0.10	0.11
Ch	----	0.10	0.03
S	0.17	0.03	0.01
H_2O	1.32	1.00	1.40
P_2O_5	0.21	99.97	99.48
Cr_2O_3	0.04		
BaO	trace		
	100.23		

1. Amphibolite inclusion in granite, Peck twp (Adams & Barlow, 1910), p. 65): "may be taken as representing a large portion of these amphibolite inclusions. Minerals present are "hornblende, augite;

TABLE 2.4

(Continued)

a rhombic pyroxene, and plagioclase, with a small amount of iron ore, a few grains of pyrite, and a trifling amount of calcite."

{2. 3.} Amphibolite resulting from metasomatism of marble (Adams and Barlow, 1910, p. 104), Maxwells crossing, Major minerals in 2 are hornblende, pyroxene, scapolite and plagioclase. 3 is supposed by Adams and Barlow to be a more altered variety of 2, with no pyroxene nor scapolite, and with a little biotite.

2.3 IGNEOUS ROCKS

According to Lumbers (1964), the Grenville province in southeastern Ontario contains five major igneous rock groups:

1. Diorite-gabbro,
2. Sodic granite,
3. Nepheline-syenite,
4. Syenite,
5. Potassic granite.

In the area covered during this study, representatives of all these groups are found, though 3 and 4 are comparatively unimportant in terms of areal extent, and will be found described elsewhere, (Adams and Barlow, 1910; Barlow, 1915; and Gittins, 1962). Representatives of groups 2 and 5 might be described better as "igneous-looking rocks" and are placed in a separate section below.

2.3.1 Diorite - Gabbro

The Glamorgan gabbro outcrops in the southeast part of the township, just outside the immediate map area.[1] The rock is generally indistinctly banded and, in places, sheared though some parts are homogeneous and appear to have escaped metamorphism (Gittins, personal communication). Foye (1916a) described the body as a laccolith emplaced

> "before the intrusion of the granites and nephelite syenites, which form so distinct a part of this region."

The gabbro is a medium-grained augite, hornblende, and andesine rock with accessory magnetite and apatite. Scapolite is found replacing feldspar, in many examples. Titaniferous magnetite ores are associated with the body.

[1] See Figure 3.1, p.36.

Diorite is a minor component of the gabbro mass (Harrison, 1953; Foye, 1916), and occurs in two distinct bodies in the area mapped, (see Map 1).

Towards the middle of the central mass of diorite, the rock is dark gray, unfoliated and coarse-grained (five to eight mm). At the edges of the mass, it is finer-grained and has an indistinct banding. The central mass is conformable with granite gneiss along its southern edge, but on the north side, exposure is too poor to permit definite characterisation. The northeastern body of diorite appears to be conformable with its country rock.

Diorite pre-dates grey granite gneiss, a fact indicated by the presence of fine-grained diorite inclusions in grey granite gneiss outcropping in sample squares G5 and G6.

Study of this rock in thin section reveals unzoned andesine, pale blue-green hornblende, colourless augite, light brown biotite, and a little interstitial microcline. Amphibole is poikiloblastic with respect to plagioclase and, in some instances, to augite. Sphene, apatite, zircon, and magnetite occur as accessories. In the middle of the central body, some of the plagioclase has been replaced by scapolite.

The isolated and disconnected blocks of amphibolite referred to in Section 2.2.3, are similar to those found in granite gneiss by Eckelmann and Poldervaart (1957); e.g., compare their Plate 3, Figure 1 with Figure 2.2 here. They refer to this rock as agmatite. Wherever these blocks are found in Glamorgan township, foliation in the country rock appears to "flow" round them. The amphibolite is finer-grained than diorite. In thin section amphibole, clinopyroxene and andesine

FIGURE 2.3. PINK GRANITE GNEISS OVERLAIN BY MIGMATITE. INCLUDED MARBLE BLOCK IS OUTLINED.

(4.5 miles west of GOODERHAM).

FIGURE 2.4. TRANSGRESSIVE GRANITE VEINS IN MIGMATITE. ONE OF THE VEINS HAS LIT-PAR-LIT OFFSHOOTS.

(0.5 miles north of hwy. 500 along the Buckhorn Road.)

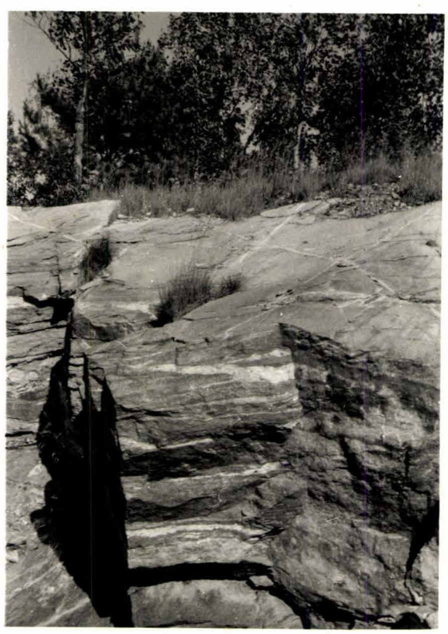


TABLE 2.5

CHEMICAL ANALYSES OF DIORITES AND GABBROS

	B13[1]	F4	G5[1]	G6	Gabbro[2]
SiO_2	49.7	50.8	52.1	53.1	47.90
TiO_2	2.46	2.42	1.72	2.15	2.00
Al_2O_3	16.3	16.0	17.2	16.0	13.76
Fe_2O_3	6.2	5.50	4.2	4.84	0.42
FeO	4.73	4.60	4.66	6.31	6.43
MnO	.12	.14	.07	.19	0.11
MgO	3.6	3.50	2.7	3.14	7.27
CaO	6.0	7.39	4.9	5.09	16.76
Na_2O	4.36	4.44	4.71	4.41	2.27
K_2O	3.62	2.34	3.55	2.92	0.66
P_2O_5	1.23	1.19	.75	.67	0.06
H_2O+	.59	.54	.62	.73	0.80
H_2O-	—	.21	—	.11	
CO_2	.02	.46	.98	.39	1.10
Sum	98.9	99.5	98.2	100.1	99.65

[1]Poor analyses, not used in subsequent discussion (section 5.2).

[2]Foye (1916) - Glamorgan Gabbro, total contains 0-11%.

Analyses other than gabbro by John Muysson.

TABLE 2.5

(Continued)

NORMS

	B13	F4	G5	G6	Gabbro
Quartz	—	1.3	.1	2.3	—
Orthoclase	21.4	13.8	.6	17.3	3.9
Albite	34.6	37.5	21.0	37.3	14.7
Anorthite	14.2	16.8	39.8	15.2	23.6
Diopside	6.5	7.8	13.7	3.0	41.7
Hypersthene	4.2	5.3	9.1	10.8	—
Magnetite	8.5	8.0	6.1	7.0	0.7
Ilmenite	4.7	4.6	3.3	4.1	3.8
Apatite	2.7	2.6	1.6	1.5	0.3
Calcite	—	1.0	2.2	.9	2.5
Nepheline	1.2	—	—	—	2.6
Olivine	—	—	—	—	4.1
Pyrite	—	—	—	—	0.3

MODES

	F4	G6
Plagioclase	69.7[3]	68.2
Hornblende	19.3	17.8
Biotite	5.7	9.3
Augite	1.8	1.1
Microcline	1.4	1.7
Accessories	2.1	1.9
Plag. Comp.	An_{35}	An_{33}

[3]A little scapolitised.

are found with accessory amounts of hypersthene, pyrite, and magnetite. The most distinctive feature (shared with the diorites) is a textural one - amphibole is poikiloblastic with respect to plagioclase and clinopyroxene is poikiloblastic with respect to plagioclase in places and amphibole elsewhere. Furthermore, amphibole grains are found with distinct cores of clinopyroxene.

Analyses of gabbros and diorites are given in Table 2.5.

2.4 GRANITOID ROCKS

None of the granitic rocks of Glamorgan township are completely free of more basic included bands, but some are relatively so. For mapping purposes, granite containing less than 10 per cent foreign matter is distinguished from migmatite containing greater than 10 per cent of a non-granitic component. This distinction is arbitrary and should not obscure the fact that, in the field, all gradations are found between relatively homogeneous granite, through well-banded migmatite, to granite-free paragneiss.

2.4.1 Grey granite-gneiss

The central part of Hewitt and Satterly's (1957) Glamorgan granite gneiss is a sodic granite or trondhjemite (see Section 5.3). Adams and Barlow (1910) refer to this as grey granite gneiss, (pp. 69-72). Its association in the field with a small diorite body is commented upon in Sections 5.2 and 9.2.

It is well foliated with laminations alternately rich in quartz-feldspar and in femic minerals. In some places, the feldspar is ovoidal and the rock has the appearance of an augen gneiss. Colour varies from pale grey to pinkish grey, depending on potash-feldspar content.

Essential minerals are quartz, microcline, plagioclase, and biotite. Hornblende is common and magnetite, apatite, sphene, and zircon are present as accessories. Adams and Barlow (1910) describing a specimen from the line between lots 25 and 26, concession VIII, mention "an untwinned feldspar....referred to as orthoclase." Attempts to stain untwinned feldspar in specimens collected during this study were unsuccessful and led to the conclusion that the mineral was plagioclase.

The plagioclase is an oligoclase and often contains quartz in myrmekitic intergrowth. Sub-parallel flakes of biotite are pleochroic with the following scheme: X = straw yellow, Y = Z = dark brown. Greyer varieties of the rock contain hornblende (usually with a corroded appearance), with X = pale greenish-yellow, Y = green, Z = deep green; $Z \wedge c = 10\text{-}20°$, $2V = 80\text{-}85°$. Some specimens contain hornblende with Z = deep green with a slight blueish tint.

Accessory magnetite is often found invested with a rim of sphene.

On the southeast corner of Bark Lake, the grey granite contains about five per cent of dark, fine-grained inclusions about six inches across. The inclusions are composed of a mosaic aggregate of mainly quartz, plagioclase, and hornblende, with subordinate biotite and microcline. The surrounding granite is unfoliated unlike the grey granite elsewhere. About a half mile west of this exposure, the granite gneiss contains irregular patches of this fine-grained material, rather

2.6 CHEMICAL ANALYSES OF GREY GRANITE GNEISS

	C7	D1	F2	H4	K2
SiO_2	69.9	69.71	70.6	72.0	69.8
TiO_2	.56	.67	.46	.44	.51
Al_2O_3	14.5	14.08	14.0	14.2	13.8
Fe_2O_3	1.81	2.33	1.86	1.59	1.32
FeO	1.84	1.92	1.78	1.57	2.33
MnO	.05	.11	.05	.03	.07
MgO	1.01	.87	.72	.81	1.8
CaO	2.61	2.37	1.8	1.86	3.3
Na_2O	4.76	4.45	4.47	4.25	4.00
K_2O	1.59	2.28	2.45	3.06	2.11
P_2O_5	.14	.21	.14	.12	.13
H_2O_4	.35	.36	.39	.36	.45
H_2O-	.07	.11	.03	.05	.03
CO_2	.05	.04	.02	.00	.03
Sum	99.2	99.51	98.8	100.3	99.7

Analyses by John Muysson

2.6 NORMS

	C7	D1	F2	H4	K2
Quartz	28.7	28.8	29.8	30.0	28.2
Orthoclase	9.4	13.3	14.5	18.1	12.5
Albite	40.2	37.7	37.8	35.9	33.8
Anorthite	12.6	10.8	8.9	9.2	13.4
Diopside	----	----	----	----	2.4
Hypersthene	B.6	3.0	2.9	2.9	5.8
Magnetite	2.6	3.5	2.7	2.3	1.9
Ilmenite	1.1	1.2	.9	.8	1.0
Calcite	.1	----	----	----	----
Corundum	.3	.3	.7	.5	----
Apatite	----	.5	----	----	----

MODES

Microcline	9.8	10.6	11.9	14.8	7.7
Plagioclase	45.9	51.1	48.2	44.4	48.3
Quartz	35.1	30.2	32.1	32.3	23.6
Biotite	6.2	6.7	6.8	7.4	12.6
Hornblende	1.5	trace	trace	----	6.7
Accessories	1.5	1.4	1.0	1.1	1.1
Plag. Comp	An_{25}	An_{19}	An_{15}	An_{21}	An_{28}

than clearly-defined inclusions. Some of the patches contain ovoids of potash feldspar. As noted in Section 2.3.1, the granite gneiss has also been found containing inclusions of diorite.

In surrounding districts, two apparently intrusive bodies of grey, hornblende-bearing granitic rock have been found. On the south side of Bluehawk Lake in Dysart township, a dike of grey granite cuts paragneiss discordantly and, in a roadcut north of Tory Hill (Monmouth township), a sill-like body of grey granite occurs in marble from which it is separated by a rim of hornblende-apatite-scapolite skarn.

Table 2.6 shows the composition and mineralogy of the grey granite gneiss.

2.4.2 Pink granite gneiss

Adams and Barlow (1910) refer to this rock as red granite though in Glamorgan township, at least, it is pink. It is distinguishable from grey granite gneiss in its lower content of ferromagnesian minerals and higher content of microcline, which accounts for its bright pink colour, unalloyed by any trace of grey.

The rock is coarse- to fine-grained and occurs in semi-conformable lenses and sheets ranging from several feet to about two miles long. In the area mapped, there is one phacoidal body of this rock and south of the map sheet, Armstrong (1958) has mapped a second phacoidal body of pink granite gneiss. Parallelism of biotite flakes imparts a foliation to the rock, and some examples are layered by alternating lensoid bands of coarser- and finer-grained rock.

The distinguishing features of this rock in hand specimen are the smaller percentage of dark minerals compared with grey granite gneiss and the higher percentage of microcline, which gives the rock its bright pink colour.

The phacoidal mass, which is south of Stormy Lake, is free of foreign inclusions. The other bodies mapped have less than 10 per cent of the non-granitic component found in migmatite. As with grey granite gneiss, there is a gradual transition between pink granite gneiss and migmatite. One lens of pink granite in the migmatite is slightly disruptive of the surrounding marble, of which it contains an included block (Fig. 2.3).

Microtexture of the pink gneiss can be described as hypidiomorphic granular. The phacoidal granite is finer grained than the rest and, at the edges of the body, individual grains have a fragmented, clastic appearance.

The major minerals are strained, anhedral quartz, albitic plagioclase, microcline, and biotite (X = straw yellow, Y = Z = brown), similar in appearance to the biotite of the grey gneiss. Magnetite, tourmaline, zircon, apatite, sphene muscovite, fluorite, and hematite are common as accessories, and in sample AI, a few grains of corroded hornblende were found. Plagioclase is usually partly sericitised, myrmekite is common, as too is perthite in the more quartz rich specimens.

Just north of the phacoidal mass and partly continuous with it, there is a northerly-dipping sheet of pink granite-pegmatite, which has a graphic texture in part. The rock is made up almost entirely of quartz, albite, and microcline. The latter, in places, is found in crystals up to four inches long, and is also seen rimming albite in thin section. Quartz appears as elongate, anhedral stringers in both feldspars. A specimen picked up as float contained a little pyrite.

2.7 CHEMICAL ANALYSES OF PINK GRANITE GNEISS[1]

	A1	A11	C12	C13	D13	E13	G13	H13	J13	N7
SiO_2	74.9	77.9	72.4	72.5	76.9	79.4	78.5	75.0	73.6	71.54
TiO_2	.16	.15	.01	.01	.14	.22	.13	.11	.06	.33
Al_2O_3	14.2	12.7	14.7	15.1	12.8	11.1	12.4	14.5	16.2	14.78
Fe_2O_3	.57	1.1	.10	.16	1.0	.86	.52	.77	.04	.67
FeO	.42	.52	.07	.05	.65	.68	.46	.37	.42	1.44
MnO	.00	.00	.00	.01	.00	.02	.01	.00	.00	.04
MgO	.26	.22	.06	.19	.18	.36	.20	.26	.20	1.21
CaO	1.02	.43	.17	.34	.36	.33	.32	.72	.82	1.52
Na_2O	3.93	3.09	3.31	3.27	3.56	2.79	3.20	3.48	4.43	3.66
K_2O	4.43	4.31	7.95	7.82	4.38	4.36	4.57	5.08	4.57	4.41
P_2O_5	.02	.00	.04	.02	.00	.03	.00	.01	.00	.05
H_2O+	.18	.22	.14	.16	} .19	} .14	} .13	} .21	} .17	.37
H_2O-	.06	----	.04	.03						.08
CO_2	.02	.00	.01	.00	.03	.01	.02	.00	.00	.01
Sum	100.2	100.6	99.0	99.7	100.2	100.3	100.5	100.5	100.5	100.1

---

[1] D13, E13, G13, H13, J13, are from the phacoidal body. C12 (poor analysis) and C13 are graphic granite/pegmatite.

Analyses by John Muysson

2.7 NORMS

	A1	A11	C12	C13	D13	E13	G13	H13	J13	H7
Qtz	32.2	42.2	22.3	22.5	38.3	45.2	41.2	33.4	28.0	27.6
Or	26.5	25.5	47.0	46.3	25.9	25.8	1.6	30.0	27.0	26.1
Ab	33.2	26.1	28.0	27.6	30.1	23.6	27.0	29.4	37.4	30.9
An	5.1	2.1	.8	1.7	1.6	1.6	27.0	3.6	4.1	7.5
Hyp	1.0	.6	.1	.6	.8	1.1	.9	.7	1.3	4.6
Mte	.8	1.6	----	----	1.5	1.2	.8	1.1	----	1.0
Ilm	----	----	----	----	----	.4	----	----	----	.6
Cte	----	----	----	----	.1	----	----	----	----	----
Cor	1.0	2.2	.3	.6	1.6	1.2	1.6	2.0	2.5	----

MODES

	A1	A11	C12	C13	D13	E13	G13	H13	J13	H7
Micro	23.3	16.0	54.6	56.4	16.2	15.0	15.7	25.7	24.2	23.7
Perth	----	15.1	----	----	15.8	17.3	16.1	2.1	2.0	----
Plag	36.9	32.5	21.3	20.1	24.1	19.1	20.6	26.2	36.0	43.8
Qtz	35.8	34.5	23.7	23.0	38.9	45.8	40.2	37.9	28.1	29.2
Bio	2.8	1.0	----	----	tr.	0.4	0.4	4.7	5.9	1.1
Musc	0.2	----	----	----	----	----	1.7	1.9	2.0	1.3
Acc	1.0	0.9	0.4	0.5	1.3	2.4	1.3	1.5	1.8	0.9
Plag Comp	An_{12}	An_{10}	An_{5}	An_{6}	An_{9}	An_{6}	An_{10}	An_{10}	An_{14}	An_{19}

Analyses of pink granite gneiss are given in Table 2.7.

2.4.3 Pink granitoid veins

Two types of veins occur: one close to an "ideal" granite[1] in composition and the other richer in potash feldspar. The former are fine-grained and will be referred to as pink granite veins; the latter are coarse to very coarse in grain and will be called pegmatites. In size, they range from an inch wide to several feet, (dikes).

Pink granite veins were found cutting grey granite gneiss and migmatite, but not pink granite gneiss. Texture is hypidiomorphic granular, and quartz, plagioclase, and biotite are the main minerals. A prominent accessory is muscovite, which was found in segregations up to an inch across in a vein occurring north of Stormy Lake, on the Buckhorn Road. Analysis of Sample J3 is of a dike of pink granite intruding grey.

Similar rock has been called alaskite by Buddington (1939).

Pegmatite is found in transgressive, semi-conformable, and irregular veins, lenses, and patches. Mineralogy is simple on the whole - about 60 per cent microcline being accompanied by 20 per cent each of albite and quartz. The pegmatite sampled in Square A12 was unusual in being rich in biotite.

Tourmaline is fairly common, usually in graphic intergrowth with quartz, though in a sample from Square H3, the tourmaline was

[1]Ideal in Mehnert's sense, (see Section 1.2).

euhedral. In Square K12, along the Buckhorn Road, tourmaline occurs with pale green scapolite in an irregular transgressive pegmatite.

In adjacent Snowdon township, half a mile along the Gelert Road from Highway 500, a block of grey granite gneiss is cut by a pegmatite vein, which has an aplitic core.

Analyses and modes of vein rocks are given in Table 2.8.

2.4.4 Migmatites

As already indicated, the migmatite map unit (9) is defined to contain at least 10 per cent of non-granitic bands associated with layers and lenses of granite.

THE LEUCOSOME

A close analogy can be drawn between the composition of the granitic component of these mixed rocks, and that of the granites mappable as separate bodies. Mostly, the granite is grey or grey-pink, but on the outer edges of Hewitt and Satterly's (1957) Glamorgan granite gneiss, pink granite gneiss bands occur in the migmatite.

The grey leucosome invariably occurs in medium- to fine-grained, conformable folia, from a fraction of an inch to many feet thick. Major minerals present are: quartz, plagioclase, microcline, and biotite. Hornblende is scarce, and occurs as corroded relicts. Myrmekite is common, and perthite is absent.

Pink granite leucosome contains the same minerals as the grey variety except that hornblende is absent. Microcline is more abundant

TABLE 2.8

CHEMICAL ANALYSES OF VEIN ROCKS

	Pegmatite[1]				Granite
	A12	B14	N4	014	J3
SiO_2	68.7	63.49	73.5	73.8	71.29
TiO_2	.12	.61	.09	.03	.33
Al_2O_3	16.0	17.05	15.6	15.6	14.90
Fe_2O_3	1.0	1.43	.13	.07	1.22
FeO	.78	1.17	.23	.14	.84
MnO	.04	.07	.00	.00	.03
MgO	.68	.80	.25	.21	.07
CaO	.18	2.96	1.2	.07	2.25
Na_2O	3.73	4.85	2.89	4.08	4.19
K_2O	7.84	6.76	6.40	6.42	4.34
P_2O_5	.00	.13	.00	.00	.09
H_2O+	.32	.25	.11	.19	.22
H_2O-	—	.21	—	—	.09
CO_2	.01	.07	.01	.01	.02
Sum	11.4	99.85	100.4	100.6	99.88

[1]Too coarse to determine mode from thin section.

Analyses by John Muysson

TABLE 2.8

(Continued)

NORMS

	A12	B14	N4	O14	J3
Quartz	15.3	4.1	29.1	25.9	26.0
Orthoclase	46.4	40.0	37.9	38.0	25.7
Albite	31.5	41.0	24.4	34.5	35.4
Anorthite	.9	4.7	6.0	.3	9.0
Diopside	—	4.5	—	—	.1
Wollastonite	—	1.6	—	—	.9
Hypersthene	2.4	—	1.0	.8	—
Magnetite	1.5	2.1	—	—	1.8
Ilmenite	—	1.2	—	—	.6
Calcite	—	.2	—	—	—
Corundum	1.0	—	1.7	1.8	—

MODES

	1	2	3	4	5	6	J3
Microcline	32.0	12.5	31.1	32.5	22.3	37.1	23.1
Perthite	—	—	6.1	3.4	9.4	20.5	4.7
Plagioclase	46.6	53.9	28.9	19.3	20.4	19.3	.3
Quartz	15.2	25.5	33.7	44.0	47.2	19.5	32.3
Biotite	5.0	7.9	—	0.7	0.2	3.4	0.8
Accessories	1.2	.2	.2*	.1	.5*	.2	1.8*
Plag. Comp.	An_{17}	An_{19}	An_{8}	An_{5}	An_{5}	An_{12}	An_{15}

*Includes muscovite

Modes: Granite veins 1,2,3,4,5 collected in sample squares G5,I3,J5, F7, and B8 respectively. Micropegmatite vein: 6 collected in I4.

and both myrmekite and perthite occur. The granite is semi-conformable as in Figure 2.3, or in transgressive veins with lit-par-lit offshoots, (Figure 2.4).

Coarse-grained pegmatite veins also give off lit-par-lit bands to form a leucosome rich in microcline. The lithological unit 9c (marble migmatite) contains pink granite and pegmatite veins and folia together.

THE MELANOSOME

Two types of melanosome are distinguished - one of which grades into marble and the other into paragneiss.

The marble-like melanosome commonly contains calcite, phlogopite and amphibole. Within the 9c map unit, there is a gradation between calcite-bearing melanosome, and melanosome composed almost wholly of plagioclase and amphibole. Calcite and quartz have been found coexisting in some examples of the latter. The marble-like bands contain less calcite the closer the approach to granitic leucosome. Directly adjacent to the latter, a selvedge of amphibole, or rarely diopside, is common.

The paragneiss-like melanosome is similar in mineralogy to the variety of paragneiss containing amphibole. Microcline, however, is less abundant, and almost always is texturally associated with ragged, sub-parallel biotite flakes and hornblende. Segregations of biotite, hornblende, microcline, and sphene are not uncommon in thin section. Close to the leucosome, a selvedge rich in hornblende is common.

ANALYSES

The analyses of Tables 2.9 and 2.10 include those of individual migmatite bands and also that of a whole rock migmatite, (Sample J8). Separate samples of either leucosome or melanosome were only taken when the bands were at least five feet wide. Narrower bands would have been more difficult to sample and would have presented problems of contamination which did not arise with the wider bands. The whole-rock analysis represents a migmatite banded on a fine scale, individual bands being .5 centimetres thick, or less.

2.5 THE FIELD RELATIONS OF PARAGNEISS, MIGMATITE, AND GRANITE

In the field, unequivocal examples of paragneiss, migmatite, and granite gneiss occur. However, migmatite grades on the one hand into granite gneiss, and on the other into paragneiss, so that a clear cut boundary between the rock types does not exist. Consequently, arbitrary boundaries have been drawn according to specifications already described.

Paragneiss with no granite bands at all contains quartz, plagioclase and biotite in major amounts. Where sparse granitic bands are present, hornblende and microcline also occur in the paragneiss in roughly equal proportions. Migmatite contains dark bands superficially like hornblende-bearing paragneiss, but in which microcline is a very subordinate phase. Towards the centre of the Glamorgan gneiss complex, migmatite grades into grey granite gneiss, towards the eastern and northern edges it grades into pink granite gneiss.

TABLE 2.9

CHEMICAL ANALYSES OF MIGMATITE DARK BANDS, (MELANOSOME)

	D4[1]	D6[2]	H2[1]	H9	J1[1]	K3[1]	K8	K11	L6	L10
SiO_2	61.9	61.5	63.2	62.89	63.5	63.38	61.42	63.6	62.5	63.30
TiO_2	.9	.90	.75	.71	.69	.68	.79	.70	1.24	.83
Al_2O_3	16.3	15.9	16.6	15.89	15.9	16.33	15.89	15.5	15.5	15.02
Fe_2O_3	2.81	2.47	2.25	1.98	1.71	1.91	2.08	2.21	2.99	1.84
FeO	3.73	3.62	3.08	3.76	3.56	3.27	4.30	3.48	3.44	3.66
MnO	.12	.13	.13	.12	.10	.10	.11	.11	.17	.06
MgO	2.32	2.48	1.80	2.54	2.35	2.25	3.07	2.47	1.92	2.94
CaO	4.78	4.90	4.10	4.96	4.53	4.39	5.71	4.64	4.16	4.90
Na_2O	4.65	4.29	5.43	4.31	4.47	4.53	4.05	4.11	5.83	3.75
K_2O	1.51	2.27	1.54	1.57	1.83	1.57	1.54	1.82	1.32	2.53
P_2O_5	.28	.26	.22	.17	.15	.16	.18	.17	.43	.17
H_2O+	.34	.73	.65	.62	.70	.72	1.08	.88	.59	.72
H_2O-	.11	.06	.05	.16	.06	.19	.16	.10	.11	.14
CO_2	.01	.06	.02	.16	.03	.02	.02	.03	.01	.00
Sum	99.8	99.6	99.8	99.84	99.6	99.50	100.40	99.8	100.2	99.91

[1]Dark, non-granitic inclusions in grey granite gneiss.

[2]D6 contains a thin vein of micropegmatite.

Analyses by John Muysson

TABLE 2.9

(Continued)

NORMS

	D4	D6	H2	H9	J1	K3	K8	K11	L6	L10
Quartz	15.5	13.6	13.9	16.8	16.4	17.2	14.5	18.5	13.2	16.7
Orthoclase	8.9	13.4	9.1	9.3	10.8	9.3	9.1	10.8	7.8	15.0
Albite	39.3	36.3	45.9	36.4	37.8	38.3	34.2	34.7	49.3	31.7
Anorthite	19.2	17.4	16.3	19.3	17.9	19.6	20.6	18.4	12.2	16.6
Diopside	2.0	5.6	3.3	3.5	3.6	1.8	6.3	3.7	4.8	6.2
Hypersthene	7.7	6.8	5.7	9.0	8.3	8.2	9.7	8.0	4.6	8.4
Magnetite	4.2	3.6	3.3	2.9	2.5	2.8	3.0	3.2	4.3	2.7
Ilmenite	1.8	1.7	1.4	1.3	1.3	1.3	1.5	1.3	2.4	1.6
Calcite	—	—	—	.4	.1	—	—	—	—	—
Apatite	0.7	—	—	—	—	—	—	—	0.9	—

MODES

	D4	D6	H2	H9	J1	K3	K8	K11	L6	L10
Microcline	8.2	7.3	10.7	8.4	7.6	7.2	trace	13.1	6.6	7.9
Plagioclase	49.9	47.5	47.7	44.0	49.8	48.5	48.4	37.6	49.3	45.4
Quartz	16.9	20.5	17.1	15.3	21.6	25.0	11.2	22.1	24.9	10.3
Biotite	7.7	5.2	6.5	10.6	7.1	6.1	9.0	8.7	6.1	8.0
Hornblende	15.7	18.1	16.9	20.3	12.6	11.9	29.7	17.4	11.3	27.2
Accessories	1.6	1.4	1.1	1.4	1.2	1.3	1.7	1.1	1.8	1.2
Plag.Comp.	An_{28}	An_{28}	An_{25}	An_{29}	An_{25}	An_{28}	An_{30}	An_{27}	An_{28}	An_{30}

TABLE 2.10

CHEMICAL ANALYSES OF MIGMATITE LIGHT BANDS, (LEUCOSOME)

	Grey Granite Type											
	B4	B8	D10	E8	F9	H8	I10	J11	L5	L13	M1	M6
SiO_2	75.84	75.8	71.1	75.6	72.8	74.16	69.65	74.0	73.5	70.4	69.5	63.38
TiO_2	.20	.17	.39	.18	.34	.30	.54	.24	.33	.41	.39	.68
Al_2O_3	12.46	12.6	15.2	13.5	14.3	13.82	14.37	14.8	13.4	15.3	14.8	16.33
Fe_2O_3	1.30	1.37	.94	.71	1.4	.74	1.56	1.0	1.65	1.2	1.57	1.91
FeO	.80	.71	1.55	.84	1.44	1.08	2.28	.99	1.09	1.77	2.19	3.27
MnO	.03	.04	.05	.02	.08	.02	.06	.02	.05	.04	.09	.10
MgO	.21	.28	.98	.39	.64	.41	1.27	.39	.48	1.5	1.17	2.25
CaO	.93	.57	2.54	1.14	1.2	1.50	2.00	.99	1.6	1.8	2.99	4.39
Na_2O	4.38	5.21	4.27	4.72	4.77	3.96	4.31	4.83	4.90	5.13	4.87	4.53
K_2O	3.08	2.86	2.44	2.65	2.60	3.18	2.82	2.21	1.83	1.67	1.96	1.57
P_2O_5	.04	.02	.10	.02	.07	.05	.13	.00	.10	.05	.13	.16
H_2O+	.21	.15	.46	.22	.38	.36	.60	.21	.22	.40	.32	.72
H_2O-	.15	.05	.09	.03	—	.11	.25	—	.02	—	.05	.19
CO_2	.01	.02	.02	.03	.00	.01	.03	.00	.02	.00	.01	.02
Sum	99.64	99.9	100.1	100.1	100.0	99.70	99.87	99.7	99.2	99.7	100.0	99.50

Analyses by John Muysson

TABLE 2.10

(Continued)

				Pink Gte. Type	
	→	→	→	←	→
	M8	M10	M11	A6	E6
SiO_2	69.57	70.78	73.24	75.42	74.7
TiO_2	.61	.66	.44	.27	.13
Al_2O_3	15.13	14.56	13.53	13.01	14.8
Fe_2O_3	2.04	2.08	1.71	.77	.98
FeO	1.76	1.48	1.18	.46	.62
MnO	.10	.08	.03	.00	.00
MgO	.78	.58	.66	.22	.52
CaO	1.99	2.00	1.52	.60	.11
Na_2O	5.47	5.64	4.96	3.39	4.38
K_2O	1.92	1.89	2.31	5.19	3.87
P_2O_5	.13	.12	.11	.04	.03
H_2O+	.36	.35	.38	.63	.21
H_2O-	.15	.11	.07	.09	—
CO_2	.04	.00	.01	.00	.03
Sum	100.05	100.33	100.15	100.09	100.4

TABLE 2.10

(Continued)

NORMS

	B4	B8	D10	E8	F9	H8	I10	J11	L5	L13	M1	M6
Quartz	36.3	33.1	29.4	34.7	31.1	34.7	27.1	34.5	33.8	29.4	25.1	30.7
Orthoclase	18.2	16.9	14.4	15.7	15.4	18.8	16.7	13.1	10.8	9.9	11.5	10.6
Albite	37.0	44.0	36.1	39.9	40.3	33.5	36.4	40.8	41.4	43.4	41.2	47.7
Anorthite	4.6	2.5	12.6	5.7	6.0	7.4	9.7	4.9	7.9	8.9	12.8	6.2
Diopside	—	—	—	—	—	—	—	—	—	—	1.7	—
Hypersthene	.6	.7	4.0	1.7	2.7	1.9	5.3	1.6	1.4	2.0	4.3	1.3
Magnetite	1.9	1.9	1.4	1.0	2.0	1.1	2.3	1.5	2.4	1.7	2.3	2.8
Ilmenite	.4	.3	.7	.3	.6	.6	1.0	.5	.6	.8	.7	.5
Corundum	.2	—	.9	.8	1.4	1.1	.6	2.7	.4	1.8	—	—
Calcite	—	—	—	—	—	—	.1	—	—	—	—	—

TABLE 2.10

(Continued)

MODES

	B4	B8	D10	E8	F9	H8	I10	J11	L5	L13	M1	M6
Microcline	11.8	21.7	12.4	15.7	13.1	14.6	12.7	11.0	19.8	13.4	7.0	11.2
Plagioclase	42.1	42.3	44.9	41.4	45.4	42.0	46.9	48.6	40.6	47.2	51.7	48.5
Quartz	38.6	34.0	26.8	38.2	30.0	37.5	28.2	31.3	36.8	30.2	29.1	32.1
Biotite	6.0	1.2	10.2	3.5	10.0	4.1	11.0	6.3	1.9	8.4	6.1	7.1
Muscovite	—	trace	—	—	0.3	—	—	1.1	—	—	—	—
Hornblende	—	—	0.6	—	trace	—	—	—	—	—	4.8	—
Accessories	1.5	0.8	1.1	1.2	1.2	1.4	1.2	1.2	0.9	0.8	1.3	1.1
Plag Comp	An_{9}	An_{6}	An_{20}	An_{15}	An_{13}	An_{18}	An_{21}	An_{14}	An_{13}	An_{15}	An_{21}	An_{10}

TABLE 2.10

(Continued)

NORMS

	M8	M10	M11	A6	E6
Quartz	24.7	25.9	31.3	34.2	33.3
Orthoclase	11.4	11.2	13.7	30.7	22.9
Albite	46.2	47.7	41.9	28.7	37.0
Anorthite	9.9	8.8	7.5	3.0	.5
Diopside	—	.9	—	—	—
Hypersthene	2.7	1.1	1.7	.6	1.6
Magnetite	3.0	3.0	2.5	.7	1.4
Ilmenite	1.2	1.3	.8	.3	—
Corundum	.4	—	.1	.7	3.2
				Hem. .3	

MODES

	M8	M10	M11	A6	E6
Microcline	9.9	12.2	13.3	30.8	25.2
Plagioclase	49.8	43.8	44.0	29.3	36.3
Quartz	28.7	29.1	32.1	36.9	35.1
Biotite	10.2	13.8	10.1	1.8	1.0
Muscovite	—	trace	—	—	1.5
Hornblende	trace	trace	—	—	—
Accessories	1.4	1.1	0.5	1.2	0.9
Plag. comp.	An_{20}	An_{18}	An_{20}	An_{9}	An_{9}

In the next section, it will be shown that this field gradation is reflected in the chemistry of the rocks which, as a group, will be referred to as the Glamorgan gneiss series.

2.6 AGE RELATIONS

The oldest rocks in the area are metamorphosed, sedimentary, and volcanic rocks of the Grenville series. Subsequent to their deposition, these rocks have been intruded by the five groups of igneous rocks outlined by Lumbers (1964).

The earliest intrusions were the Glamorgan gabbro (Foye, 1916a) and associated diorites. Nepheline syenites were intruded after the basic rocks (Gittins, 1961) and before the syenites, quartz syenites, and granites, (Hewitt 1956). Included diorite in grey granite gneiss indicates the latter to be younger than the former. Pink granite and pegmatite intrude grey granite as cross-cutting veins, and are the last intrusives in the region.

The general conformable character of the granitic rocks (other than late veins), the migmatites and paragneiss, and the well-developed gneissosity in granite, are explainable on the grounds that the granites were emplaced synkinematically (Grant, 1959), or at the time of metamorphism, (Hewitt, 1956). However, an unusual feature of some of the grey granite is the absence of directional texture. Parts of the Glamorgan gabbro, and some of the nepheline syenites (Tilley and Gittins, 1961), share these characteristics. Flow in surrounding rocks may have provided these examples with a hydrostatic environment so that gneissosity did not develop.

3. STRUCTURAL CONSIDERATIONS

The detailed structural analysis of an area such as Glamorgan township is beyond the scope of this thesis. What follows here is in the nature of a reconnaissance.

A sketch map of Glamorgan township and its immediate environs (Figure 3.1), shows that the gneiss complex is bordered on three sides by a marble-marble migmatite envelope. The arcuate structure is explainable as a large inclined[1] fold (Figure 3.2), with the trace of its axis approximately as shown in Figure 3.1, trending ENE. Roughly in the centre of this fold is the grey granite gneiss and diorite. Younger, pink granite occurs in a sheetlike mass and in two anticlinal NW-SE folds. The example of the latter mapped in this study is shown in section A-A' in Figure 3.3.

The presence of younger granite in the simple folds suggests the possibility of the latter being younger than, and therefore superimposed upon, the larger inclined fold.

The generally flat, glaciated nature of outcrops in Glamorgan township, occasions a certain difficulty in the measurement of attitudes of structural features there. Where possible planar and linear fabric elements were measured and the resulting data is presented below.

3.1 PLANAR FABRIC ELEMENTS

3.1.1 Foliation

In migmatite, foliation is the result of alternating bands respectively of a granitic component and a non-granitic one. In

[1] Fleuty (1964), p. 482.

FIGURE 3.1. SKETCH MAP SHOWING THE GEOLOGICAL STRUCTURE IN GLAMORGAN TOWNSHIP AND ITS IMMEDIATE ENVIRONS.

Scale: 1 inch ≡ 2 miles

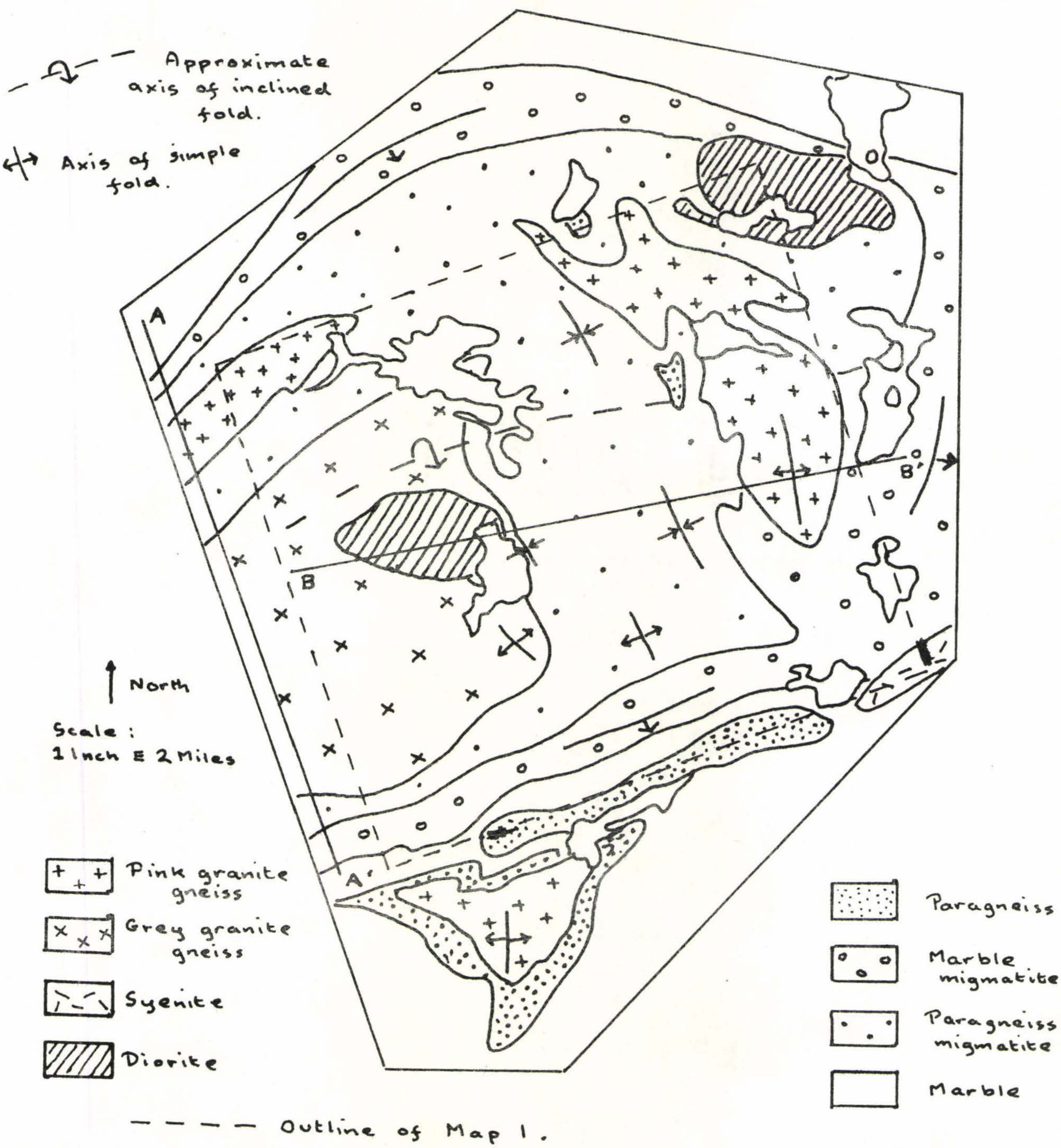


FIGURE 3.2. SECTION B-B' OF FIGURE 3.1.

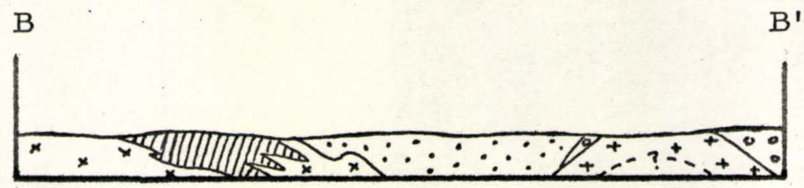
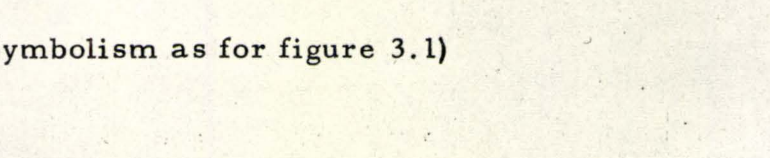


FIGURE 3.3. SECTION A-A' OF FIGURE 3.1.



(Symbolism as for figure 3.1)

paragneiss and grey granite gneiss a foliation is imparted by the parallel arrangement of biotite flakes, and by a small scale (2 mm or less) lamination of the rocks into respectively felsic and mafic rich folia. In pink granite gneiss foliation is again imparted by biotite flakes, and also (particularly at the edges of the phacoidal body) by bands of rock, alternatingly larger or smaller in grain size.

Apart from inferred relict sedimentary bedding, the marble in Glamorgan township has flowed along planes parallel to the bedding.

Foliation attitudes are plotted on Map 1. More data was not plotted on this figure, in the interests of clarity. Figure 3.4 is a series of pi-diagrams using foliation data.

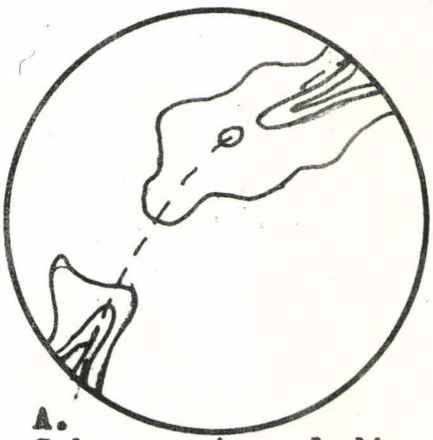
In sub-area A, foliation in pink granite gneiss and the surrounding rocks is seen to be conformable in the field. This is shown by Figures 3.4a and 3.4b. In this sub-area the simple fold referred to above appears as a girdle on Figures 3.4a, 3.4b, and 3.4c.

In sub-area B, grey granite gneiss is conformable to its country rock, (Figures 3.4d and 3.4e). Cross folding, possibly a combination of the larger inclined fold referred to above, and smaller folds of the sub-area A type, could account for the distribution of points in these figures. In Figure 3.4f two possible girdles are shown, one nearly coincident with that of Figure 3.4c, and a second that could reflect the attitude of the larger fold.

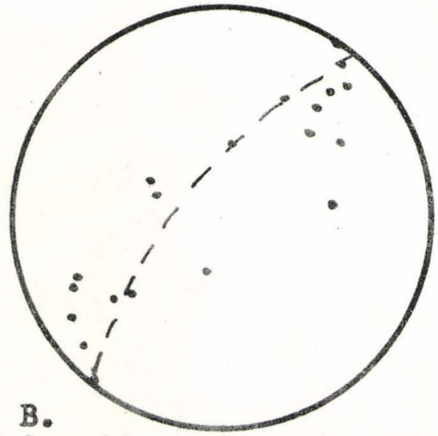
3.1.2 Joints and granitoid veins

Joints are shown in Figure 3.5a and show a considerable scatter. Granitoid veins (late granites and pegmatites intruding grey granite and migmatite) possibly define a girdle (Figure 3.5b) normal to that of

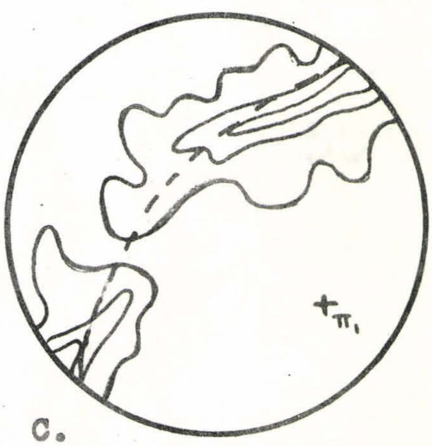
FIGURE 3.4. FOLIATION IN SUB-AREAS A AND B. See Map 1 for location.



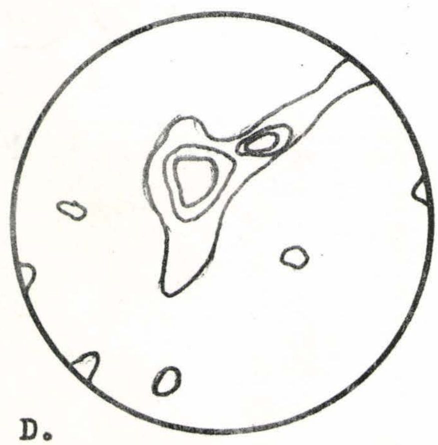
A.
Sub-area A excluding gte. gneiss. 52 points, contours at 2, 4 and 8 % of points per 1% area.



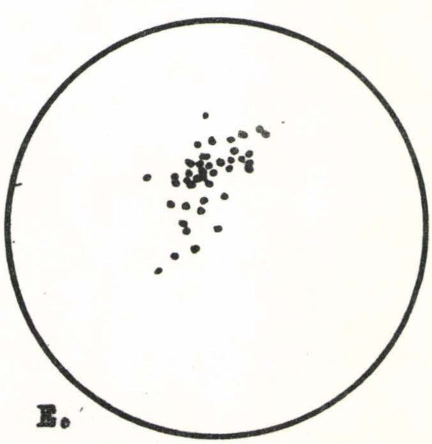
B.
Granite gneiss in sub-area A.



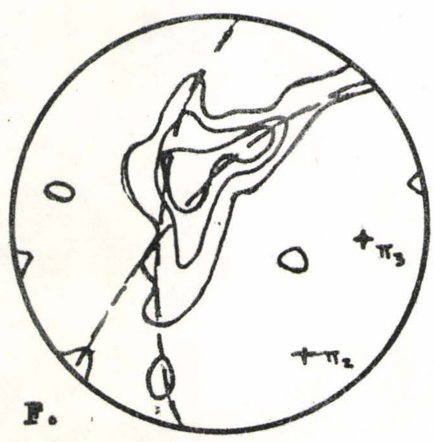
C.
All foliations in sub-area A. 71 points, contours at 2, 4, and 8% of points per 1% area.



D.
Sub-area B excluding gte. gneiss.88 points, contours at 2, 4, and 8% of points per 1% area.



E.
Granite gneiss in sub-area B.



F.
All foliations in sub-area B. 129points, contours at 2,4, and 8 points per 1% area.

FIG. 3.5 A.
JOINTS

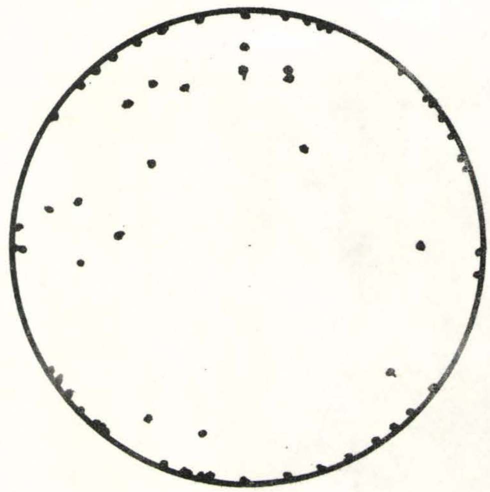


FIG. 3.5 B.
VEINS.

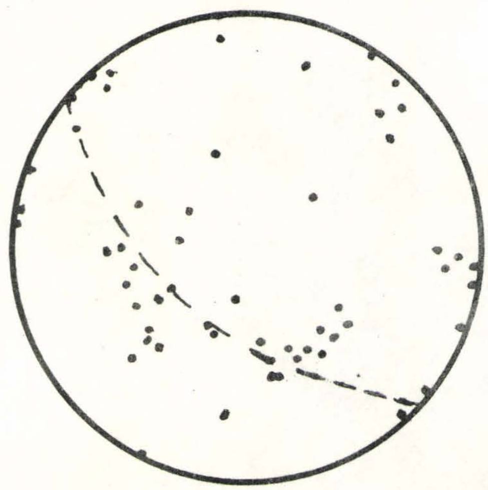


FIG. 3.6.
LINEATION.

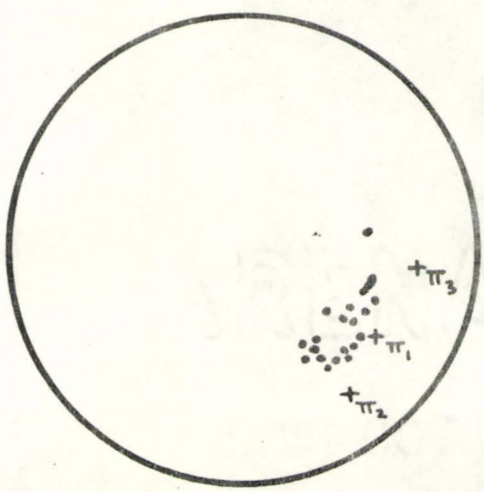


Figure 3.4c. This suggests a possible relationship between the two, which could have arisen by the intrusion of vein material, into longitudinal fractures caused by formation of sub-area A type folds. This would demand that the latter were younger than the larger inclined fold. It would also indicate that the joints are younger still (i.e., they were not available for intrusion of granite).

3.2 LINEAR FABRIC ELEMENTS

3.2.1 Lineation

The lineation shown on Map 1, is the orientation of hornblende grains in grey gneiss and migmatite melanosome. The evident scatter of these data about the pi-poles in Figure 3.6 is also suggestive of cross folding. Not enough data is available, however, for a rigorous analysis to be made.

Lineation[1] in Glamorgan township is generally not sub-parallel to the foliation. This accords with Hewitt's (1962) generalisation concerning lineation in the Haliburton-Hastings Highlands as a whole. However, unlike Hewitt, we cannot conclude that it is an "A" lineation.

3.3 SOME OBSERVATIONS ON THE GENERAL STRUCTURAL STYLE AND HISTORY

The absence of unequivocal faults in this area is probably a consequence of the fact that the rocks tended to flow rather than fracture. That some rocks fractured, however, while others flowed is shown by many examples of tectonic breccias to be found in this region, (see Figures 2.1 and 2.2). Other evidences of flow are ptygmatic folding in migmatite (Figure 3.7), and schlieren in grey granite gneiss (Figure 3.8).

---

[1] Azimuth

FIGURE 3.7. PTYGMATIC FOLDING IN MIGMATITE.

(6 miles west of Gooderham on hwy. 500).

FIGURE 3.8. FLOW AROUND INCLUSION IN GREY GRANITE GNEISS.

(S.W. shore of Bark Lake).

Concerning the structural history of Glamorgan township, we conclude that there is some evidence for two episodes of folding. The earlier inclined fold may have formed during the emplacement of grey granite gneiss, which is found at its core. The later NW-SE folds, are smaller and have pink granite gneiss in their cores. Beyond this it is useless to speculate, until more data is available.

4. SAMPLING

There are many ways of sampling a population, and the grid design (Figure 4.1) used in this study was chosen because it is well-suited to sampling a population that is initially unknown.

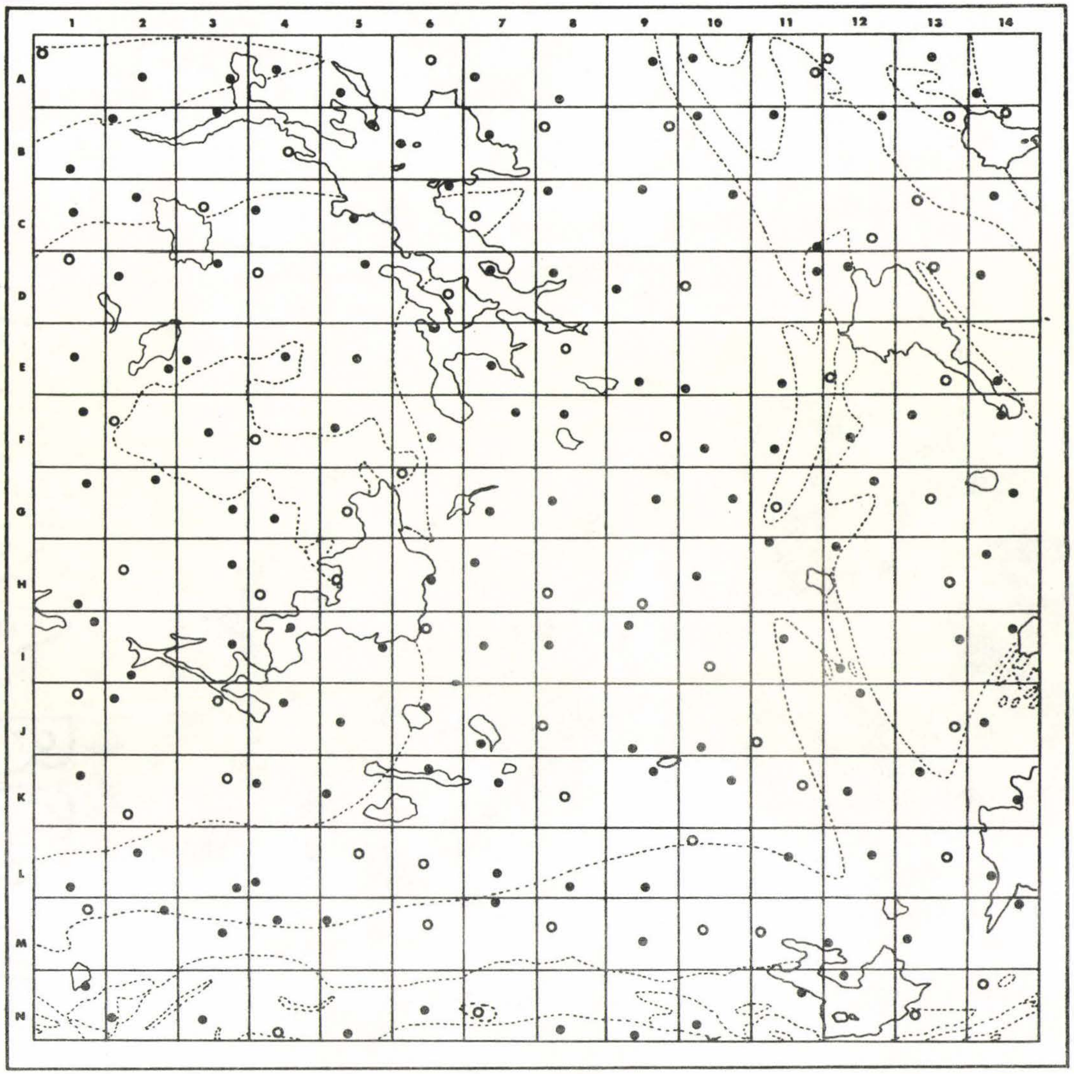
Sampling, according to a pre-arranged grid pattern, is a form of systematic sampling in two dimensions. In Glamorgan township, random samples were taken within each grid square. This constitutes unaligned (Cochran, 1953) or non-orthogonal (Krumbein, 1959) grid sampling. Krumbein (1936) was the first to use a grid system of sampling in a geological study.

In deciding the size of sample to be collected, an important factor is the size of individual species (for example mineral grains) that make up a rock. According to Wentworth (1926):

> "the sample should be large enough to include several fragments (grains) which fall in the largest grade present"

in the rock. The grain size of the gneisses sampled in this study was generally in the range of two to five millimetres. By comparison, the size of sample collected (2 pounds) was very large. Where grain size was much bigger (e.g., in some of the pegmatites), the two pound sample may not have been truly representative. However, increasing sample size would have created difficulties regarding transport in the bush.

Sampling of migmatite presented special problems arising from the evident heterogeneity of these rocks. Where the granitic and non-granitic components were present as fine bands (five millimetres or less),



SAMPLING DESIGN.

Circles represent sampling points; dashed lines - lithological boundaries. Open circles represent chemically analysed samples.

Direction of true north.

0 Miles 1

Fig. 4.1.

it was easy to take a representative sample of the whole rock. Where banding was coarse, the two pound sample would have been inadequate. Therefore, where migmatite bands were thick enough to allow it (five feet or more), samples of individual granitic and non-granitic layers were separately collected. Samples of migmatite with bands between five millimetres and five feet were not analysed because a two pound sample was probably not representative.

The mechanics of sampling in the field were as follows: the orthogonal grid with a uniform spacing of half a mile (Figure 4.1) was translated to aerial photograph overlays, on a scale of four inches to the mile. A random station was chosen within each square and the nearest outcrop to this random point was sampled. In cases where the random point fell in water, the nearest lake-shore outcrop was sampled. At the stations, a two pound chip sample was collected from an area of approximately 100 square feet. In some cases, this gave a composite sample of more than one rock type. Composite samples were not subsequently analysed.

Analyses were obtained for one sample chosen randomly from the four collected for each square mile of the grid. If the first choice was a composite sample, a second choice was made. In this way, the following heirarchy of samples was chosen:

A1	B4	A6	B8	B9	A12	A14
D1	D4	D6	C7	D10	C12	D13
F2	F4	E6	E8	F9	E12	E13
H2	H4	G5	H8	H9	G11	H13
J1	J3	I6	J8	I10	J11	J13
K2	K3	L6	K8	L10	K11	L13
M1	N4	M6	M8	M10	M11	N13

In addition to these randomly chosen samples, the following were also analysed:

A11 B13 C3 C13 G6 G13 H5 L5 N7 N14

These were chosen to give additional compositional information in special cases. For example, C3 and H5 are hornblende-paragneiss remnants in migmatite, N14 is a whole rock marble-migmatite, A13 is a sample of the northeasterly diorite mass, and so on (see the individual tables of analyses).

In the following table, the 49 samples randomly chosen for analysis have been used to estimate percentages of each rock unit in the sampled area. The figures from Table 2.1 are given for comparison.

	Rock Unit	Percentage based on sampling		Percentaged based on map	
Granitoid Rocks	Pink granite gneiss	10	86	10	90
	Grey granite gneiss	22		17	
	Migmatite	46		62	
	Pegmatite	6		1	
	Graphic granite	2		--	
	Diorite	4		2	
Grenville Series	Marble	2	8	5	8
	Paragneiss	6		2	
	Other	--		1	

Prior to chemical analysis, each sample was crushed between hardened steel jaws and then ground between ceramic plates. A splitter was used to sub-sample, and the sub-samples were ground to pass a 200 mesh sieve. This material was then analysed.

Modal analyses were made on thin sections cut from suitable hand specimens collected in the field. At least 1,500 points were counted on each slide.

5. COMPOSITIONAL RELATIONS

In this section the analyses of Section 2 are examined from the point of view of rock nomenclature and also of possible relationships between rocks. Averages appear in Table 5.1.

5.1 PARAGNEISS

An unusual feature of the quartz-plagioclase-biotite paragneiss, and one that is the basis of much speculation concerning the origin of the rock, is its high Na_2O/K_2O ratio. Similar rocks are known from other parts of the Grenville province (Engel and Engel, 1958, Simony, 1960, Buddington and Leonard, 1962).

Isochemical metamorphism would obviously require the same high alkali ratio in parental rocks, a fact that has been taken to rule out shale and arkosic sandstone. Consequently greywacke (Engel, 1956) and dacitic tuff (Gilluly, 1945) have been suggested as possible pre-metamorphic rocks. However, compositional similarity between Glamorgan paragneiss and average greywacke is not overwhelming (Figure 5.1), though dacite remains a possibility.

A belief that sodium-rich sediments are scarce in the geological column, has led to the alternative suggestion that sodium rich para-gneisses are metasomatic, and in particular that Na_2O was introduced. This belief has been lately challenged by Coombs (1965). He presents analyses of analcime-rich sediments with Na_2O/K_2O ratios ranging from 1.1 to 44, a spread obviously wide enough to include the Glamorgan rocks.

TABLE 5.1

MEANS AND STANDARD DEVIATIONS OF ROCK UNITS DESCRIBED IN CHAPTER 2

	Least altered Paragneiss		Diorite		Grey granite gneiss + equivalent leucosome		Pink granite gneiss + equivalent leucosome	
	M	S	M	S	M	S	M	S
SiO_2	65.8	1.45	52.0	1.62	72.2	2.17	75.4	2.64
TiO_2	.8	.17	2.3	.19	.4	.14	.2	.09
Al_2O_3	15.6	.71	16.0	.00	14.0	.83	13.8	1.47
Fe_2O_3	2.1	.23	5.2	.46	1.6	.45	.8	.32
FeO	2.9	.24	5.5	1.20	1.5	.48	.6	.30
MnO	.1	.01	.2	.03	.1	.03	.0	.01
MgO	1.7	.02	3.3	.25	.7	.41	.3	.31
CaO	3.7	.37	6.2	1.62	1.8	.68	.8	.62
Na_2O	4.7	.35	4.4	.02	4.8	.51	3.6	.53
K_2O	1.6	.27	2.6	.41	2.3	.54	4.5	.36
No. of Analyses	2		2		22		11	

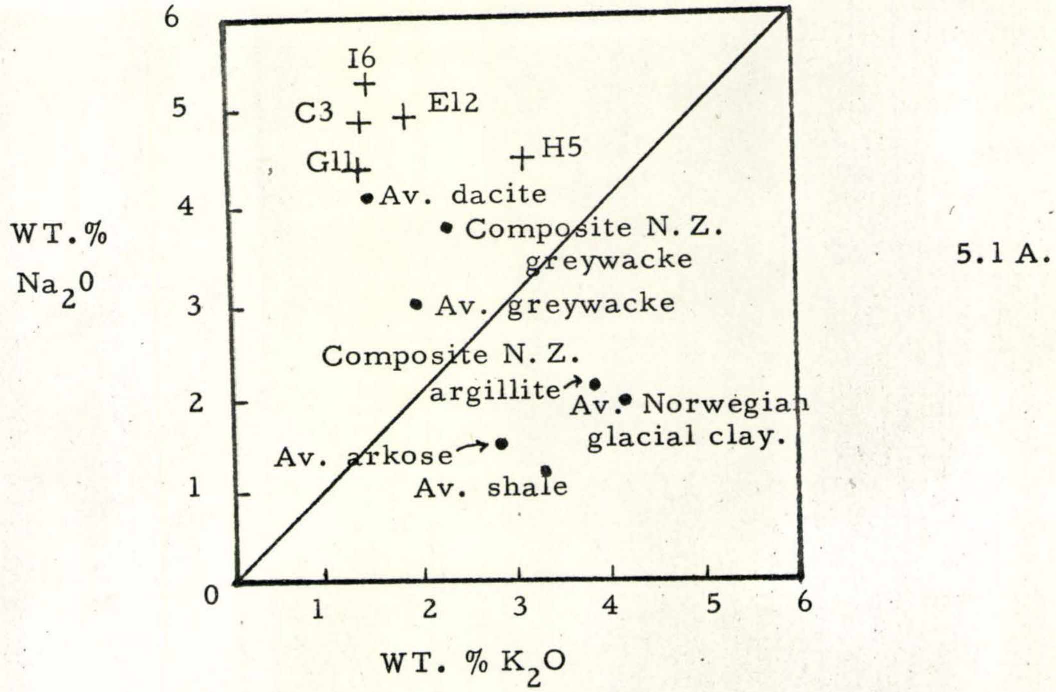
	All granite gneiss + leucosome		Graphic granite/pegmatite		Pegmatite		Migmatite melanosome	
	M	S	M	S	M	S	M	S
SiO_2	73.3	2.76	72.5	.07	69.9	4.85	62.8	.79
TiO_2	.3	.16	.0	.00	.2	.25	.8	.19
Al_2O_3	13.9	1.06	14.9	.28	16.1	.68	16.0	.39
Fe_2O_3	1.3	.55	.1	.04	.7	.66	2.2	.44
FeO	1.2	.58	.1	.01	.6	.48	3.6	.36
MnO	.0	.03	.0	.00	.0	.03	.1	.02
MgO	.6	.42	.1	.09	.5	.29	2.3	.39
CaO	1.5	.82	.3	.12	1.1	1.33	4.7	.51
Na_2O	4.4	.75	3.3	.03	3.9	.81	4.7	.63
K_2O	3.0	1.18	7.9	.09	6.9	.68	1.6	.16
No. of Analyses	33		2		4		8	

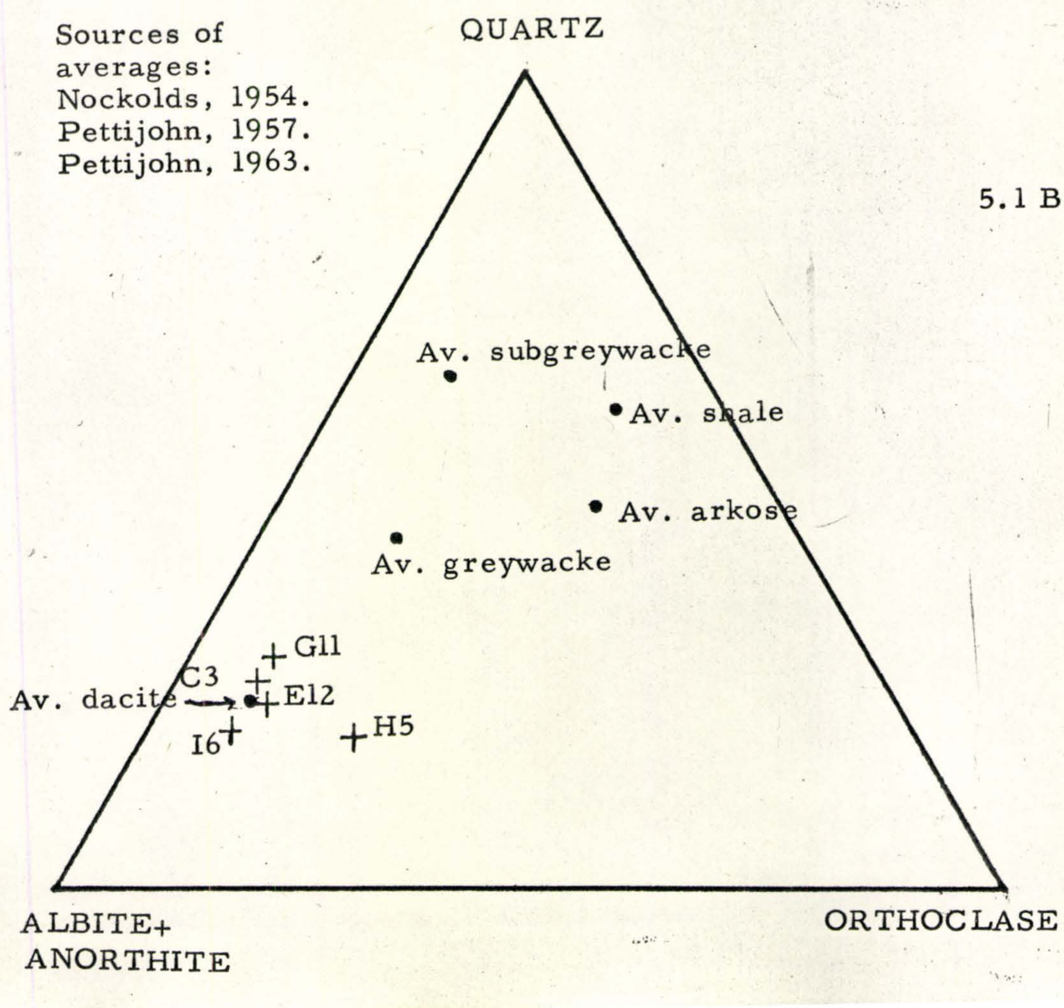
TABLE 5.1 (Continued)

	All quartzo - feldspathic rocks	
	M	S
SiO_2	70.3	4.93
TiO_2	.4	.28
Al_2O_3	14.6	1.26
Fe_2O_3	1.5	.73
FeO	1.7	1.17
MnO	.1	.04
MgO	1.0	.85
CaO	2.2	1.57
Na_2O	4.4	.73
K_2O	3.1	1.82

[1]Includes intrusive vein of pink granite - sample J3.
M = Mean, S = Standard deviation.

FIGURE 5.1. COMPOSITIONAL COMPARISONS BETWEEN GLAMORGAN PARAGNEISS AND SOME AVERAGE ROCKS.





He points out that rocks derived isochemically from sediments of this sort (assuming, not unreasonably, the presence of potash feldspar) must have the ratio $SiO_2/4Na_2O + 6K_2O$ greater than or equal to 1. When the ratio is less that 1 (as for example, in some of the nephelite gneisses of the York river area) a metasomatic origin may be seriously entertained. For the Glamorgan paragneisses, this ratio is greater than 1 (Table 5.2) so that an isochemical origin is not impossible. Even so metasomatism cannot be ruled out on these grounds. In fact

> "it has become increasingly apparent that most matamorphic processes, from the lowest grade to the point at which an anatectic melt may be formed, involve some degree of metasomatism," (Turekian, 1963, p. 4).

This will complicate any attempt to determine the original parent of a metamorphic rock.

However if metasomatism were the main process in the production of quartz-biotite-plagioclase paragneiss, we could expect to find relicts of an earlier mineralogy. On the contrary, we find a surprising uniformity for this formation over vast reaches of the Grenville province (Engel, 1956).

With Engel and Engel (1953 and 1958), we therefore conclude that metasomatism was not of overiding importance in forming Grenville paragneiss, though some minor amount of metasomatism is likely to have accompanied metamorphism. We must also conclude with Buddington and Leonard (1962, p. 34) that:

> "the present data do not enable a definite choice to be made between ..... hypotheses for the origin of the metasedimentary plagioclse rich gneisses."

TABLE 5.2

LEAST ALTERED PARAGNEISS COMPARED WITH ANALYSES FROM COOMBS (1965).

	$\frac{SiO_2}{(4Na_2O + 6K_2O)}$	
E12	2.51	Least altered paragneiss, Gl. twp.
G11	3.03	
1	2.45	Porphyroblastic albite schist
4	2.45	Felsitic volcanic arenite
5	3.07	Composite N.Z. greywacke
28	2.49	Analcime rich tuff

5.2 BASIC INTRUSIVE ROCKS

In Glamorgan township, basic rock (specifically diorite) is spatially associated with grey granite, which virtually surrounds the central body of Map 1. This might indicate a "biotite diorite series" of related rocks, (Lumbers, 1964, pp. 10-11), with sodic granite as a differentiate. It should be instructive therefore to look at the compositions of Glamorgan basic rocks with this in mind.

The Glamorgan gabbro, having both normative nepheline and olivine, plots in the undersaturated (alkali-basalt) section of the simplified basalt tetrahedron, (Yoder and Tilley, 1962, Figure 2). A projection of the latter (Figure 5.2) indicates that the gabbro is unlike either an average alkali basalt or an average alkali gabbro, and plots close to the composition of an average teschenite.

Diorites are an ill-defined group of rocks as a comparison of Daly's and Nockold's averages would suggest, Table 5.3. The Glamorgan rocks (designated 4di by Hewitt and Satterly, 1957) have roughly the same SiO_2 content as Nockold's average, but ferric iron and alkalies are unusually high.

Unlike the gabbro, the diorite (analyses F4 and G6, Table 2.5) contains a little normative quartz. This could be a consequence of the high ferric iron, and if the diorite is derived from Glamorgan gabbro, it points to the possibility of deriving a slightly oversaturated melt from an undersaturated one by oxidising the iron. As an illustration, the diorite norms have been recalculated on the basis of no ferric iron. Nepheline appears in these norms, (Table 5.4).

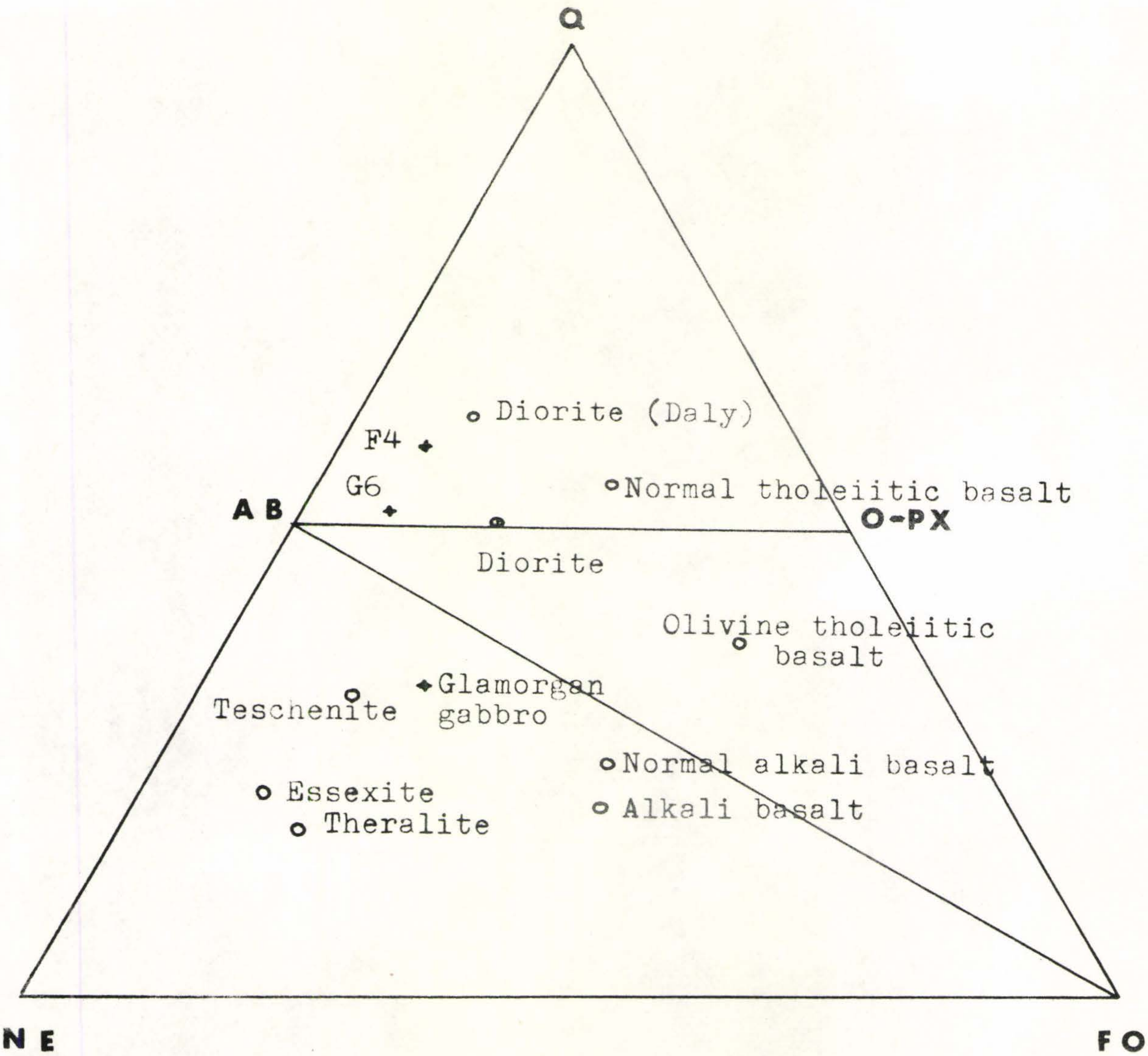


FIGURE 5.2. BASE OF THE SIMPLIFIED BASALT TETRAHEDRON. AVERAGE IGNEOUS ROCKS FROM NOCKOLDS (1954) EXCEPT FOR ONE AVERAGE DIORITE FROM DALY (1933).

TABLE 5.3

A COMPARISON OF THREE AVERAGE DIORITES

	Daly (1933)	Nockolds (1954	Glamorgan Twp.
SiO_2	58.90	51.86	51.9
TiO_2	.76	1.50	2.3
Al_2O_3	16.47	16.40	16.0
Fe_2O_3	2.89	2.73	5.2
FeO	4.04	6.97	5.5
MnO	.12	.18	.2
MgO	3.57	6.12	3.3
CaO	6.14	8.40	6.2
Na_2O	3.46	3.36	4.4
K_2O	2.11	1.33	2.6
H_2O+	1.27	.80	.9
P_2O_5	.27	.35	.2

TABLE 5.4

NORMS OF DIORITE CALCULATED ON THE BASIS OF ALL IRON BEING FERROUS

	F4	G6
Nepheline	1.1	.3
Orthoclase	13.8	17.3
Albite	35.5	37.0
Anorthite	16.8	15.2
Hypersthene	—	7.1
Diopside	10.2	4.8
Olivine	12.9	11.0
Ilmenite	4.6	4.1
Apatite	2.8	1.6

If the gabbros and so-called diorites are indeed parts of the same rock series, then the high ferric iron and alkalies, in the diorites, suggests strong fractionation. This is shown in Figure 5.3a, and in this regard it is pertinent to note the Pusey iron ore body, associated with the Glamorgan gabbro, (Foye, 1916). Figure 5.3b shows that there is some similarity between this hypothetical series and the alkali-series of volcanic rocks. The end products of an alkali volcanic series are almost always either saturated or undersaturated with respect to silica, and where oversaturated differentiates have been produced, they are readily recognised. It would therefore be worthwhile to investigate the possibility of some of the syenites or nepheline syenites found in this region, being differentiation products of more basic rocks. This seems more likely than obtaining sodic granite from these rocks.

Another way that the diorites might be derived from gabbro is by contamination. In this case the chemical components of gabbro, diorite and the contaminant, would need to show a simple additive relationship, (Bowen, 1928). Because of this the comparatively high K_2O content of the diorite rules out paragneiss as the contaminant. Indeed, in order to raise the K_2O percentage from .66 in gabbro to 2.3 to 2.9 in diorite, would require a great deal of contamination - 30 per cent or more even by potash rich pink granite gneiss, which is a younger rock than diorite anyway. This is a great deal of contamination of which to find no trace. Indeed addition of potash feldspar itself, is about the only process that could sufficiently raise K_2O content without drastically changing the content of other components.

FIGURE 5.3A. TREND OF IRON ENRICHMENT IN THE GLAMORGAN ROCKS;
Sk - Skaergaard trend
Ca - calc-alkalic trend

(after Osborne, 1959).

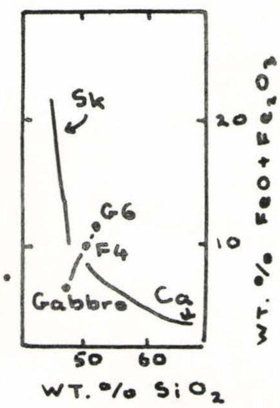
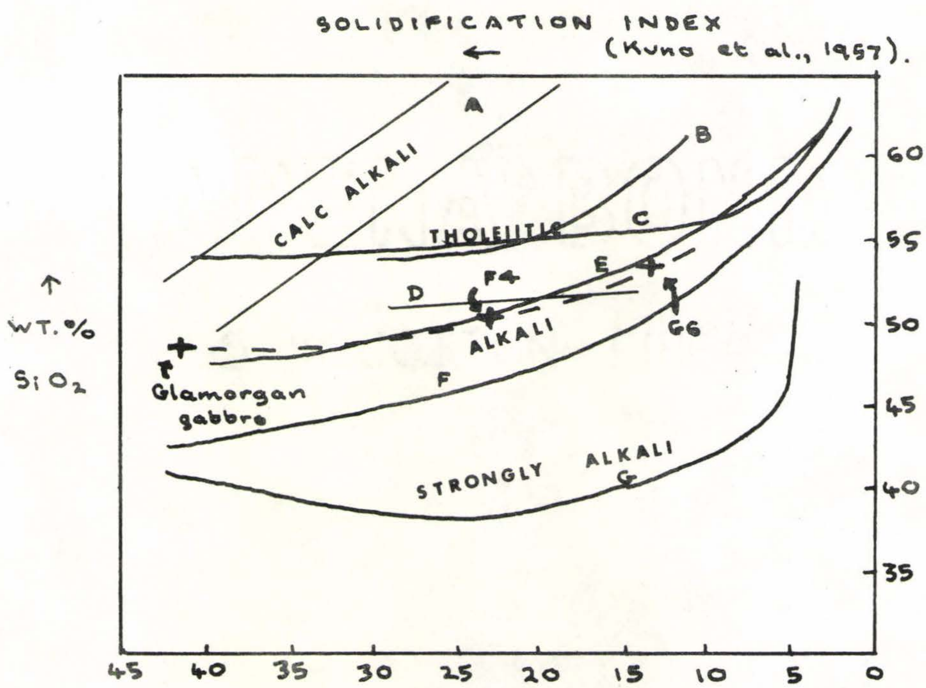


FIGURE 5.3B. BASIC ROCKS FROM GLAMORGAN TOWNSHIP INTERPRETED AS PART OF AN ALKALI TYPE SERIES.

Sources of data -
A White (unpublished)
B and D Kuno et al., (1957)
C McDougall (1962)
E Carmichael (1964)
F and G Saggerson and Williams (1964).



5.3 GRANITOID ROCKS

Grey and pink granite gneisses are plotted in figure 5.4, which shows that the former are generally trondjhemitic and the latter granitic, in the restricted sense. Figure 5.5 illustrates this point with respect to the haplogranitic system, which also shows that the graphic granite (and pegmatite too) are very rich in potash feldspar, (c.f. Simpson, 1962).

The scatter of the pegmatite analyses probably reflects more the difficulty of obtaining a representative sample of these very coarse grained rocks, than a real compositional difference. The average pegmatite is probably a better guide to the true composition.

5.4 MIGMATITE

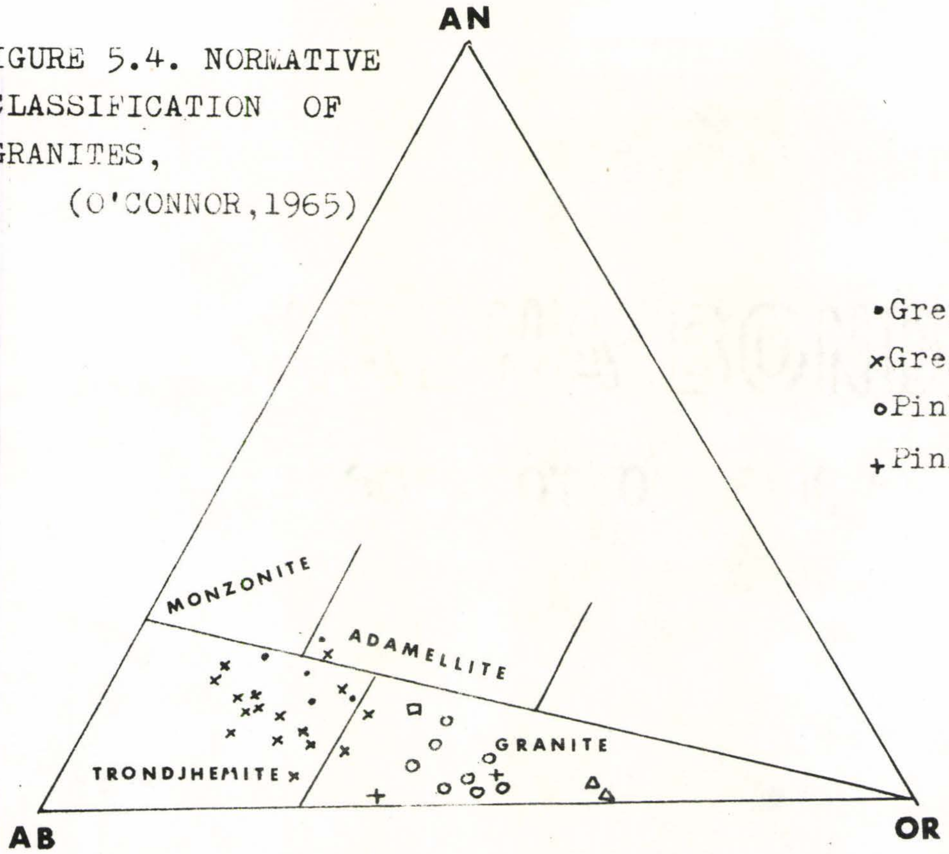
Two bulk analyses of finely banded migmatite were obtained, sample N14 (Table 2.2) of rock unit 9c and Sample J8 (Table 2.3) of rock unit 9q. Figure 5.6 shows that Sample J8 is comparable in composition to paragneiss.

The granitic component of the migmatite has a similar composition to the larger bodies of granite gneiss, (Figure 5.4). The non-granitic bands are more mafic, being similar in composition to an average tonalite, (Daly, 1933, p. 15).

5.5 COMPOSITIONAL RELATIONSHIP BETWEEN GRANITE GNEISSES MIGMATITE AND PARAGNEISS

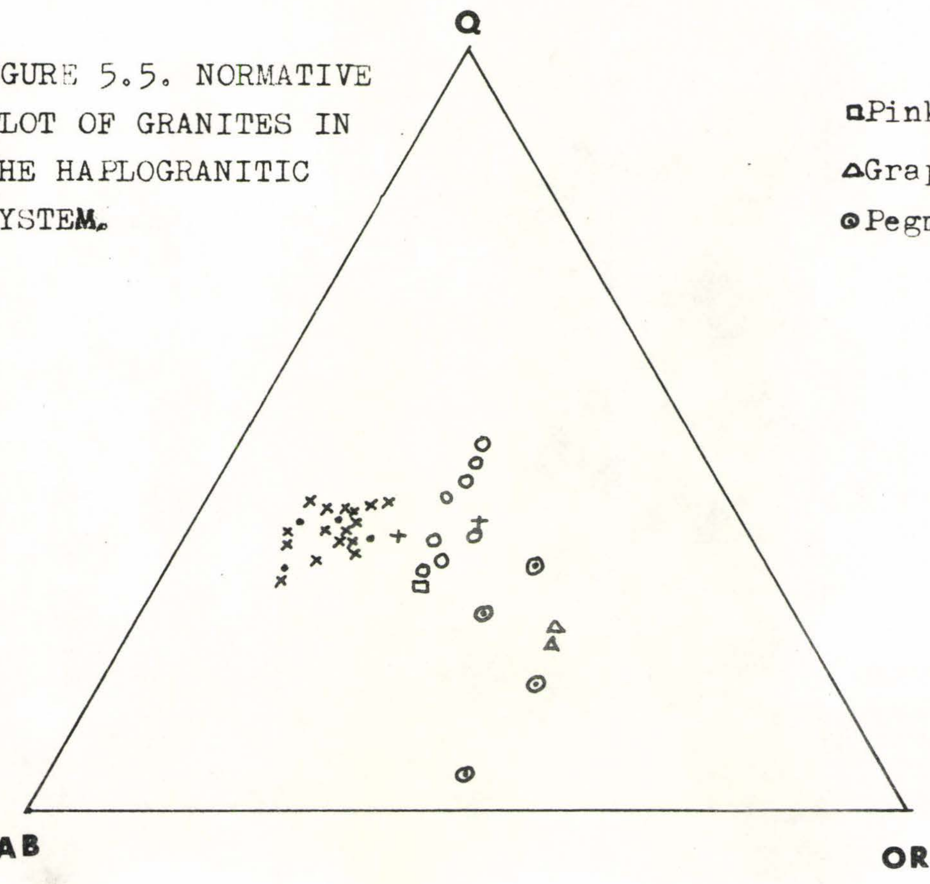
The evident gradation between rock types seen in the field is reflected in a well-defined chemical gradation, (Figure 5.7). This

FIGURE 5.4. NORMATIVE CLASSIFICATION OF GRANITES, (O'CONNOR,1965)



•Grey granite gneiss
×Grey gte. leucosome
○Pink granite gneiss
+Pink gte. leucosome

FIGURE 5.5. NORMATIVE PLOT OF GRANITES IN THE HAPLOGRANITIC SYSTEM.



□Pink granite vein J3
△Graphic granite/peg.
⊙Pegmatite

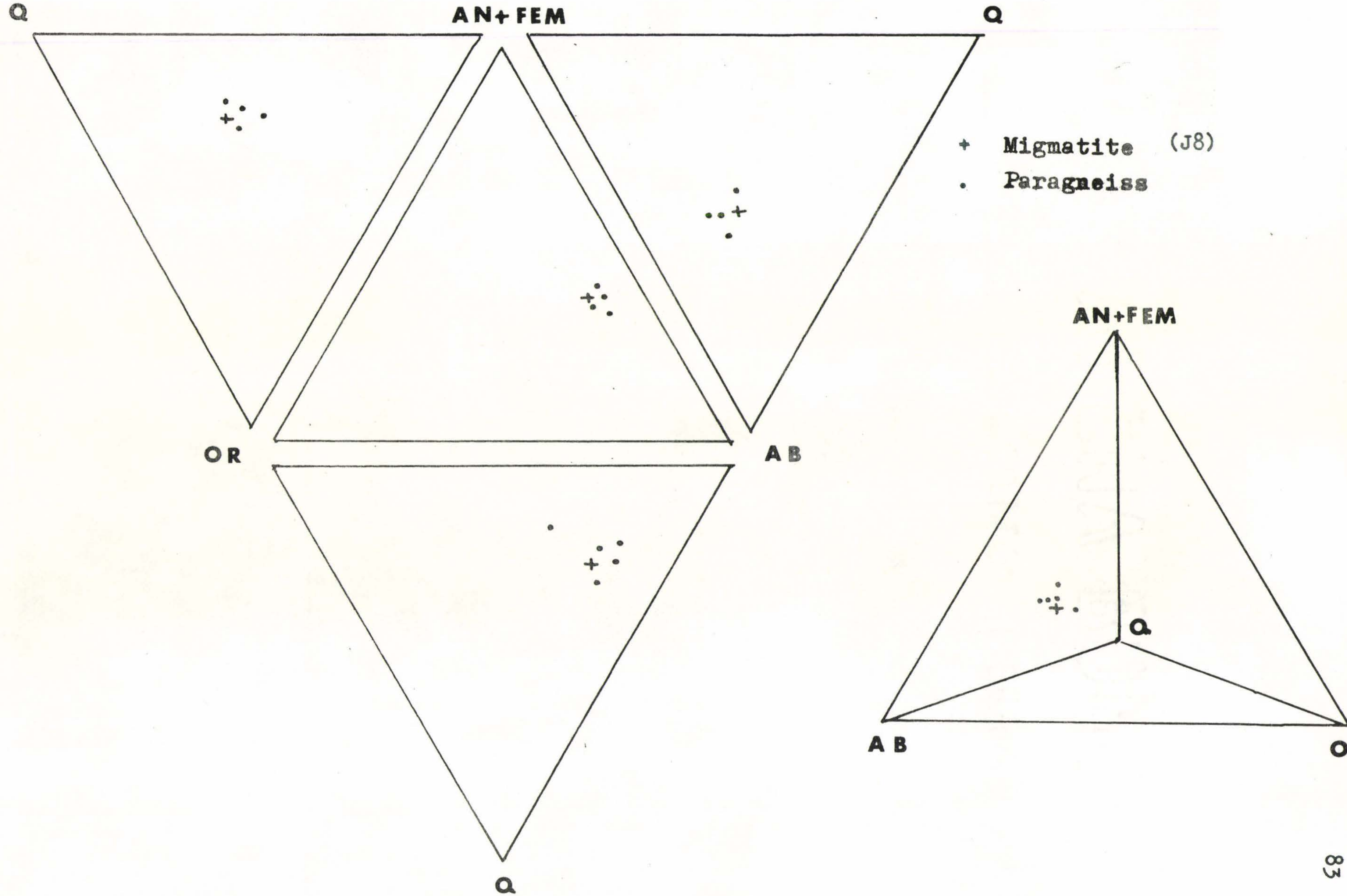
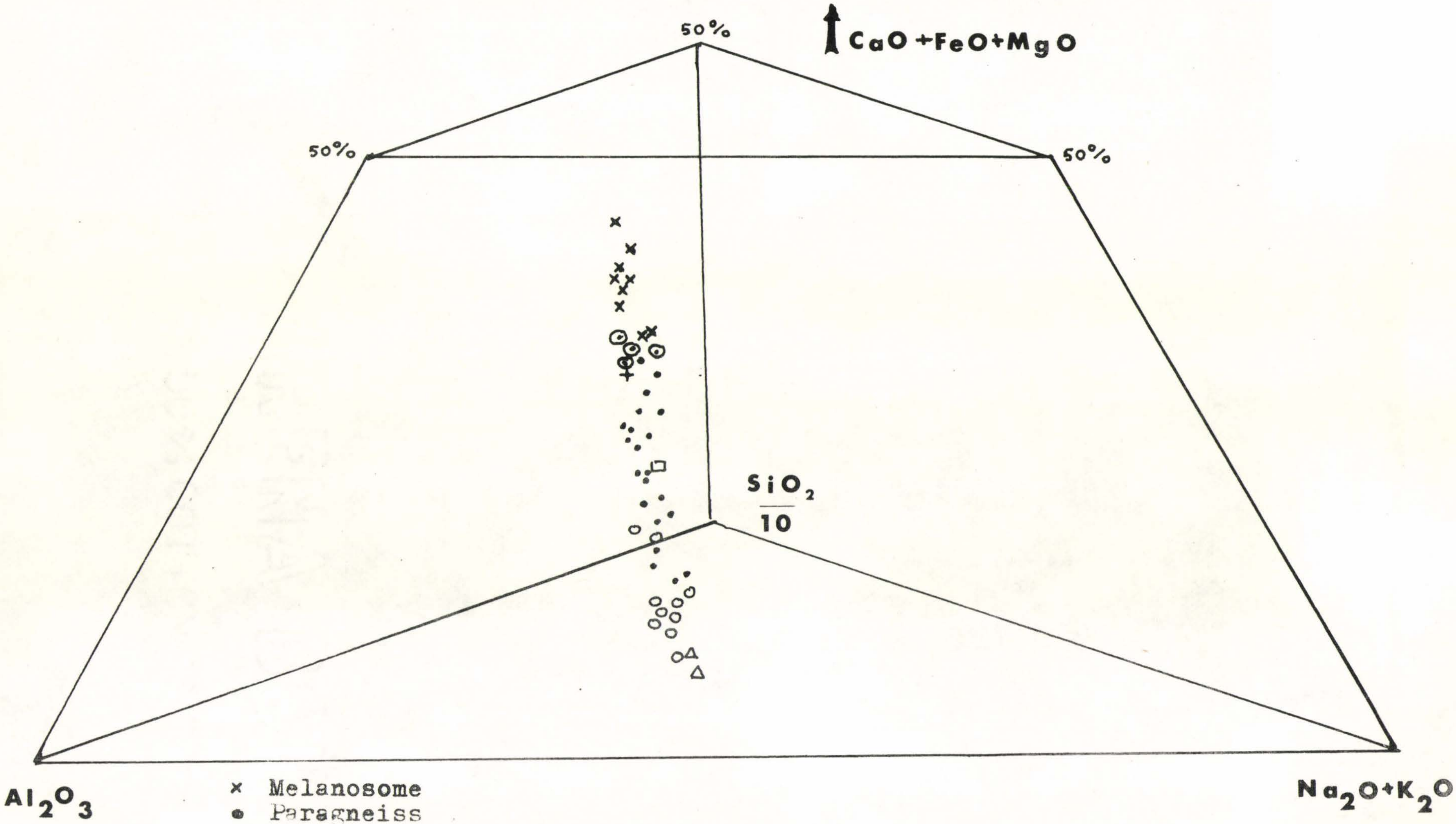


FIGURE 5.6. COMPARISON BETWEEN PARAGNEISS COMPOSITIONS AND THAT OF WHOLE ROCK MIGMATITE, (NORMS).

FIGURE 5.7. CHEMICAL GRADATION IN THE GLAMORGAN GNEISS SERIES



× Melanosome
● Paragneiss
\+ Whole rock migmatite
· Grey granite gneiss and leucosome
□ Pink granite vein
○ Pink granite gneiss and leucosome
△ Graphic granite(pegmatite

gradation is also shown in terms of the differentiation index[1], (Figure 5.8) which shows how closely the series approaches a haplogranitic composition (D.I. = 100).

In terms of the haplogranitic system the granite gneisses and the granitic bands in migmatite, display a bimodal frequency distribution, (Figure 5.9). The chemical gradation and the bimodal frequency distribution of the granites must be explained by any theory of origin advanced for these rocks.

Confirmation of the presence of two separate granite populations in this area, can be obtained by the use of Student's t test. First a value for t is computed according to

$$t = \frac{\bar{d}}{s_{\bar{d}}} = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where $\bar{X}_1$ and $\bar{X}_2$ are means of a given parameter of the two populations, s_1^2 and s_2^2 are the variances and n_1 and n_2 are the numbers of samples in each group. A value of t is then obtained from a table for $(n_1-1)+(n_2-1)$ degrees of freedom at a preset level of significance. If computed t is preset greater than tabular t, then the null hypothesis $\mu_1 = \mu_2$ is rejected.

For example Figure 5.10 would indicate that one set of granites is richer in normative potash feldspar than the other. Therefore we set up the null hypothesis

$$\underset{(\mu_1)}{\mu K_2O} \text{ in grey granites} = \underset{(\mu_2)}{\mu K_2O} \text{ in pink granites}$$

---

[1] Defined as "the sum of the normative percentages of quartz, orthoclase, albite, leucite, and kalsilite, " (Thornton and Tuttle, 1960, p. 665)

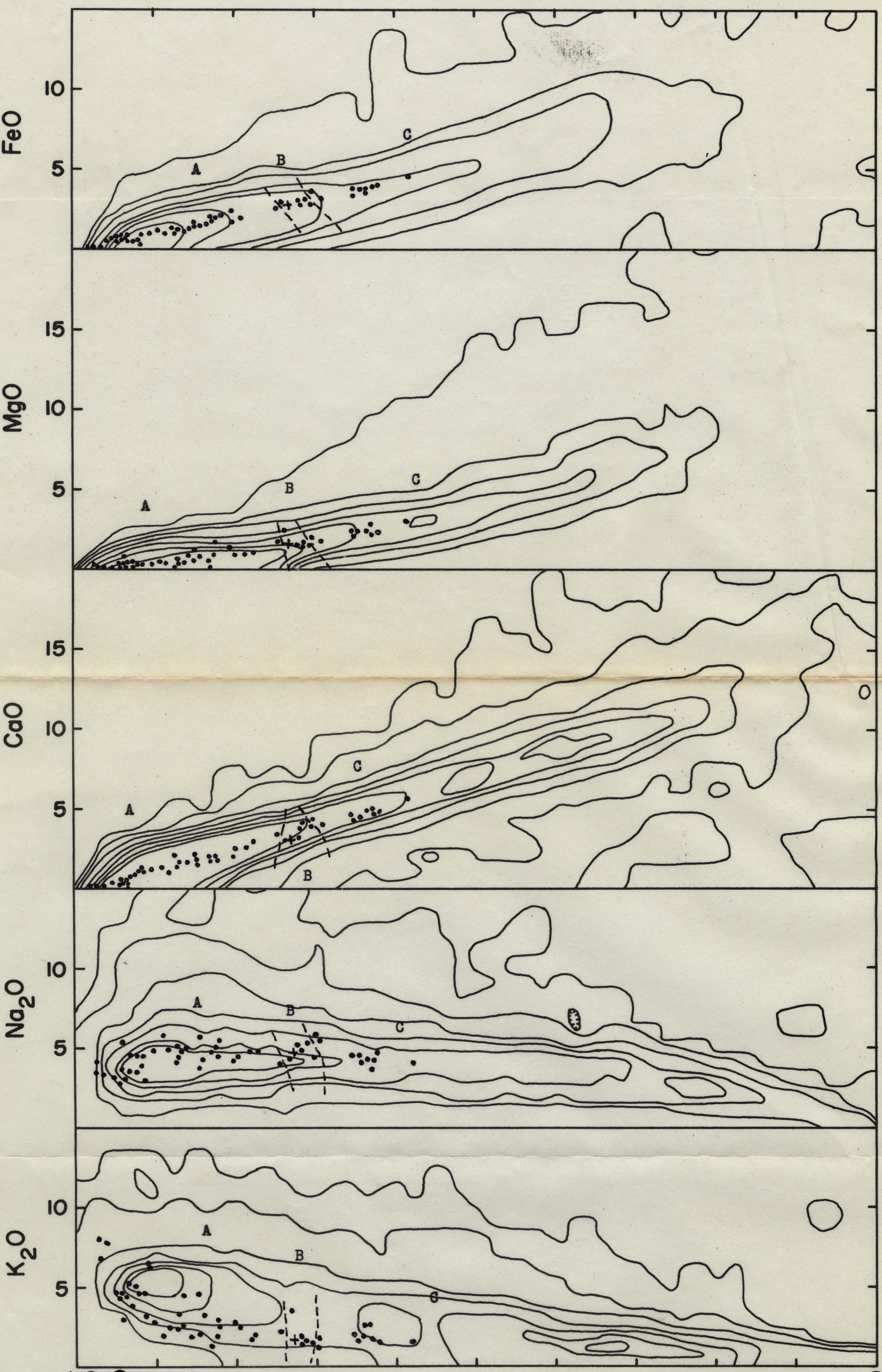
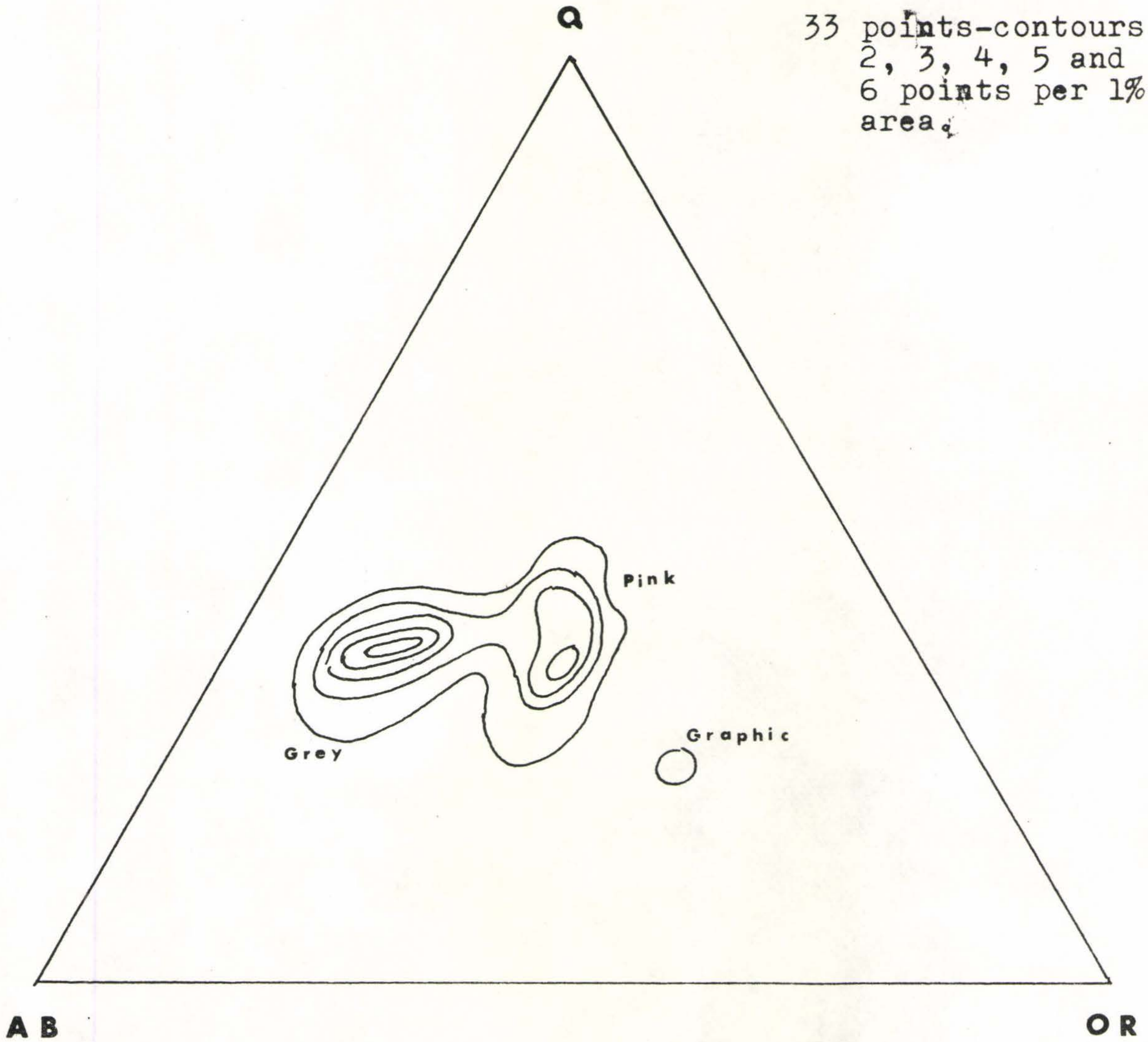


FIGURE 5.8. WEIGHT PERCENT OXIDE VERSUS DIFFERENTIATION INDEX. A. granitic rocks and granitic component of migmatite, B. paragneiss and whole rock migmatite (+), C. non-granitic component of migmatite and inclusions in granitic gneiss.

FIGURE 5.8. (cont.)

FIGURE 5.9. CONTOUR DIAGRAM BASED ON THE POINTS OF FIGURE 5.5, (PEGMATITE OMITTED), SHOWING THE BIMODAL DISTRIBUTION OF PINK AND GREY GRANITE GNEISS AND LEUCOSOME.

33 points-contours 2, 3, 4, 5 and 6 points per 1% area.



Then having chosen t for an α of .005 (=2.75) we calculate t using statistical data from table 5.1. This comes to 88.49 so that the hypothesis is rejected. In other words, using the parameter K_2O percentage, two populations of granite are distinguishable.

6. PETROGENESIS OF THE GLAMORGAN GNEISS SERIES

It has been shown that granite, migmatite and paragneiss form a gradational series of rocks both in terms of field relations and chemistry, and this has been called the Glamorgan gneiss series. The topic now to be considered is how it came to be formed.

For purposes of simplification, the gneiss series will be discussed in two parts - sub-series A (migmatite, paragneiss and grey granite gneiss) and sub-series B (pink granite gneiss). The basis for this is the recognition of two granite populations (Figure 5.9) separable in terms of K_2O content (Section 5.5). Figure 6.1 shows the inter-relation of the two sub-series.

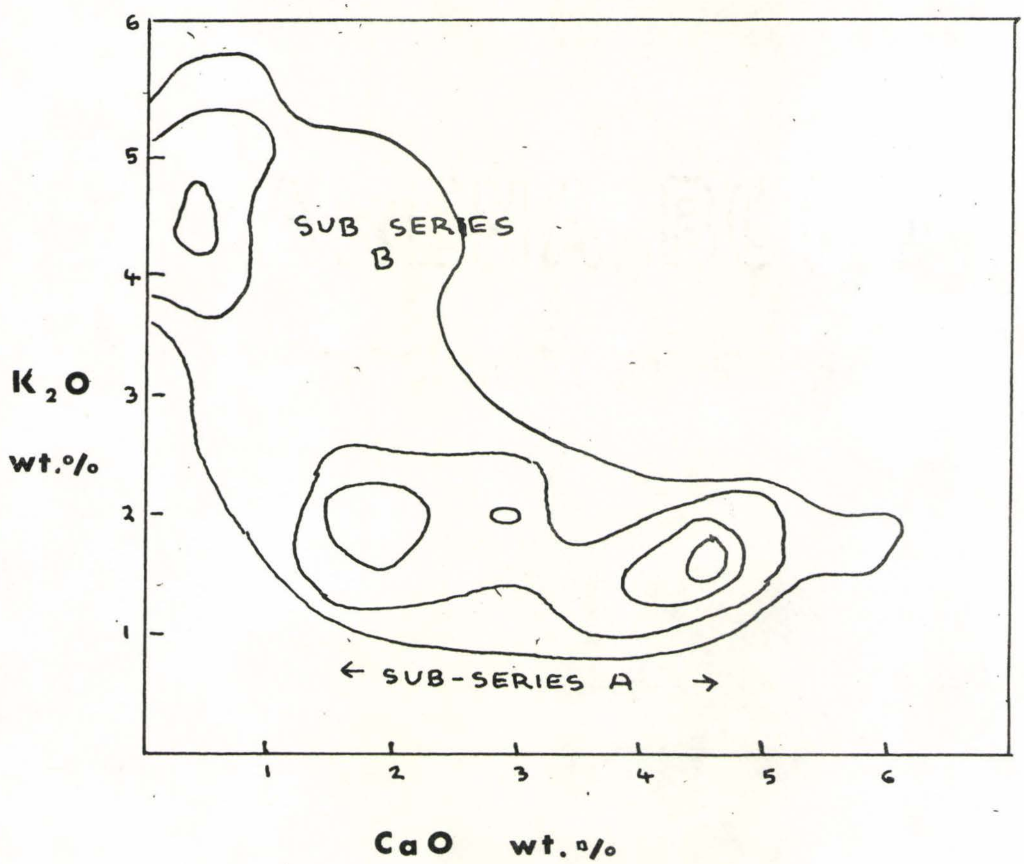
The present section considers geological and geochemical evidences of origin, and is, therefore, inductive in nature. The next section supplies a deductive analysis of the problem by considering pertinent findings of experimental petrology.

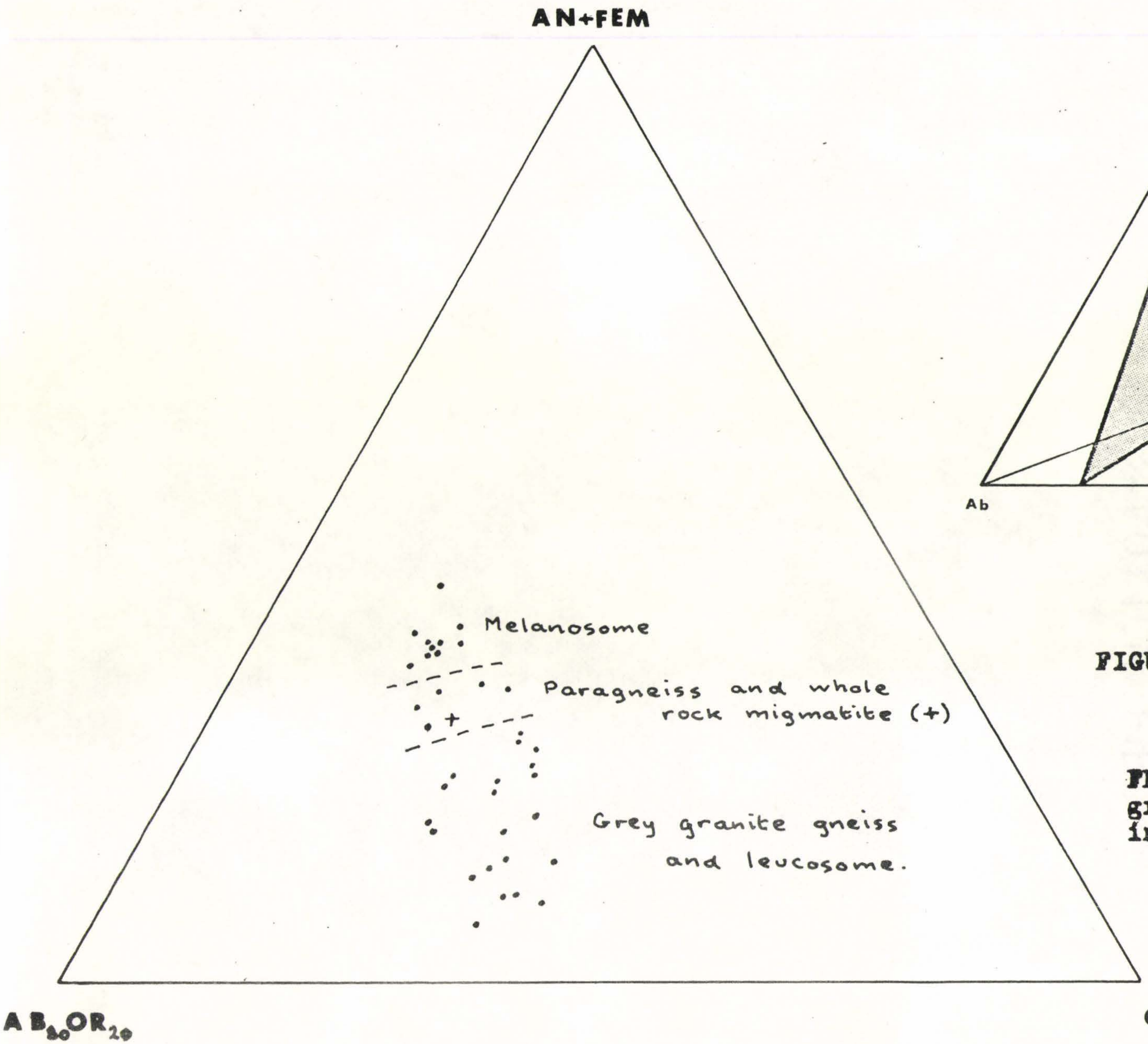
6.1 PETROGENESIS OF SUB-SERIES A

Analyses of migmatite melanosome, paragneiss, grey granite gneiss and equivalent leucosome are plotted on Figure 6.2 in terms of normative An + Fem - Ab_{80} Or_{20} - Quartz. The rocks in question contain 80 per cent or more of these components so that the plane is a fairly good fit for the analyses. Three working hypotheses can be proposed to explain the approximately linear chemical gradation of sub-series A, revealed by this diagram. They are:

FIGURE 6.1. DISTRIBUTION OF ANALYSES IN TERMS OF THE COORDINATES K_2O AND CaO.

49 points - contours at 2, 3, 5 and 6 points per unit square.





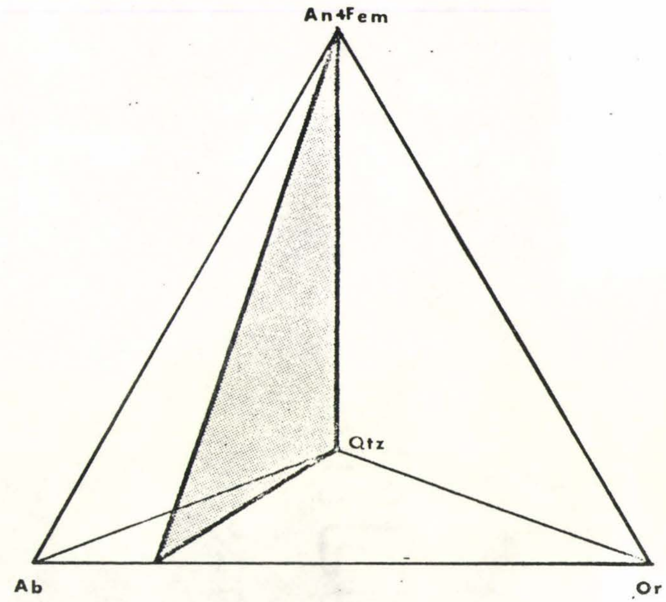


FIGURE 6.2. SUB-SERIES A, (NORMS).

FEM is the femic group of minerals in the CIPW norm.

1. An inheritance hypothesis,
2. An addition hypothesis, and
3. A subtraction hypothesis.

Below, each is stated and examined in turn.

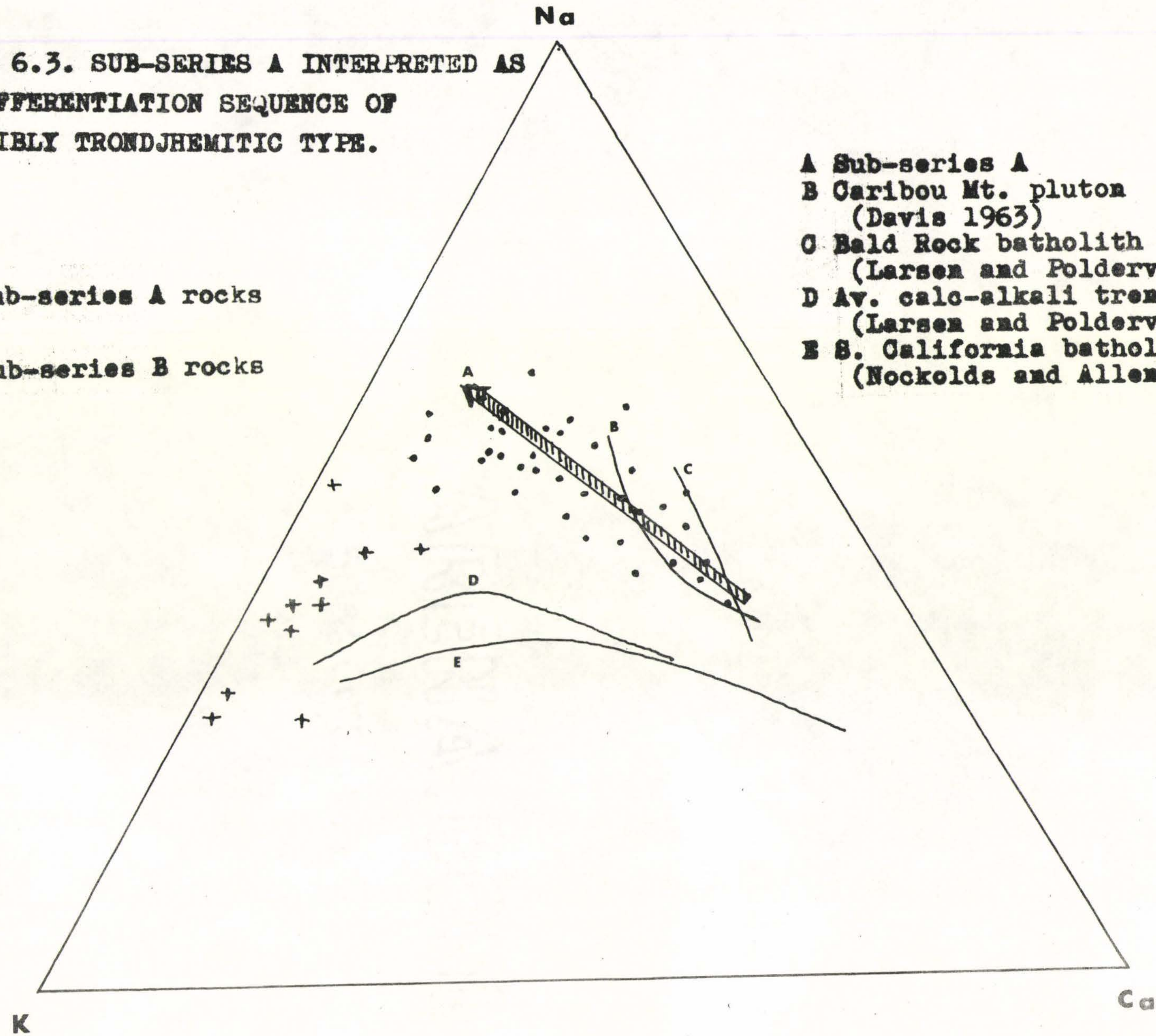
6.1.1 The inheritance hypothesis

On chemical evidence alone, sub-series A might be the metamorphosed equivalent of a series of pre-existing rocks with the same chemical characteristics. In other words, metamorphism was isochemical and the trends that have been recognised in sub-series A, resulted from the operation of igneous or sedimentary processes, prior to metamorphism.

Let us first consider a possible igneous origin. For example, Series A may represent a differentiation sequence of essentially trondjhemitic type (Figure 6.3). The well-bedded nature of migmatite and of so called paragneiss (with respect to marble) would suggest a volcanic origin rather than a plutonic one. At first glance, the presence of gabbro and diorite in the area would seem to provide basic end members for the series, the plutonic rocks being interpreted as invading comagmatic lavas.

However, the proportion of basic rocks to granite in Series A is small (about one to eight), and ought to be larger to be consistent with a differentiation hypothesis. Furthermore, the gabbro is of an alkali type (Section 5.2) and would generally not be expected to give rise to oversaturated (i.e., quartz-bearing) differentiation products. In the rare cases where this does happen, the oversaturated differentiates are easily recognisable chemically, e.g., comendites and

FIGURE 6.3. SUB-SERIES A INTERPRETED AS A DIFFERENTIATION SEQUENCE OF POSSIBLY TRONDJHEMITIC TYPE.



. Sub-series A rocks

+ Sub-series B rocks

A Sub-series A
B Caribou Mt. pluton (Davis 1963)
C Bald Rock batholith (Larsen and Poldervaart 1961)
D Av. calc-alkali trend (Larsen and Poldervaart 1961)
E S. California batholith (Nockolds and Allen 1953)

pantellerites (Carmichael, 1962). Finally, if the gabbro and diorite had invaded comagmatic lavas, it would be difficult to explain the age relations of Section 2.6, which sought to show that the basic rocks were the oldest intrusives in the region.

We might more profitably, therefore, investigate a sedimentary origin, which could also explain the well-bedded character of some of the gneisses referred to above. The sedimentary sequence, however, would have to have an unusually constant Cao/(FeO + MgO) ratio (Figure 6.4). Moreover, a selection of Grenville paragneisses do not show this phenomenon.

In summary, little evidence can be found to support an inheritance hypothesis for Series A as a whole, though part of the sequence may indeed have inherited its composition, (see Section 6.1.3).

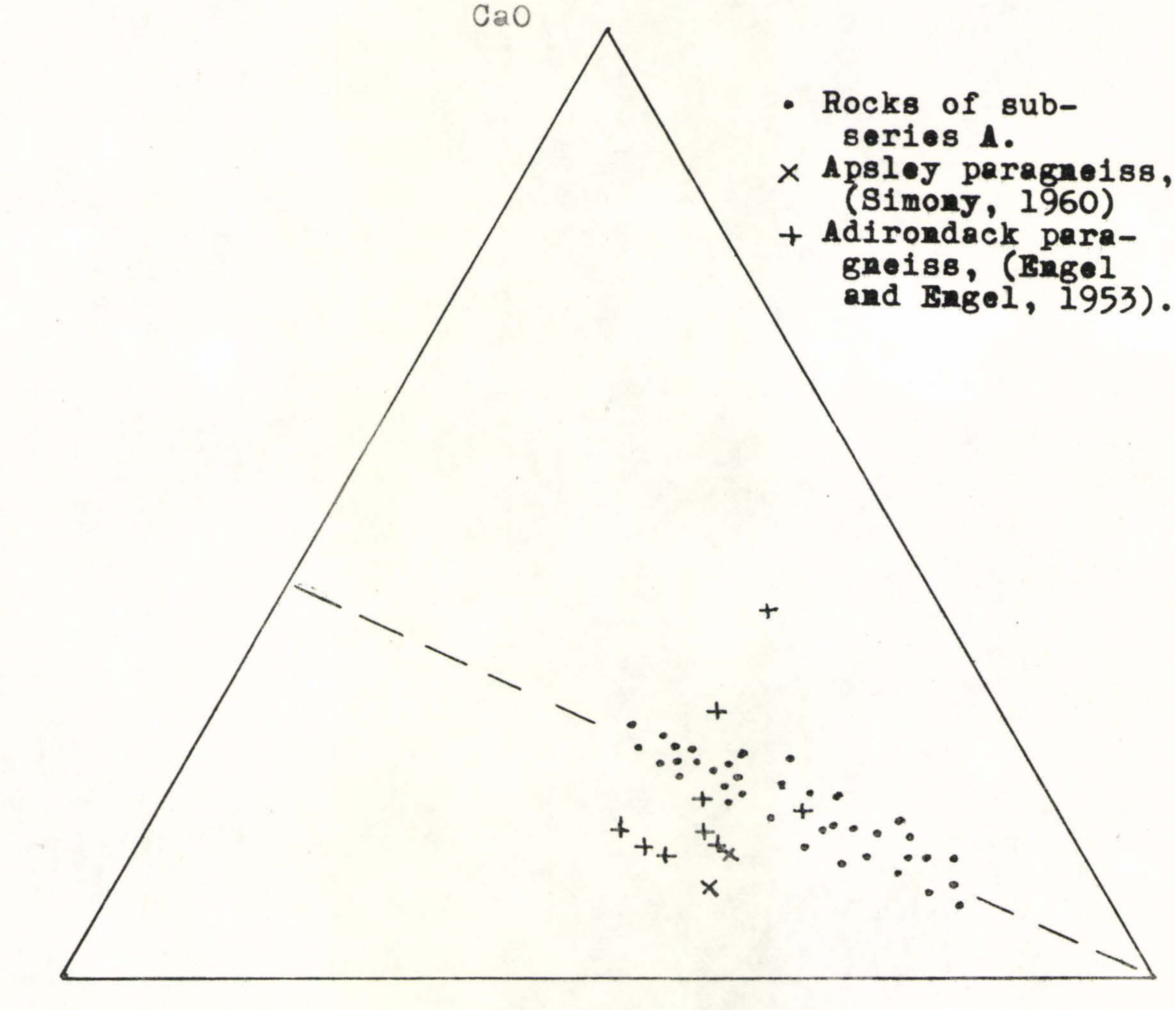
6.1.2 The addition hypothesis

The rocks of sub-series A may have arisen by the mixing of end members. Nockolds (1934), amongst others, has found much geological evidence that suggests that the interaction of acid magma with more basic rock can give products of intermediate composition.

Solid-solid interaction between silicates is too slow to give appreciable products in a reasonable time, (see Section 1.3.2). Therefore, two possibilities remain - interaction of two fluids, or of a fluid and a solid. Imperfect or arrested reaction could thus explain the bimodal frequency distribution of Sub-series A shown in Figure 6.1.

Field evidence that part of the sub-series was once fluid, is available only for the more acid rocks:

FIGURE 6.4. SUB-SERIES A (MOLECULAR PROPORTIONS). Note the near-constant CaO/FeO+MgO ratio of the Glamorgan rocks, compared with the scatter of some Grenville paragneisses.



1. Grey unfoliated granite of igneous aspect is found on the south shore of Bark Lake, containing inclusions that would here be interpreted as xenoliths;

2. A dike of grey granite cuts paragneiss on the south side of Bluehawk Lake; and

3. A grey granitoid sill, with a skarn reaction rim, occurs in marble in a roadcut just north of Tory Hill.

The question that now arises is - was the fluid phase a silicate melt or an aqueous rich, silicate-bearing solution (which,for convenience,we may call a vapour)?

It is not clear how a viscous magma could intrude country rock intimately enough to form migmatite. It is equally unclear how a vapour could give rise to a grey granite mass and to granite lenses within the migmatite. Some compromise is therefore needed, and an obvious one would have the larger bodies of granite formed from melt that was in equilibrium with a vapour capable of pervading the surrounding gneiss.

One very important feature of the rocks of Series A, however, cannot be explained on the basis of this hypothesis. It is that the rocks that have the typical paragneiss assemblage (quartz-plagioclase-biotite) of the Grenville series are intermediate members of Sub-series A. Two analyses are available for this rock type (Samples E12 and G11, Table 2.3), and Sample E12 contains typical paragneiss accessory minerals, calcite and graphite. In other words, what appears to be least altered paragneiss lies in the middle of the series and not at one end as an addition hypothesis would demand.

6.1.3 The subtraction hypothesis

A final hypothesis is that Sub-series A may have formed by the segregation of an acid fraction from paragneiss, leaving behind a more basic residuum. The two maxima of Sub-series A shown in Figure 6.1 could correspond to the residuum and the mobilisate (extracted matter) respectively. The two maxima would also indicate a fairly good separation of the two components from the original material.

A major complication avoided by this hypothesis is the so-called "room problem" since no new material need by introduced.

Geological literature contains reference to two general types of segregation processes, namely metamorphic differentiation and anatexis.

Metamorphic differentiation collectively covers various processes (Turner and Verhoogen, 1960, p. 581) that:

> "bring about a segregation of certain minerals into lenses and bands, thereby producing chemical segregation on a small scale, (Mason, 1952, p. 214).

To explain the characteristics of the Glamorgan rocks on the basis of this process is to explain one mystery in terms of another. Metamorphic differentiation is very poorly understood (White, 1966), and opinion is sharply divided on whether it should be considered an essentially chemical phenomenon (Eskola, 1932) or a mechanical one (Sclar, 1965). In any case, it has never been proposed as a mode of origin for anything other than narrow folia and lenses in metamorphic gneisses. Large lenses and bodies of granite, such as are found in Glamorgan township, need an alternative explanation. Thus, anatexis seems a more fruitful line of inquiry.

Anatexis is the process of differential fusion by which magma is produced from solid rock within the earth. In order to test the applicability of this process to Sub-series A, we must look for representatives of parental, pre-anatectic rocks, for igneous rocks formed by solidification of the presumed anatectic melt, and for rocks that represent the infusible residuum of this process.

A prerequisite of parental rocks is that they should have a composition intermediate in Sub-series A, so that extraction of a melt to leave an infusible residuum would generate the approximately linear chemical gradation of Figure 6.2. The fact that apparently least altered paragneiss has an intermediate composition in Sub-series A was an important argument against an addition hypothesis, (Section 6.1.2). By contrast, it is an important point in favour of the subtraction hypothesis now being considered, and paragneiss can be taken as representative of the material that underwent anatexis.

The anatectite sweated out from the parental rock could only be the more acid part of Sub-series A since it is only for these rocks that there is field evidence for an igneous origin, (Section 6.1.2). It will be shown in section 7.1.2 that experimental evidence supports this conclusion.

Migmatite melanosome and quartz-plagioclase-hornblende inclusions in grey granite gneiss (Section 2.4.1) are explainable as residua of anatexis.

Partial melting can be considered to take place in a thermodynamically open system, involving as it does material transport of melt out of the parental rock. The technique of analysing natural open systems has been developed by Korzhinskii (1959) and Thompson (1957). An important aspect of such studies

> "should be a systematic analysis of the paragenetic relationships of the minerals," (Korzhinskii, 1964, p. 388).

Such a paragnetic analysis is useful in determining, as far as possible, to what extent equilibrium obtained in a natural system, and what the physico-chemical parameters of equilibrium were.

Sub-series A contains the following minerals in major proportions - quartz, plagioclase, microcline, biotite, hornblende, and magnetite. Sphene, apatite, zircon, pyrite, calcite, and graphite have been found as accessories.

The particular assemblages that occur in Sub-series A are as follows:

a) Quartz-Plagioclase-Biotite-Hornblende-Microcline-Magnetite[1] (assemblage found in migmatite melanosome, hornblende-paragneiss, and some grey granite gneiss);

b) Quartz-Plagioclase-Biotite-Magnetite (assemblage found in least altered paragneiss);

c) Quartz-Plagioclase-Biotite-Microcline-Magnetite (assemblage found in some grey granite gneiss and migmatite leucosome).

Bulk compositions in the rocks and, therefore, mineral assemblages can almost completely be expressed in terms of the following oxides: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, ZrO_2, P_2O_5, and H_2O.

---

[1] An assemblage designated in this way implies that the minerals listed have been found sharing grain boundaries and that these boundaries are not implicated or corroded. Equilibrium can thus be inferred, (Barker, 1964, p. 620).

In order to perform a graphical analysis of Sub-series A, it is necessary to identify the determining inert components, (Korzhinskii, 1959, p. 71). These are the extensive factors of equilibrium of the system, (Korzhinskii, 1963).

Following Korzhinskii (1959), TiO_2, P_2O_5 and ZrO_2 are classed as accessory components, and MnO and all trace elements as trace components. As such, they are assumed to have a negligible effect on equilibria amongst the major minerals.

If a number of components are "fully inert" (Korzhinskii, 1950, p. 52) in an open system, then their mutual ratios should remain constant throughout the system. In the Glamorgan rocks, this is sensibly so for MgO, FeO, and CaO (Figure 6.5), and approximately so for Al_2O_3 with respect to the ones mentioned, (Figure 6.4).

SiO_2 is an excess component since quartz is present in all assemblages. "It is clear that an increase in the amount of SiO_2 in a quartzose rock will be reflected in an increase or decrease of quartz, other things being equal, and the minerals present other than quartz are dependent on the relative amounts of components other than SiO_2," (Thompson, 1957). Similarly, $FeO{\cdot}Fe_2O_3$ is considered an excess component, (Korzhinskii, 1959, p. 107), magnetite being ubiquitous.

The remaining components are Na_2O, K_2O, and H_2O, and they all increase throughout Sub-series A with respect to those components considered inert. It is possible, therefore, that they can be considered "perfectly mobile," (Korzhinskii, 1959, p. 71). If so, they can be omitted from a graphical treatment of the assemblages since the chemical potentials of K_2O, Na_2O, and H_2O become externally controlled intensive parameters of the system, while the extensive parameters n_{K_2O},[1] n_{Na_2O}, and n_{H_2O} become dependent variables.

If this analysis is correct, then Sub-series A would have the following independently variable parameters of equilibrium:

Intensive variables - P_{total}, T, μ_{K_2O}, μ_{Na_2O}, μ_{H_2O}.

Extensive variables - n_{CaO}, n_{FeO}, n_{MgO}, $n_{Al_2O_3}$, n_{SiO_2}, and $n_{Fe_3O_4}$, the last two being present in excess.

It should, therefore, be possible to make a graphical description of the Glamorgan assemblages, containing no incompatibilities in terms of the composition tetrahedron CaO-FeO-MgO-Al_2O_3, (Figure 6.6).

On this diagram, the six phase tie figure,[2] Microcline-Biotite-Plagioclase-Hornblende-Quartz-Magnetite, is bound by four five-phase tie figures:

Hornblende-Plagioclase-Biotite
Hornblende-Plagioclase-Microcline
Plagioclase-Microcline-Biotite
Microcline-Biotite-Hornblende
} - Quartz-Magnetite

and by six four-phase tie figures:

---

[1] n is the number of moles. The early mobility of H_2O in metamorphic processes is attested to by most petrologists, and is implicit in the use of ACF and AKF diagrams. The mobility of Na_2O and K_2O in katazonal petrogenesis is stressed by Korzhinskii (1950) and by Engel and Engel (1960).

[2] This projects as a four-phase tetrahedron in the diagram, the two phases quartz and magnetite, being in excess.

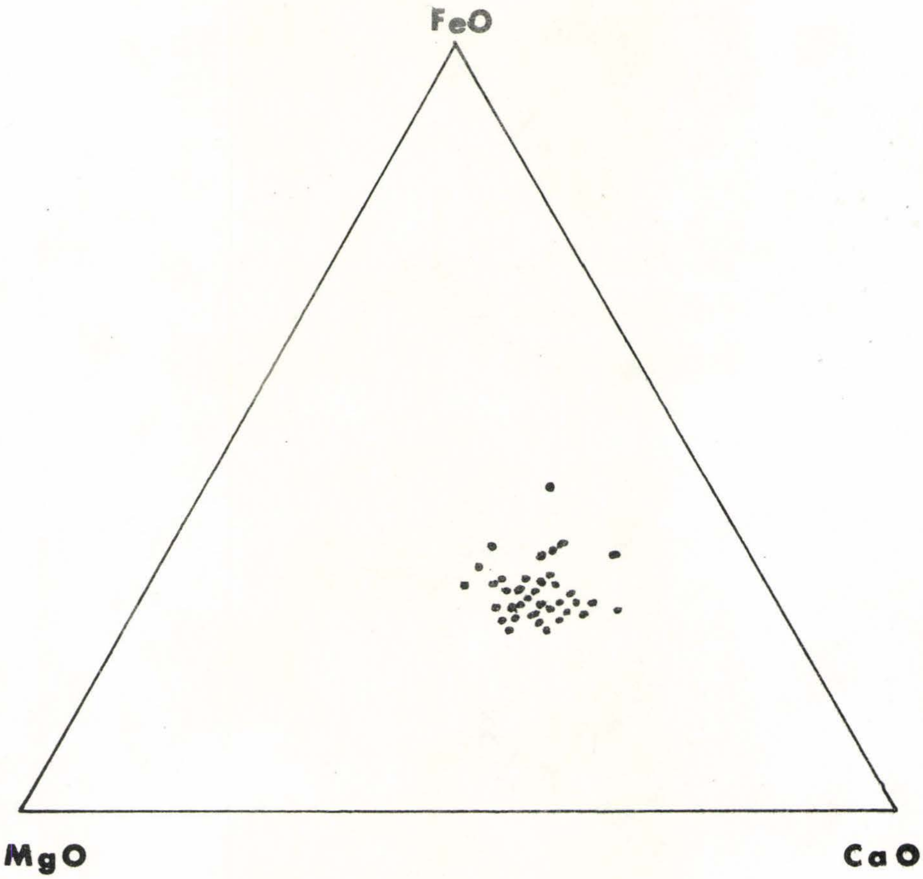


FIGURE 6.5. ROCKS OF SUB-SERIES A (MOLECULAR PROPORTIONS).

FIGURE 6.6. SUB-SERIES A MOLECULAR PROPORTIONS PLOTTED IN THE PARAGENESIS TETRAHEDRON $CaO-FeO-MgO-Al_2O_3$

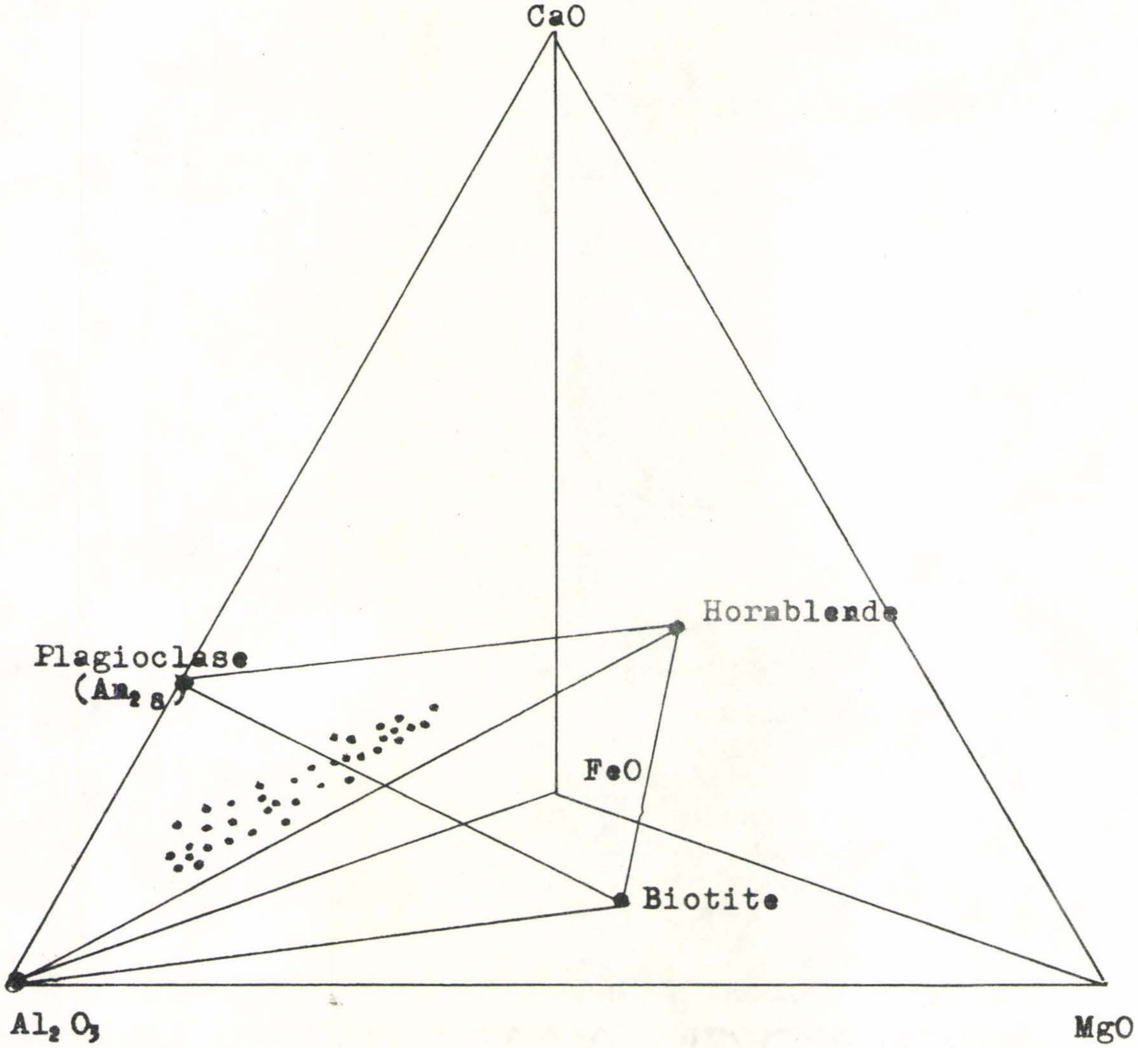
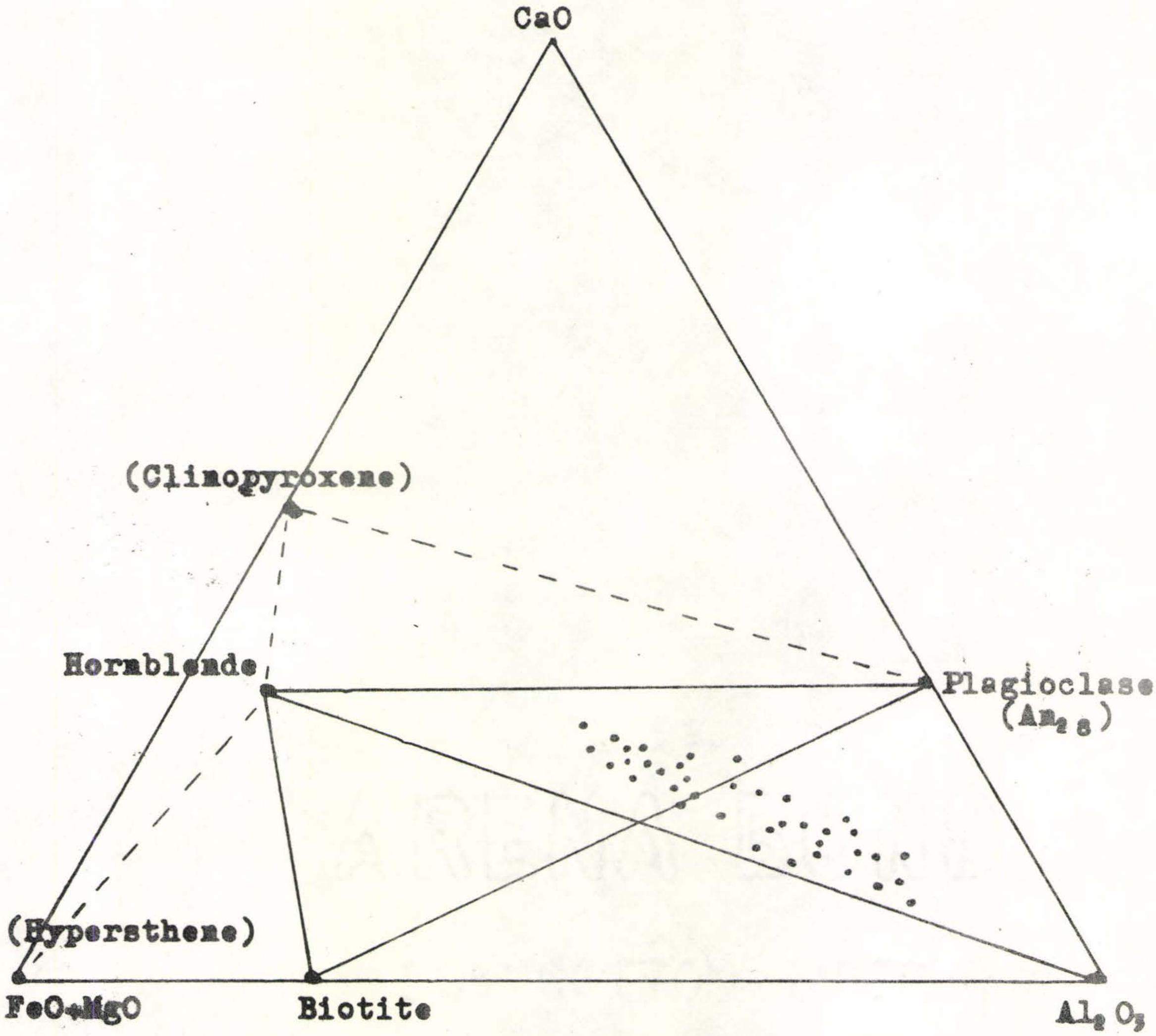


FIGURE 6.7. PROJECTION OF FIGURE 6.6.



Hornblende-Plagioclase
Hornblende-Biotite
Hornblende-Microcline } - Quartz-Magnetite
Microcline-Biotite
Plagioclase-Biotite

Of special interest to the present study are the assemblages found in Sub-series A:

Microcline-Hornblende-Biotite-Plagioclase-Quartz-Magnetite

Biotite-Plagioclase-Quartz-Magnetite

Microcline-Biotite-Plagioclase-Quartz-Magnetite

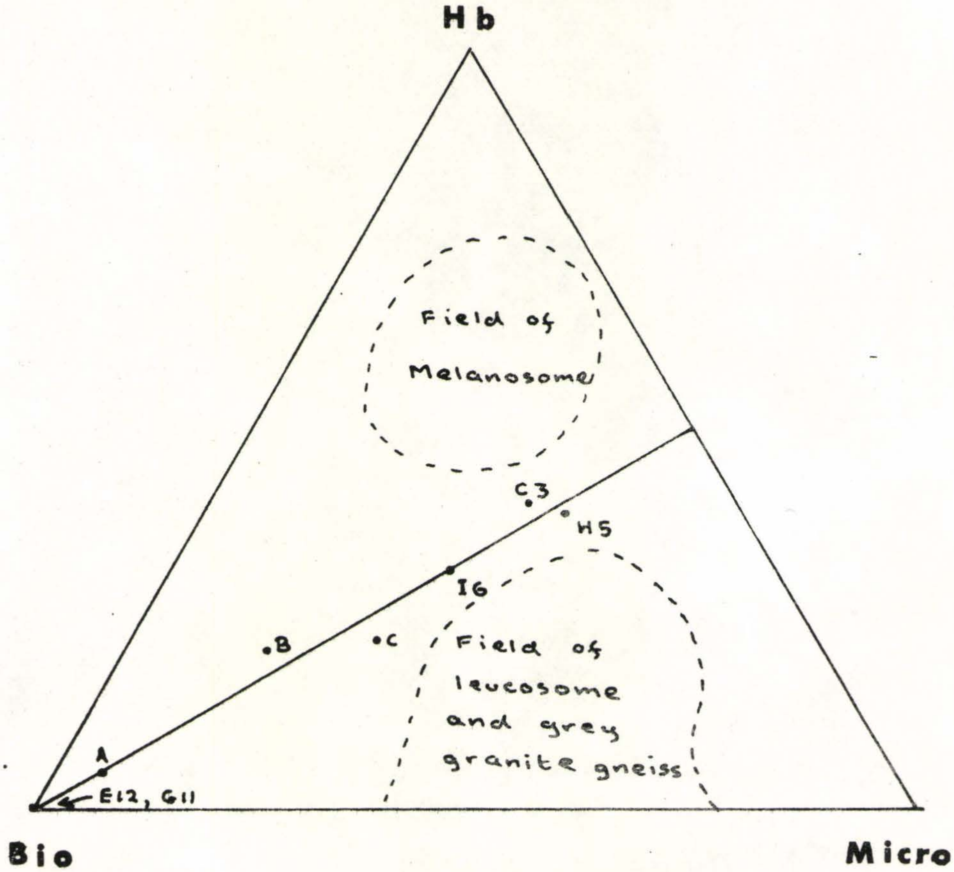
The interrelationship of these assemblages is not readily seen in the tetrahedron, so a Schreinemakers' projection has been made, (Figure 6.7). This is very similar to the diagram used by Korzhinskii (1959, Figure 77), to depict granitoid parageneses. However, Korzhinskii's plot did not predict a field of stability for the assemblage, Microcline-Hornblende-Biotite-Plagioclase-Quartz-Magnetite, which, under the conditions studied by him, would be a univariant reaction assemblage and, therefore, one unlikely to be encountered under arbitrary petrological conditions. In the present case, this problem is circumvented by considering FeO and MgO as separate components in contrast to Korzhinskii (1959, p. 107) who considers them to constitute a single (isomorphous) component.

This diagram is qualitatively consistent with the Glamorgan parageneses in that it depicts the assemblages found in nature, and in that it predicts a decrease in hornblende and concomitant increase in microcline in going from one end of Sub-series A to the other.

Inconsistencies arise in regard to rocks of intermediate (paragneissic) composition. For example, the assemblage of least-altered paragneiss is not topologically intermediate in Figure 6.6, but is along one edge of the tie figure (the line plagioclase-biotite). Furthermore, considering paragneiss and hornblende-paragneiss together, we find a positive correlation between microcline and hornblende and a negative one between these minerals and biotite (Figure 6.8). These difficulties disappear if we ignore the least-altered assemblage and consider it to be relict. The hornblende-paragneiss could then be produced from least-altered rock by a reaction involving breakdown of biotite and formation of hornblende and microcline shown schematically in Figure 6.9.

According to this interpretation, the quartz-plagioclase-biotite assemblage would be older than the hornblende-microcline-quartz-plagioclase-biotite one. This, of course, is implicit in the recognition of the former as being least-altered paragneiss, and such recognition was based on its occurrence farthest removed from granite and migmatite. Where the rock becomes incipiently banded with granite, the hornblende-paragneiss assemblage appears and, indeed, it is the characteristic assemblage (with different mineral proportions) of migmatite melanosome, which by the anatectic hypothesis is representative (together with leucosome) of highly altered paragneiss that it would, therefore, post-date.

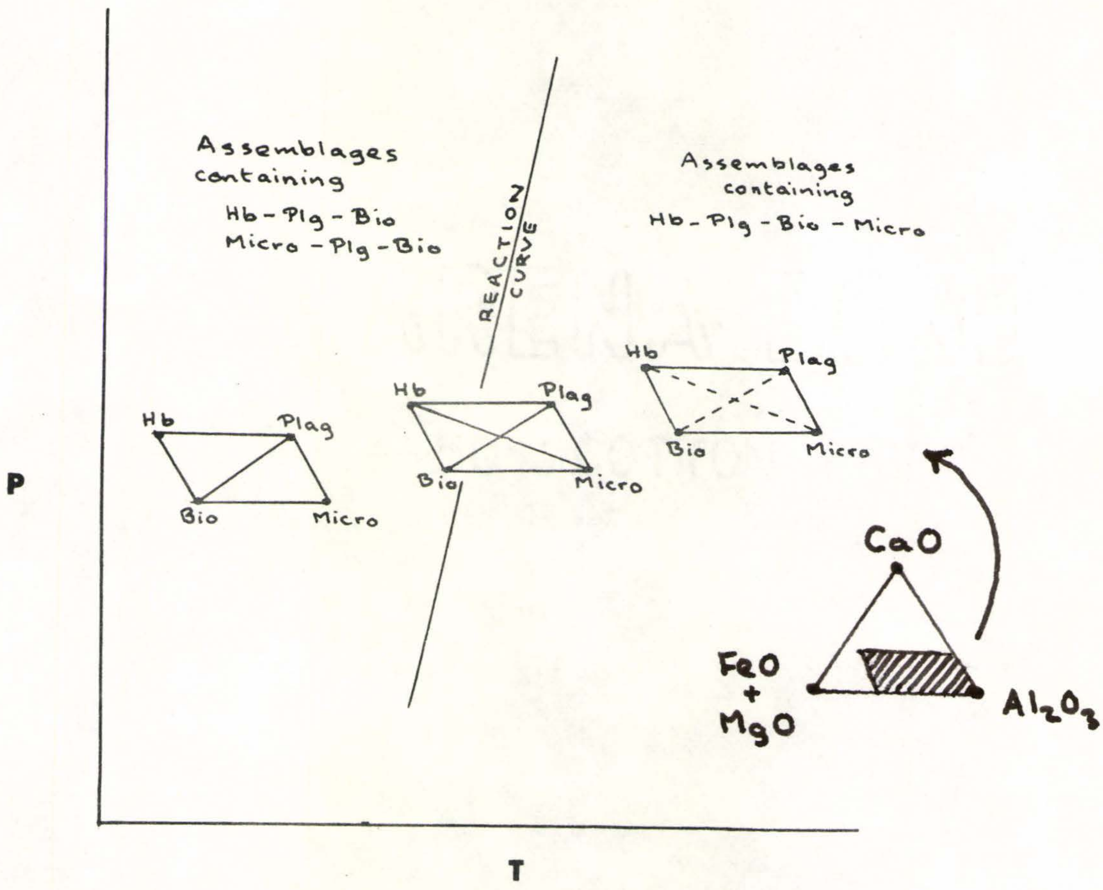
Some textural support of the hypothetical reaction relationship is provided by the fact that, in hornblende paragneiss, hornblende, biotite, and microcline cluster together commonly with attendant sphene. Calcite, which is present in least-altered paragneiss, is absent from



C3, E12, G11, H5 and I6 are rocks for which chemical analyses are available. A, B and C are paragneiss from the edges of the body from which samples E12 and G11 (least altered paragneiss) were taken.

FIGURE 6.8. THE POSITIVE CORRELATION OF HORNBLENDE AND MICROCLINE IN PARAGNEISS FROM GLAMORGAN TOWNSHIP.

FIGURE 6.9. A POSSIBLE SCHEMATIC PRESENTATION OF THE REACTION RELATION POSTULATED IN SECTION 6.1.3.



the more altered variety. It might be used up in the production of hornblende and to fix Ti produced in the breakdown of biotite, thus forming sphene.

From the paragenetic analysis, the reaction can only be written in the general form: Biotite + Plagioclase = Hornblende + Microcline ($\pm$) other reactants). It is interesting to note that this is very similar to the reverse direction (as written) of a reaction proposed by Ramberg (1952, p. 94):

$$3Ca_2\ (Mg,Fe)_4\ Al_xSi_yO_{22}\ (OH)_2 + K^+ + H_2O =$$

Hornblende

$$4K(Mg,Fe)_3\ Al_{x_2}\ Si_{y_2}\ O_{10}\ (OH)_2 + 6Ca^{2+}$$

Biotite

and virtually identical to the backward direction of a reaction proposed by Lambert (1963):

$$Ca_2\ (Mg,Fe)_3\ Al_2Si_6Al_2O_{22}(OH)_2 + KAlSi_3O_8 =$$

Hornblende Potash Feldspar

$$K(Mg,Fe)_3Si_3AlO_{10} + 2CaAl_2Si_2O_8 + 2SiO_2$$

Biotite Anorthite Quartz

Without analyses of the minerals of Sub-series A, it is impossible to write a balanced reaction consistent with the paragenetic analysis. The possibility of the reaction being of the dehydration sort is attractive in that the production of H_2O would facilitate partial melting.

6.1.4 Summary

Field and geochemical characteristics of Sub-series A are most easily explained by an anatectic hypothesis of origin. There is a distinct possibility that an early stage of anatexis involved the breakdown of biotite to produce microcline and hornblende. This would provide an assemblage containing quartz, plagioclase, and microcline with a comparatively low melting temperature (see next section). It is possible also that the breakdown of biotite might produce H_2O which could then act as a fluxing agent. This is not to deny the presence of H_2O from other sources such as higher grade rocks deeper in the crust.

6.2 PETROGENESIS OF THE PINK GRANITE GNEISS

Field evidence pointing to a magmatic origin for the pink granite gneiss includes:

a) the presence of inclusions in the gneiss,

b) the disruptive emplacement of granite lenses in migmatite, and

c) the occurrence of cross-cutting veins of granite in grey gneiss and migmatite, with the granite of the veins having a virtually identical composition to the pink gneiss.

A relation between the grey and the pink granite gneisses would seem to be indicated by the close regional association of the two rock types and by their structural association with each other and with migmatite. The possibility that the two rock types are not related is suggested by a scarcity of intermediate rocks giving rise to a bimodal frequency distribution, (Figure 5.9).

A resolution of this problem is attempted in the next section using the data of experimental petrology.

7. PETROGENESIS OF THE GLAMORGAN GNEISS SERIES IN THE LIGHT OF EXPERIMENTAL STUDIES

The prime object of experimental petrology is

> "to reproduce in the laboratory the conditions of formation of rocks by conducting experiments at the temperatures and pressures believed to exist at the depths where these minerals and rocks are formed," (Wyllie, 1966).

Towards this end the petrologist will either set up a simple analogue of a natural rock in terms of constituent oxides or mineral end members; or he will use as starting materials, the natural rocks themselves.

In this chapter the Glamorgan gneiss series is reviewed in the light of experimental studies in order to see to what extent the latter support the arguments of Chapter Six.

7.1 ORIGIN OF SUB-SERIES A

The original working hypotheses are examined in turn, to see if experimental findings bear out conclusions derived from geology and geochemistry.

7.1.1 The inheritance hypothesis

One of the possibilities under this heading, albeit remote, was that sub-series A was part of an igneous differentiation series with the Glamorgan gabbro as an end member. It was shown that the gabbro is of alkali type, and that alkali-type volcanic sequences commonly have undersaturated or saturated products as their acid end-members.

This point has been well demonstrated in the laboratory, (Schairer and Yoder, 1960). Analogues of the two principal basalt types (tholeiite and alkali basalt) are found to be separated by equilibrium thermal divides at high as well as at low pressure (Yoder and Tilley, 1962). No workable mechanism has been found whereby one basalt type might be derived from the other.

7.1.2 The addition hypothesis

The strong probability that granitic rocks of Glamorgan township formed from melt is reinforced by a comparison of the distribution of the rocks in the haplogranitic system, with the low melting region of that system as determined in the laboratory, (Figure 7.1).

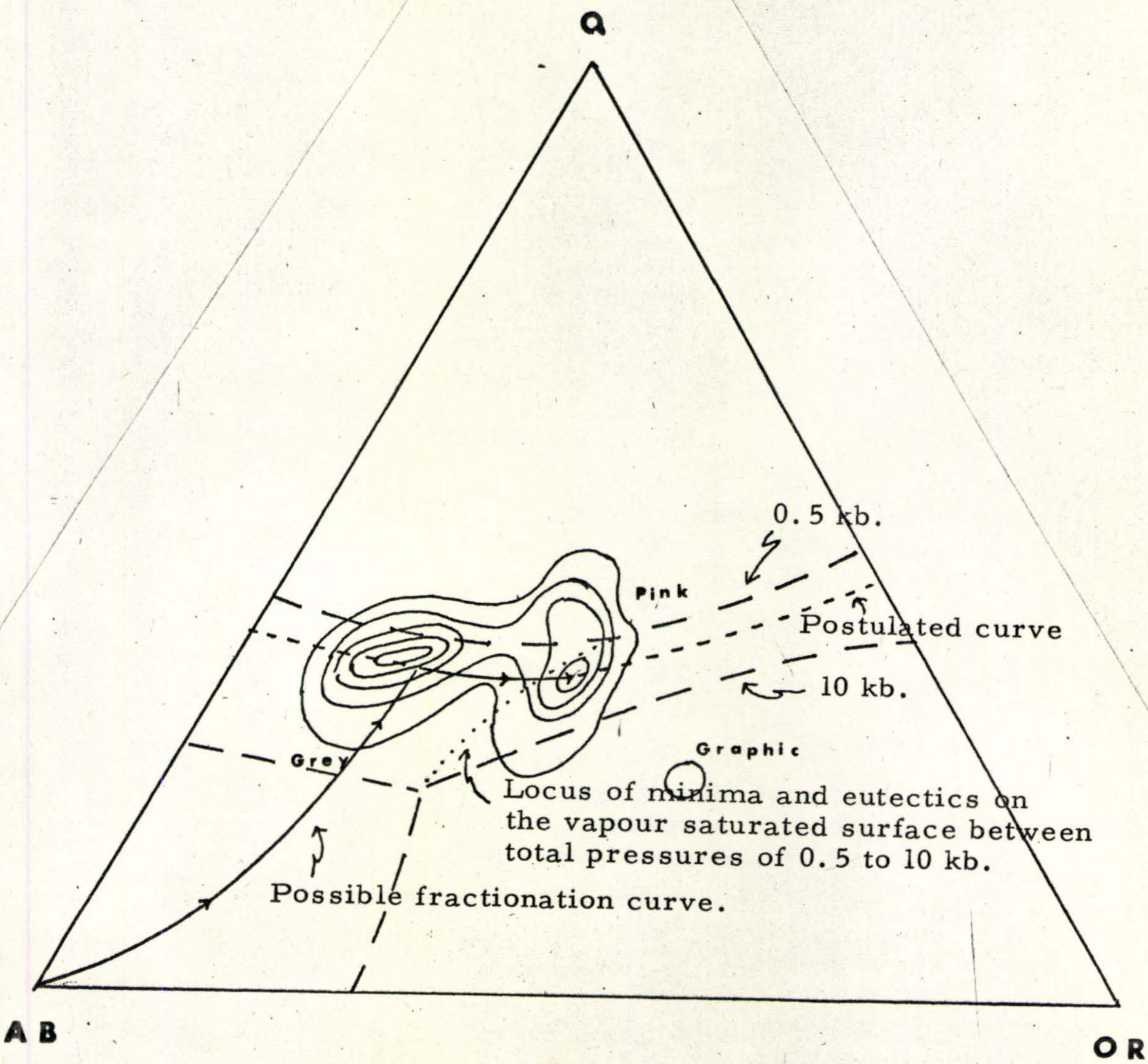
In terms of the hypothesis being considered here, the question that arises is how would an acid melt react with more basic rock? The key to this lies in one of the most useful generalisations of experimental petrology: the reaction principle. Bowen (1922) states:

> "a liquid saturated with a certain member of a reaction series is effectively supersaturated with all preceding members of that series."

In other words, if an acid magma is brought into contact with minerals high in a reaction series, it will tend to react in such a way as to convert them into phases with which it is in equilibrium. Thus in a group of rocks formed by a process of this sort, minerals high in a reaction series should show a negative correlation with minerals low in the series. Considering the minerals of sub-series A, we might predict:

FIGURE 7.1. RELATION OF THE GLAMORGAN GRANITES TO EXPERIMENTALLY STUDIED HAPLOGRANITIC SYSTEM.

The 500 bar and 10 kilobar boundary curves are projections from the vapour saturated surface. The postulated boundary curve is in the vapour absent region , which is experimentally unknown.



a. hornblende and biotite should be negatively correlated,

b. hornblende and biotite should both be negatively correlated with microcline, and

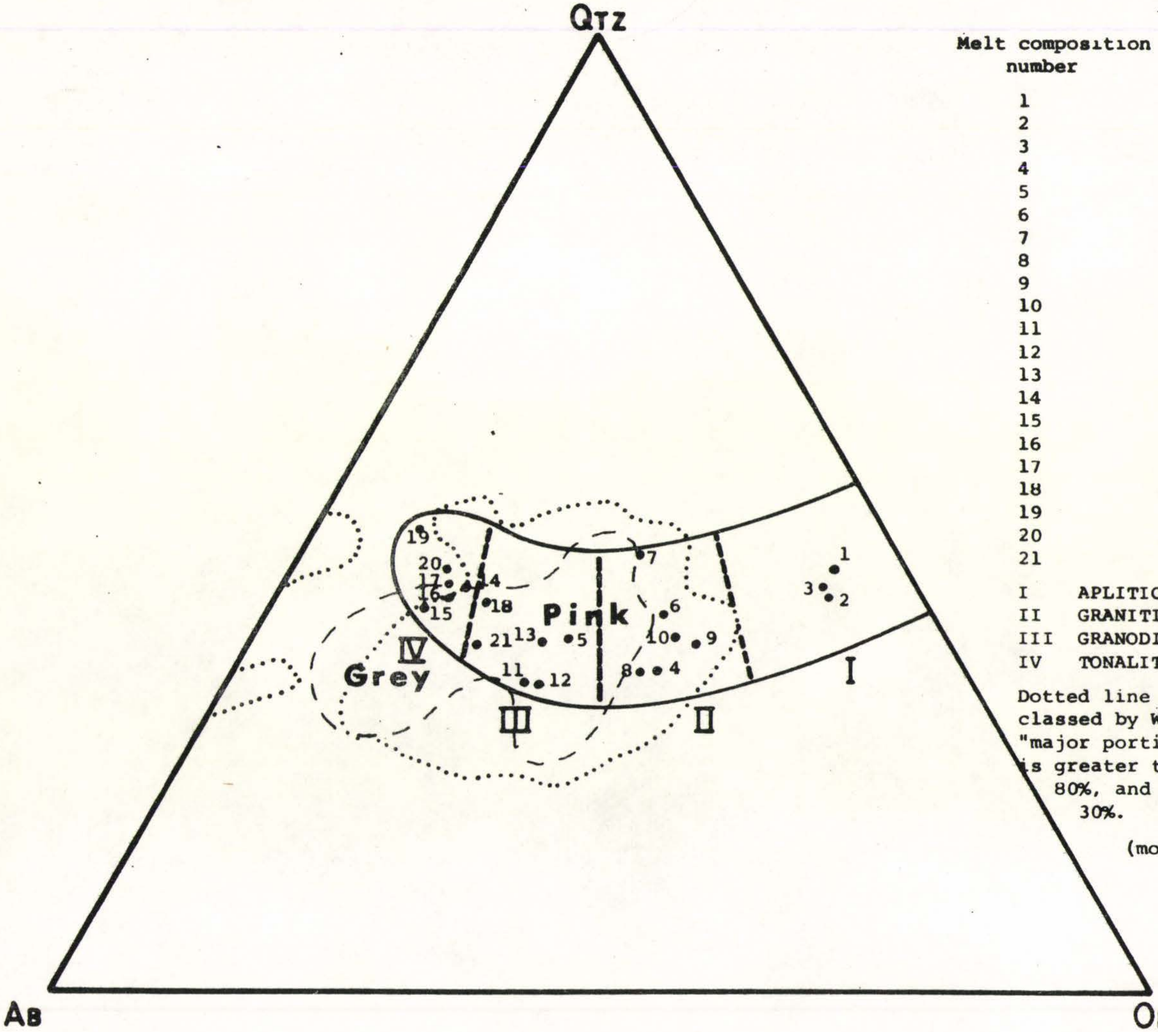
c. plagioclase should become more sodic.

In a gross way these generalisations hold good for the sub-series except, as we have seen for the paragneiss group of rocks (i.e., rocks in the middle of sub-series A) where microcline and hornblende are positively correlated with one another, and negatively correlated with biotite, (Figure 6.8). This phenomenon cannot be explained in terms of Bowen's two reaction series, though as we have seen, it is explainable as a metamorphic reaction prior to anatexis.

7.1.3 The subtraction hypothesis

The preferred hypothesis of the last chapter was one of anatexis. Hydrothermal experiments help to clarify the reason why the sweated-out melt should have a trondjhemitic rather than an ideal granitic composition. The composition of ideal granite (Mehnert, 1959), being so defined does indeed represent the composition of lowest temperature melts in granitoid systems. However the lowest temperature melts only form in the haplogranitic system quartz-albite-potash feldspar-H_2O. In most natural systems albite is bound up in the plagioclase structure, which has a profound effect on the composition of the first melt, (von Platen, 1965).

It is interesting to note that the initial melt obtained from greywacke, may have a granodioritic rather than "ideal" granitic composition, (Winkler and von Platen 1961). Figure 7.2 illustrates this point and allows



Melt composition number	Temperature of melt formation	Starting material
1	725	Clay A
2	735	Clay B
3	725	Clay C
4	675	Clay + 3.2% NaCl
5	765	Clay + 3.2% NaCl
6	725	Clay + 1.8% NaCl
7	745	Clay + 1.8% NaCl
8	810	Clay + 3% NaCl+5% $CaCO_3$
9	810	Clay + 3% NaCl+8% $CaCO_3$
10	810	Clay + 3% NaCl+15%$CaCO_3$
11	810	Clay + 6% NaCl+5% $CaCO_3$
12	810	Clay + 6% NaCl+8% $CaCO_3$
13	810	Clay + 6% NaCl+15%$CaCO_3$
14	780	Graywacke Gr.St.IV/25
15	780	Graywacke Bicken
16	780	Graywacke O. K I/33
17	780	Graywacke Gr.St. IV/29
18	780	Graywacke Schmittlotheim
19	780	Graywacke Strassberg 3b
20	780	Graywacke Gr.St. IV/16
21	780	Graywacke Strassberg 1d

I APLITIC MELTS
II GRANITIC MELTS
III GRANODIORITIC MELTS
IV TONALITIC MELTS

Dotted line encloses 86% of 1190 rock compositions classed by Washington,(1917) as containing a "major portion" of quartz, i.e. normative quartz is greater than 20%, Ab+Qtz+An is greater than 80%, and The plagioclase An content is less than 30%.

(modified from Winkler and Von Platen,1961)

FIGURE 7.2. COMPOSITION OF GLAMORGAN GRANITOID ROCKS COMPARED WITH SOME EXPERIMENTALLY PRODUCED MELTS.

a comparison between granitoid rocks of Glamorgan township and some ~~exp~~ experimentally produced melts. It can be seen that the composition of grey granite and equivalent leucosome is consistent with a derivation by partial melting of a rock with a comparatively high Na_2O/K_2O ratio, such as greywacke.

7.2 ORIGIN OF SUB-SERIES B

Experimental intimations that the pink granites of Glamorgan township are also magmatic in origin have already been recognized, (Figure 7.1). It is possible that these rocks are unrelated to the grey granites, and formed by partial melting of a different starting material, for example, an argillite, (Figure 7.2). However the sampling program failed to reveal any vestige of this hypothetical parental rock, though as we have seen, it did so for granites of sub-series A. It seems more likely that the intimate field association of both granitic types reflects an underlying genetic relationship. Hopefully, experimental studies will help to decide what processes are possible and what are impossible, in deriving one granite from the other. One important aspect of the granites requiring an explanation, is the bimodal distribution of the analyses in the haplo-granitic system (Figure 5.9).

Three processes that could be proposed are:

a. liquid-vapour equilibrium,

b. degassing of a melt,

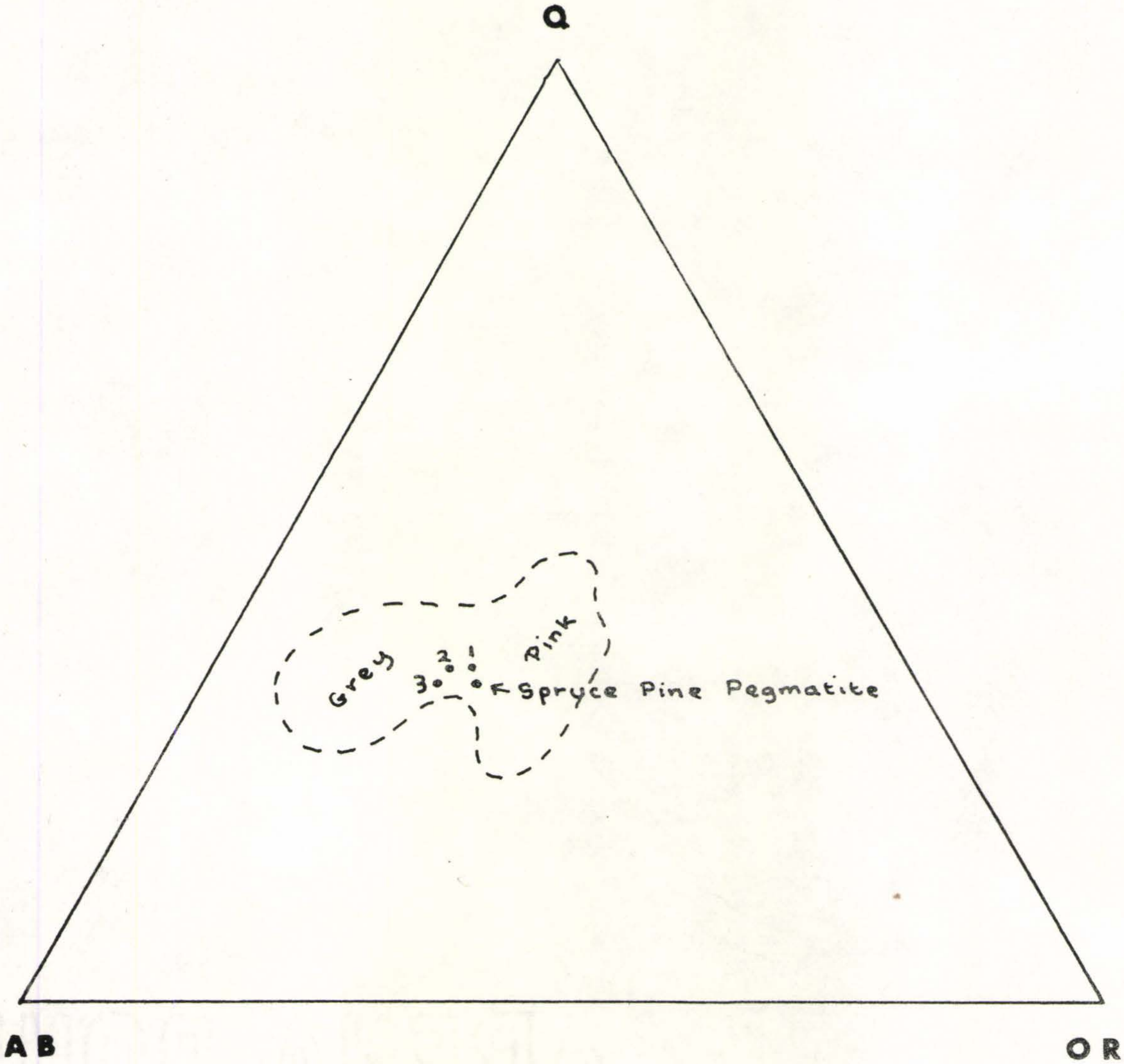
c. crystallization differentiation.

Burnham has shown (Chapter One) that the vapour phase coexisting with a granite melt may have a solid content of albitic granite composition at high pressures. It could therefore be suggested that the more albitic grey granite could represent the vapour phase in equilibrium with more potassium rich melt (Figure 7.3). Two facts militate against this. Firstly, the pink granite is younger than the grey, and secondly the grey granite has a higher CaO content than the pink. This would require that CaO be preferrentially removed from the liquid by the vapour, a situation that does not hold experimentally (Burnham, in press). Furthermore much of the potash feldspar in the pink granite is markedly perthitic, a fact that could indicate a low activity of H_2O in the original melt, (Bowen and Tuttle, 1958). In addition, the large extent of the grey granite gneiss, would require a very large amount of vapour since the solid content of the vapour phase in Burnham's experiments was just over 10 per cent at the most, and since water saturated granite melt contains about 10 per cent of H_2O at katazonal depths (Hamilton et al, 1964), a consequently larger amount of pink granite might be expected. In any case it is unreasonable to expect more than a small volume of water saturated melt, deep in the crust, simply because there is not enough water available to saturate large volumes.

Luth, Jahns, and Tuttle (1964) claim that granites formed from water saturated melts plot closer to the quartz-albite sideline of the synthetic system, than those produced from water poor melts. Accordingly, the more potassic granites might have developed from the more sodic by a process of degassing, a necessary condition being that the vapour phase should have a higher Na_2O/K_2O ratio than the melt from which it formed. However if the grey granite magma lacked superheat (as it must if formed anatectically in place), degassing would simply cause solidification by rapidly raising the solidus.

FIGURE 7.3. COMPOSITION OF GLAMORGAN GRANITES COMPARED WITH THAT OF A GRANITIC VAPOUR PHASE.

Note that two measurements have a more sodic composition than the starting material.



1, 2 and 3 are the compositions of the vapour phase in equilibrium with Spruce Pine pegmatite for the conditions 7.8 kb. 700°C, 9.8 kb. 600°C, and 10 kb. 650°C respectively, (Burnham, in press).

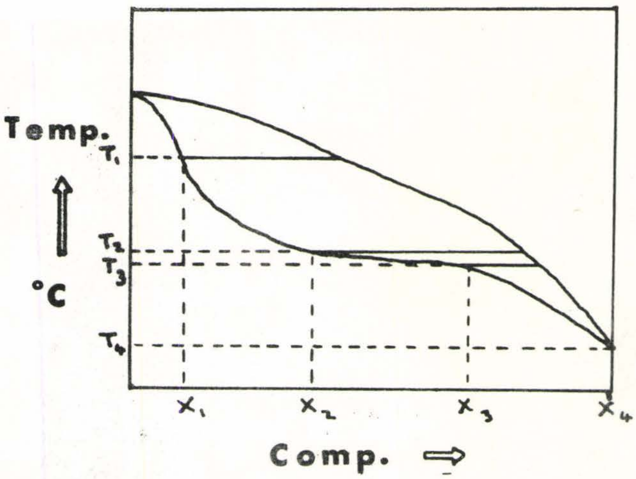
Finally crystallization differentiation could indeed produce all the granites, the pink variety being the later differentiates. A possible fractionation curve is shown in Figure 7.1. It is impossible to be more precise because available experimental work only pertains to the H_2O saturated surface in the haplogranitic system. At first glance, it seems unlikely that fractionation of this kind would give rise to two separable populations of granite. On the contrary, a continuous series of rocks might be expected to form. However the configuration of the solidus has a very direct bearing on the nature of derived products. For example a temperature plateau on a solidus could cause the separation of material from a higher and from that formed at a lower differentiation temperature by fractional crystallization (see, for example, Wyllie, 1963). Recent experiments confirm the existence of such a plateau on the granitoid "solidus," (figure 7.4), unpublished data of Piwinskii).

The conclusion therefore, is that the derivation of pink granite by the fractionation of grey granite magma is quite possible. Experiment indicates that the process is a feasible one.

The origin of a very potassium rich fluid, capable of forming graphic granite and pegmatite is more problematical. Graphic granite is associated with pink granite gneiss in the eastern half of Glamorgan township, and some of the gneiss has a high quartz content (both modal and normative). The high silica and high potassium rocks could represent fractions of a more ideal (in Mehnert's sense) granite. Jahns and Tuttle (1963) have suggested such for adjacent potassic and aplitic zones of certain pegmatites. In this case the authors believed the process of formation to have been an equilibrium one, and that the potassium rich

FIGURE 7.4.

A. ISOBARIC POLYTHERMAL SECTION OF HYPOTHETICAL SYSTEM WITH A PLATEAU ON THE SOLIDUS.



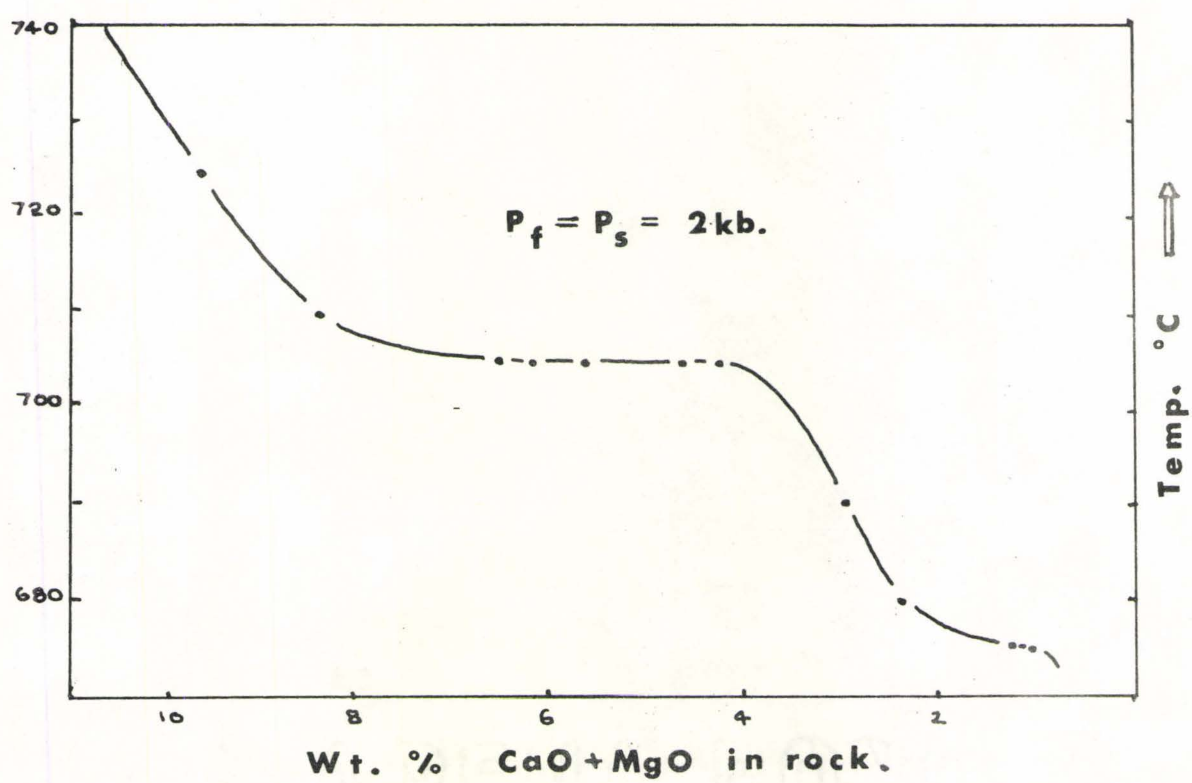
T_1 to T_2 solids X_1 to X_2 crystallise.

T_2 to T_3 an almost discontinuous jump to X_3

T_3 to T_4 solids X_3 to X_4 crystallise.

Two contrasted compositions arise by fractional crystallisation - X_1 to X_2 and X_3 to X_4.

B. GRANITOID SOLIDUS DETERMINED FOR ROCKS OF THE WALLOWA PLUTON, OREGON, (PIWINSKII, UNPUBLISHED).



fraction might represent a vapour phase in equilibrium with aplitic melt. The equilibrium granite vapour phase has not, however, been found to be potassium rich.

A remaining possibility is that the potassium rich rocks formed as a result of cation exchange between potash and sodic feldspar crystals and a fluid phase capable of transporting alkalies, (Orville, 1962). It is known from laboratory study that a temperature gradient in a system of this kind could lead to the depletion of potash feldspar in a high temperature region and its enrichment at lower temperatures. The graphic granite and the pegmatites may thus have formed in the low temperature end of a system of this kind.

8. METAMORPHISM

Two methods will be used here to describe the metamorphism in Glamorgan township. Initially, the approach will be in terms of a mineral facies. Later, an attempt will be made to put quantitative limits on the conditions of metamorphism in the light of experimental results.

8.1 THE MINERAL FACIES APPROACH

Examination of the mineral assemblages in Glamorgan township and its immediate environs reveals the common association of hornblende with plagioclase. This is diagnostic of Eskola's amphibolite facies, (Eskola, 1939). Table 8.1 is a list of assemblages from this region and Figure 8.1 shows appropriate ACF and AKF diagrams.

The Haliburton-Hastings Highlands region (of which Glamorgan township forms a part) is classified as upper almandine-amphibolite facies, (Lumbers, 1964). The latter is marked by the appearance of sillimanite in the high grade zone of Figure 1.2, (Satterly, 1956; Hewitt, 1957; Best 1966). Elsewhere, in lower grade parts of Figure 1.2, kyanite (Smith, 1958) and andalusite (Lumbers, unpublished) are found.

Current ideas concerning the nature of the amphibolite facies are in a somewhat confused state, (Fyfe and Turner, 1966, pp. 358-359). Fyfe, Turner, and Verhoogen (1958) following Francis (1956) erected three subfacies:

TABLE 8.1

ASSEMBLAGES FOUND IN GLAMORGAN TOWNSHIP:

Rock Type	Characteristic Mineral Assemblage
Basic igneous (Foye, 1916a)	Hornblende - plagioclase - augite - biotite
	Hornblende - plagioclase - augite - scapolite
	Hornblende - plagioclase - augite
	Hornblende - scapolite - augite - calcite
Granitoid	Quartz - microcline - plagioclase - biotite (muscovite)
	Quartz - microcline - biotite - plagioclase - hornblende
	Quartz - microcline - plagioclase (Magnetite is ubiquitous)
Migmatite melanosome	Quartz - plagioclase - biotite - hornblende - microcline
Paragneiss	Quartz - plagioclase - biotite
	Quartz - plagioclase - biotite - hornblende - microcline, (locally almandine and epidote, p. 22)
Calcareous	Calcite - diopside - phlogopite
	Calcite - diopside - scapolite
	Calcite - diopside - hematite
	Calcite - diopside - spinel
	Calcite - chondrodite - phlogopite - tremolite
	Calcite - diopside - hornblende
	Calcite - diopside - grossularite
	Calcite - diopside - gross.- plagioclase - epidote

TABLE 8.1

(Continued)

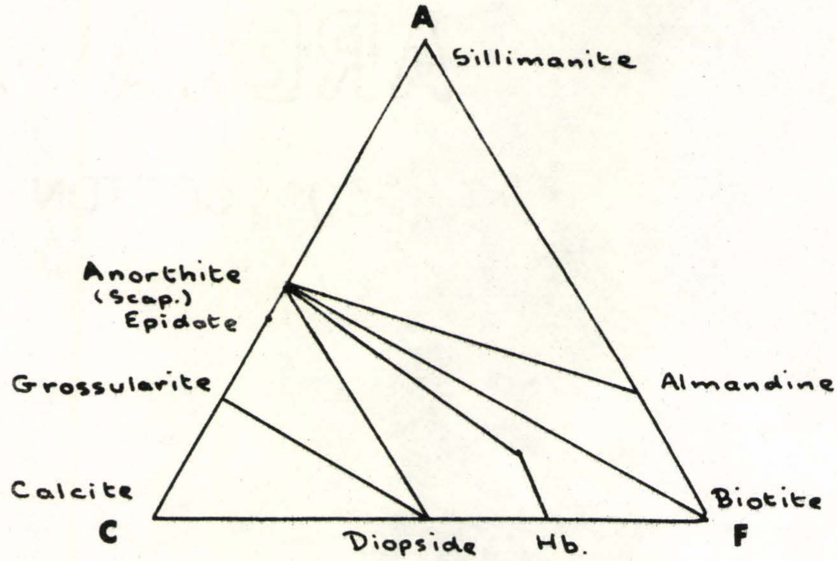
Rock Type	Characteristic Mineral Assemblage
	Calcite - hornblende - plagioclase (quartz)
	Calcite - plagioclase - hornblende - gross - - epidote
Calc - silicate	Diopside - tremolite
	Diopside - tremolite - phlogopite
	Diopside - scapolite

PSAMMO-PELITIC ASSEMBLAGES FROM ADJACENT PARTS OF THE HALIBURTON HIGHLANDS (Hewitt, 1957).

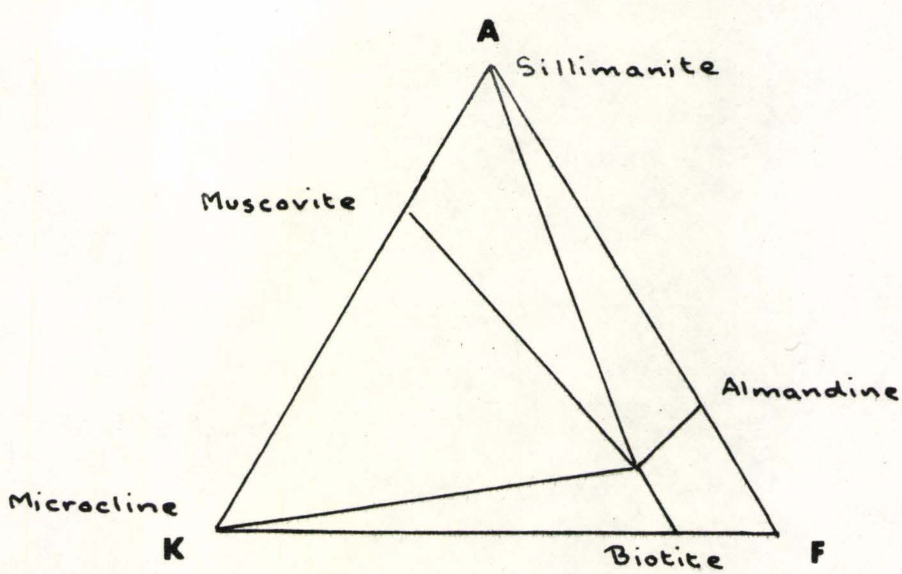
Sillimanite - garnet - biotite - quartz - plagioclase.

Sillimanite - microcline - biotite - quartz - plagioclase (±hornblende)

FIGURE 8.1. GENERALISED ACF AND AKF DIAGRAMS FOR ASSEMBLAGES FROM GLAMORGAN TOWNSHIP AND ITS ENVIRONS.



Quartz and microcline are additional phases.



Quartz is an additional phase.

1. Staurolite-quartz,
2. Kyanite-muscovite-quartz, and
3. Sillimanite-almandine.

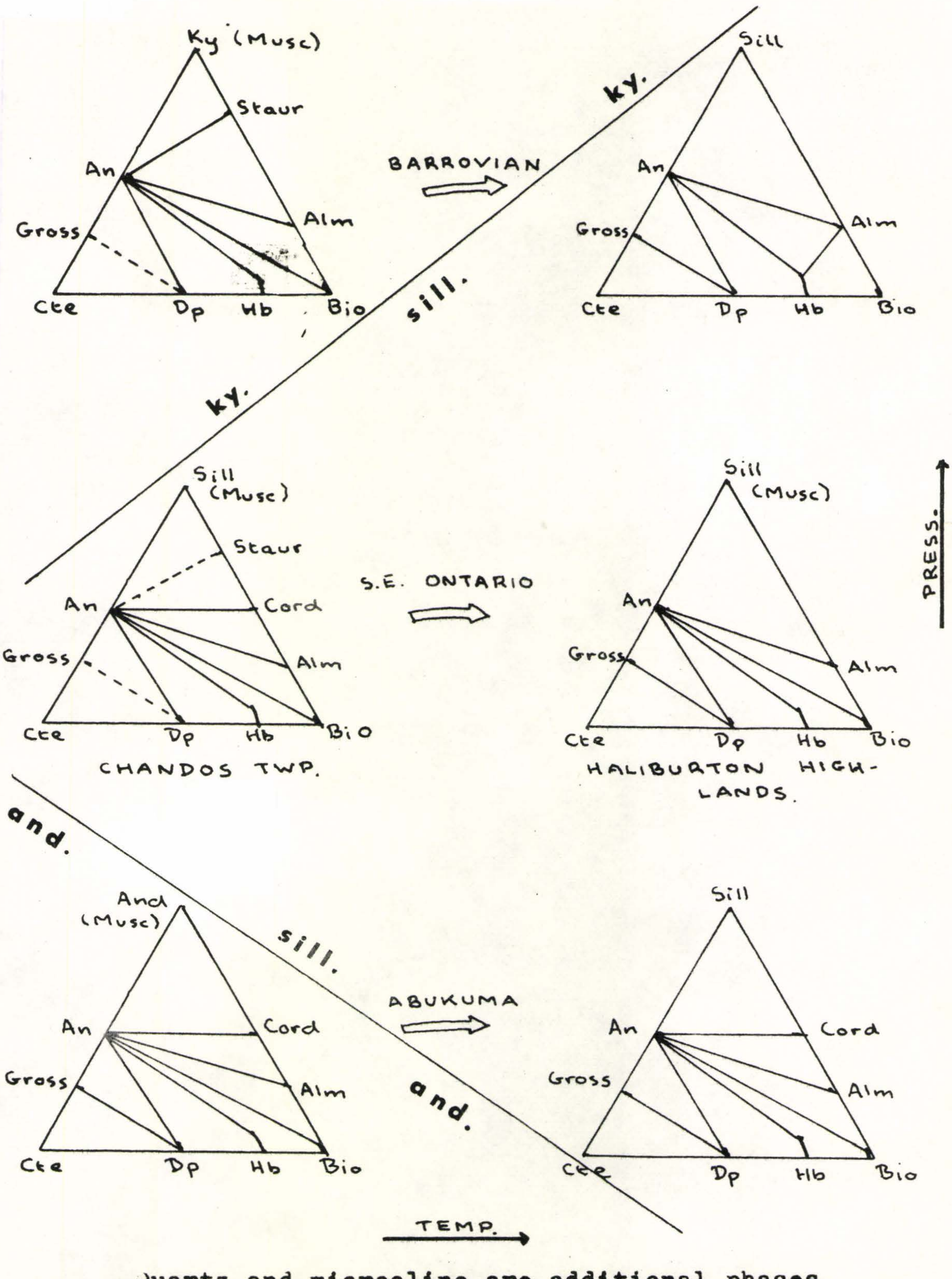
Later, the nomenclature was modified and a fourth subfacies (sillimanite-almandine-muscovite) was added between 2 and 3 above, (Turner and Verhoogen, 1960).

The recognition of different facies series in different terrains led Miyashiro (1958, 1962) to doubt the general applicability of the foregoing divisions, and to point out that they were only strictly applicable to Barrovian-type metamorphism. In fact, the fourth subfacies is not found in the Barrovian sequence, but is widely represented in the United States and is "believed to have formed at lower pressures," (Turner and Verhoogen, 1960, p. 545).

To account for regional variability, Miyashiro (1962) proposed five general types of facies series which he interpreted semi-quantitatively in terms of load pressure and temperature. Troger (1963) delimited twelve types, but in doing so, diminished the general applicability of the method.

In the present context, it is instructive to compare the Haliburton Highland's assemblages with the Barrovian ones. An overall similarity is apparent, but two points of difference stick out. Sillimanite and muscovite are incompatible in the Barrovian sequence and almandine co-exists with hornblende in quartz-bearing rocks. The opposite is true in the Haliburton Highlands. These points of difference between the Grenville assemblages and Barrovian ones are points of resemblance between the former and assemblages found at Abukuma, (Miyashiro, 1958).

FIGURE 8.2. AMPHIBOLITE FACIES IN SOUTH EAST ONTARIO COMPARED WITH THAT IN MIYASHIRO'S KYANITE-SILLIMANITE AND ANDALUSITE-SILLIMANITE TYPE AREAS.



Quartz and microcline are additional phases.

It, therefore, seems reasonable to suggest that the facies series of which the Glamorgan rocks are a part is of the low pressure intermediate type (as defined by Miyashiro, 1962) - between the kyanite-sillimanite (Barrovian) and the andalusite-sillimanite (Abukuma) types.

Two points can be made in support of this suggestion. First, all three polymorphs of Al_2SiO_5 are found in southeast Ontario, and secondly, both staurolite and cordierite have been recorded in Chandos township, (Shaw, 1962). According to Miyashiro (1962), both associations indicate metamorphism of the low-pressure intermediate type.

Shaw (1962) interprets the staurolite as relict so that the Chandos assemblages are at a slightly higher grade than the staurolite zone.[1] He claims the existence of a contact metamorphic aureole around the Loon Lake pluton, and this would indicate that the Chandos rocks are lower grade than those of the Highland region where contact metamorphism is unknown.

In conclusion, we can summarise the metamorphic state of the rocks in Glamorgan township and its environs in the following way:

a) The rocks are representative of the upper amphibolite facies, and

b) They are part of a low pressure intermediate facies series.

These conclusions form the basis of Figure 6.2.

8.2 EXPERIMENTAL EVIDENCE CONCERNING CONDITIONS OF METAMORPHISM

One of the objects of geochemistry is to relate field petrology with laboratory studies of mineral equilibria. Hopefully,

[1]Staurolite relicts in sillimanite zone rocks are common in the Dalradians, (Hinxman, *et al.*, 1914).

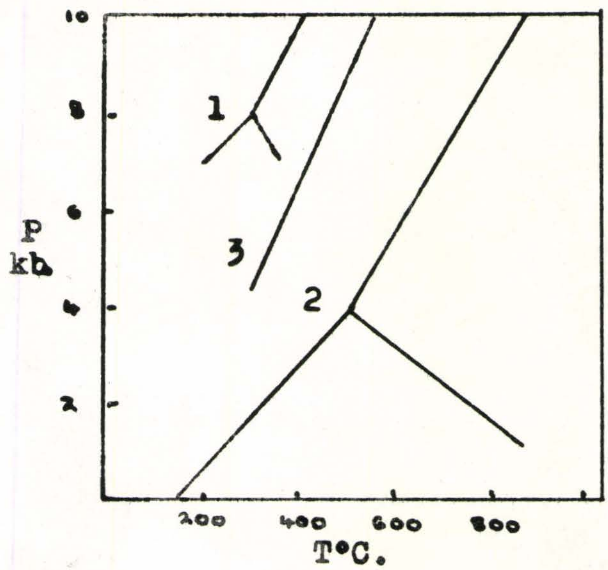


FIG. 8.3. SOLID-SOLID EQUILIBRIA.

1 Al_2SiO_5 triple point, (Bell, 1962).
2 Ditto, (Newton, 1965).
3 Ab + Neph = Jd (Robertson, 1957).

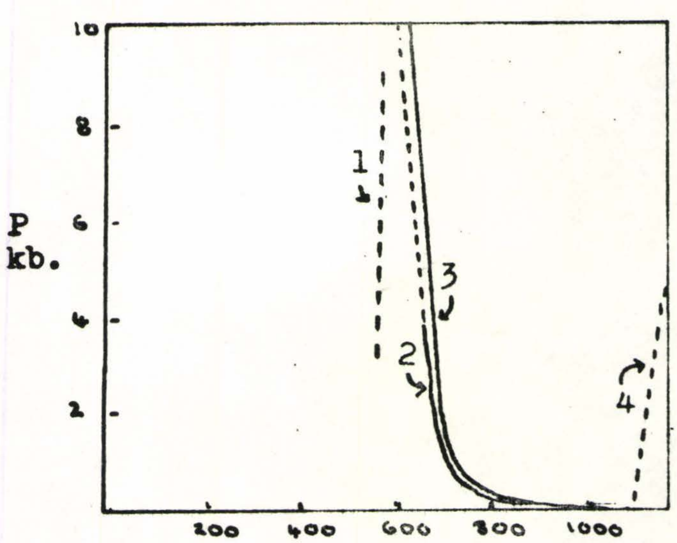


FIG. 8.4. MELTING CURVES.

1 Maximum lowering of granitic solidus, (Wyllie and Tuttle, 1964).
2 Minimum melt temp. in haplogranitic system, (Tuttle and Bowen, 1958).
3 Melting curve of granodiorite, (Burnham, in press).
4 Dry melting of granite, (Smith, 1963).

a simplified experimental model can be set up for the very complex natural state, and limits can be suggested for conditions of formation.

The method involves the construction of what Wyllie (1964) has called a metamorphic grid, which is, of course, a development of the concept of the petrogenetic grid, (Bowen, 1940). To do this, four types of chemical reactions are potentially valuable:

1. Solid-solid interactions,
2. Melting relations,
3. Dehydration, and
4. Decarbonation reactions.

The problem reduces to finding laboratory-investigated reactions that can serve as models for processes inferred to have gone on, in, and around Glamorgan township.

8.2.1 Solid-solid interactions

Two solid-solid interactions are of interest - the relations of the Al_2SiO_5 polymorphs, and the reaction jadeite = nepheline + albite.

Data concerning the Al_2SiO_5 system are in a confused state (Figure 8.3). Bell's (1962) triple point was never easy to reconcile with geological fact and it now seems likely that something is radically wrong with the method used for calculating the pressures generated in opposed anvil devices. Newton's and Weill's recent estimates are more in accord with geological evidence, (e.g., compare with Schuiling, 1957). Newton's estimates will be used below since his approach was more direct than Weill's.

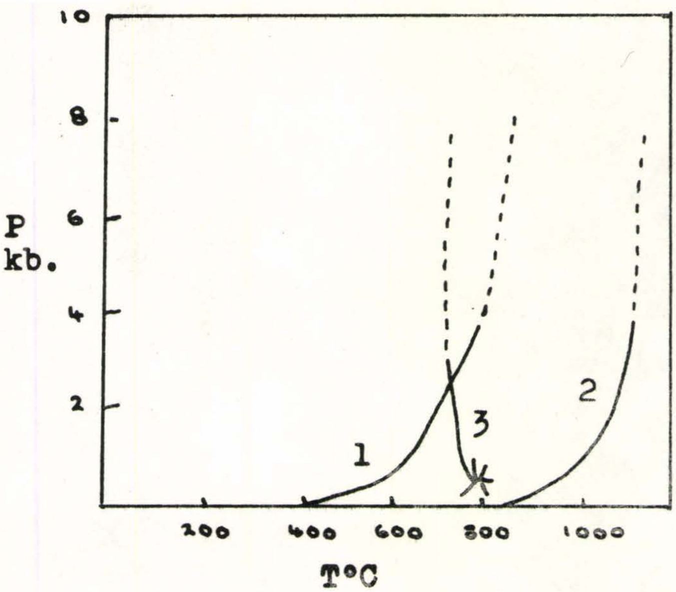


FIG. 8.5. DEHYDRATION CURVES.

1 Muscovite } Yoder and
2 Phlogopite } Eugster, 1960.

3 Upper stability limit of the assemblage Phlog-Kspar-Qtz-Melt (Luth, 1964).

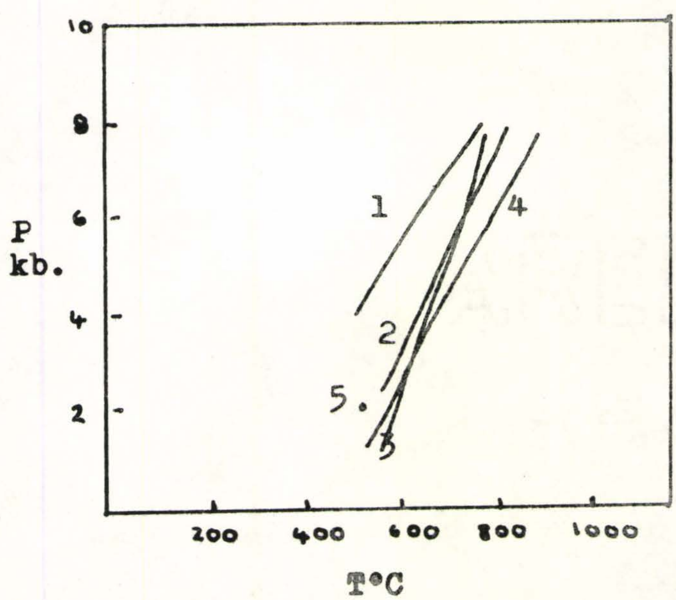


FIG. 8.6. EPIDOTE MINERALS.

1 Upper limit of Qtz-Ep(Ps_{33}) (Merrin, 1962).
2 Upper limit of Qtz-Zois, (Holdaway, 1965).
3 Upper limit of epidote (Ps_{33}), (Merrin, 1962).
4 Upper limit of Zoisite, (Newton, 1965).
5 Breakdown of a Clinozoisite, (1.9% Fe_2O_3) - Winkler, 1964.

The jadeite reaction curve (Figure 8.3) gives some confirmation that Bell's triple point is wrong. For example, where kyanite occurs in the Grenville province, jadeite could also be expected, according to Bell, instead of the association nepheline-albite. Jadeite, however, is not found in the Grenville province.

8.2.2 Melting relations

Melting curves are given for granite, granodiorite, and "haplogranite," for the conditions stated, (Figure 8.4).

A factor that did not enter into the discussion of the solid-solid interactions above, but one that is vitally important here, is the nature of the vapour phase if present. The dry melting curves (involving liquid-melt equilibria) are at a higher temperature for a given load pressure. Furthermore, the presence of volatiles other than H_2O can either raise or lower the "wet" melting curves, (involving liquid-melt-vapour equilibria). The most extreme lowering possible is about 100°C, (Wyllie and Tuttle, 1964), and the full range of beginning of melting is between curves 1 and 5 in Figure 8.4.

8.2.3 Dehydration reactions

Potentially interesting dehydration reactions are those involving the breakdown of hornblende, biotite, muscovite, and epidote. Natural hornblendes are very complex and not enough is known about end members to put reasonably certain limits on their stability fields. The stability of biotite is complicated by the importance of P_{O_2} as a variable, but the upper stability limit is given by the magnesian end

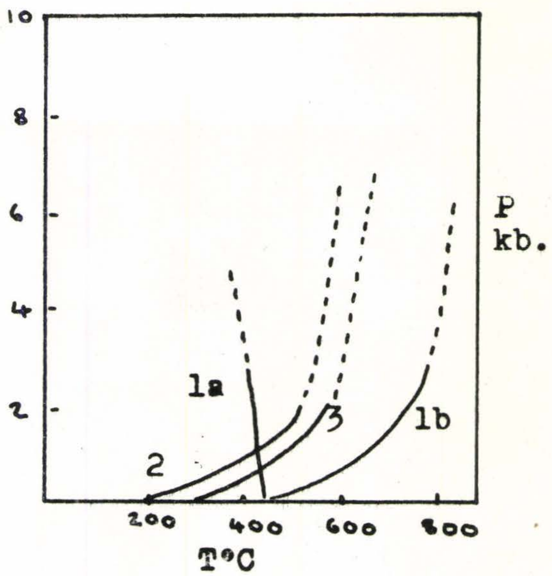


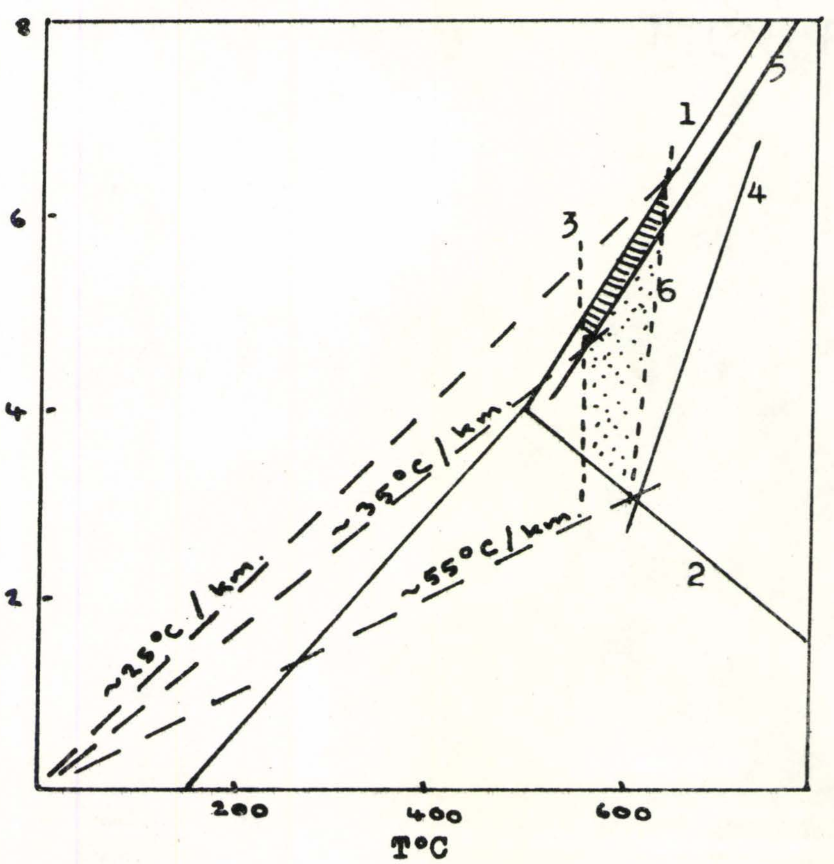
FIG. 8.7. DECARBONATION CURVES.

1 formation of wollastonite
a. at $p_{CO_2} = 0$
b. at $p_{E\,CO_2} = P_{load}$ } Winkler (1965

2 Lower stability limit of assemblage trem-diop-cte-CO_2
3 Upper stability limit of same. } Bowen (1940)

FIG. 8.8. METAMORPHIC GRID FOR GLAMORGAN TOWNSHIP AND ENVIRONS.

Shaded area represents metamorphic conditions assuming a common epidote composition, (Ps_{33}).



Stippled area represents conditions if the Qtz-Ep (Ps_{33}) curve is ignored.

P kb.

Numbered curves referred to in section 8.2.5.

member, phlogopite, when $P_{H_2O} = P_{total}$ (Figure 8.5). The upper stability limit of muscovite is given on the same figure. Curve 3 is of particular interest since the assemblage, phlogopite-feldspar-quartz, can serve as a simple model for a biotite-bearing granite.

The possibility of perfect mobility of K_2O must be taken into account here. At points along Curve 3, Figure 8.5, for example, μ_{K_2O} is at a maximum for the assemblage, phlogopite-potash feldspar-quartz-vapour. A lower μ_{K_2O} would cause melting. The curve is, therefore, a maximum.

Data on epidote stability limits is summarised in Figure 8.6, from which it is apparent that the iron-free assemblages are stable to higher temperatures than the iron-bearing ones.

8.2.4 Decarbonation reactions

Bowen (1940) qualitatively deduced the sequence of decarbonation curves that might be expected in a siliceous dolomite for the condition $P_{CO_2} = P_{total}$. Of interest in the present context are the following reactions:

1. $CaCO_3 + SiO_2 = CaSiO_3 + CO_2$
2. $CaMg_3\ (SiO_3)_4$[1] $+ 2CaCO_3 + 2SiO_2 = 3CaMgSi_2O_6 + 2CO_2$
3. $2CaCO_3 + 3CaMg_3\ (SiO_3)_4$[1] $= 5CaMgSi_2O_6 + 2Mg_2SiO_4 + 2CO_2$

---

[1] Hydroxyl-bearing minerals form only when P_{H_2O} in the gas phase exceeds a limiting value. "For tremolite, this must be low for it is one of the commonest minerals of contact metamorphism. This is why Bowen has treated tremolite as if it were an anhydrous phase," (Turner and Verhoogen, 1960, p. 518).

Reaction 1 defines the upper stability limit of the assemblage, calcite + quartz, when $P_{E_{CO_2}} = P_{total}$. Reactions 2 and 3 bracket the stability field of the assemblage, tremolite-diopside-calcite-CO_2. Figure 8.7 gives estimates of these curves.

8.2.5 A metamorphic grid for the Glamorgan rocks

From the foregoing reactions, a number have been chosen that best delimit the conditions of metamorphism in and around Glamorgan township (Figure 8.8). The following field data has dictated the choice:

a) Sillimanite occurs in the Haliburton Highlands, (Hewitt, 1952 and 1957),

b) Nepheline + albite occur together in Glamorgan township, (Fraser Quarry),

c) Epidote is found in quartz-bearing assemblages south of Bluehawk Lake,

d) Granitoid magmas were emplaced in the region and gave rise to biotite-bearing granites. Absence of chill zones in the latter is taken to indicate no appreciable temperature differences between igneous rock and country rock,

e) Tremolite-diopside-calcite is stable in the marble in Glamorgan township.

Let us now consider the numbered reactions in Figure 8.8. Curves 1 and 2 are for solid-solid interactions and are functions of total pressure and temperature. Their positions on the P-T field are unaffected by variations in the fugacities of H_2O, CO_2, and O_2.

Curve 3 is the lower stability limit of granitic melt (Wyllie and Tuttle, 1964). The conditions are $P_{fluid} = P_{solid} = P_{H_2O} + P_{Li_2O}$.

Any other conditions that have been investigated, raise this curve to higher temperatures for a given total pressure.

The effect of iron substitution in epidote seems to be to decrease the upper limit of stability (Figure 8.6) so that zoisite equilibria give an upper limit for assemblages containing epidote. Curve 4, therefore, is an upper limit for the assemblage epidote-quartz. Curve 5 is interesting in that it contains "common" epidote (33% of the iron end member). Approximate optical methods indicate a composition of around 30% of the iron end member for epidote co-existing with quartz in garnetiferous paragneiss from south of Bluehawk Lake, (Section 2.2.2).

Curve 6 gives the upper stability limit for the assemblage, calcite-diopside-tremolite, in the presence of a vapour phase with $P_{CO_2} = P_{fluid}$. In fact, this is a simplification arising from Bowen's consideration of tremolite as an anhydrous phase. A more realistic equation for reaction 6 is the following from Winkler (1965, p. 25):

$$3 \text{ tremolite} + 5 \text{ calcite} = 11 \text{ diopside} + 2 \text{ forsterite} + 5CO_2 + 3H_2O.$$

This involves two volatile components and will attain a maximum reaction temperature for a given pressure when the composition of the vapour phase satisfies the above equation, (Greenwood, 1962). This introduces a further element of uncertainty into Bowen's estimate, (Figure 8.8, Curve 6).

As a first approximation, though, we can say that Curve 6 is a maximum, Curve 3 is a minimum, and Curves 1 and 2 are constant. These four curves bracket the widest spread of conditions that operated during formation of the Glamorgan complex. A second approximation is possible if we apply Curve 5 to the epidote-quartz occurrence in Glamorgan township, but we have seen that the natural epidote is not of the same composition as the one used by Merrin (1964).

The tentative conditions of formation arrived at are:

	Assuming common epidote composition	Ignoring epidote composition
Temperature	550-650°C	550-650°C
Load pressure	4.5-6.5 kb.	3-6.5 kb.
Limiting geothermal gradients (linear)	25-35°C/km.	25-55°C/km.

A possible variable that could complicate this picture is shear stress, but evidence of flow in the rocks under discussion is so common that it is unlikely that a directed pressure could be maintained.

9. CONCLUDING REMARKS

A summary is presented here, of the petrogenetic scheme developed in Chapters 6 and 7. Later, some possible general consequences of the hypothesis are discussed.

9.1 SUMMARY OF THE PETROGENESIS OF THE GLAMORGAN GNEISS SERIES

The anatectic origin of sub-series A has grey granite gneiss and migmatite leucosome formed from a partially melted fraction of parental rock, which has a composition similar to the paragneiss found in Glamorgan township. Infusible residua of this process are inclusions in grey granite gneiss and the melanosome component of migmatite. The following main points can be made in support of this idea.

1. Migmatite-paragneiss-grey granite gneiss form a gradational series in the field, (Section 2.5).

2. The geological gradation is reflected in the bulk rock chemistry of the series, (Section 5.5).

3. Paragneiss is intermediate in the series, both geologically and chemically, (Section 6.1.3).

4. There is field evidence that some of the acid rocks of sub-series A are igneous, (Section 6.1.2).

5. The acid rocks of sub-series A have compositions similar to low temperature melts in the haplo-granitic system, studied in the laboratory, (Section 7.1.2)

6. Formation in situ, renders the fine scale, intimate banding of many of the migmatites (Section 2.4.4) easily explainable, and does not require intrusion of a viscous granite melt.

7. The whole rock composition of migmatite is virtually identical to that of paragneiss, (Section 5.4).

8. Anatexis creates no "room problem."

Regarding the pink granite gneiss, there is field (Section 2.4.2) and compositional (Section 7.2) evidence that it formed from melt. Close field association with grey granite suggests a possible relationship between the two types, and a mechanism by fractional crystallization is feasible, (Section 7.2).

In the next section three overall generalisations will be drawn from the Glamorgan occurence and these will be used as a basis of comparison with other areas.

9.2 SOME COMPARISONS

In three important respects the Glamorgan region resembles many other metamorphic terrains:

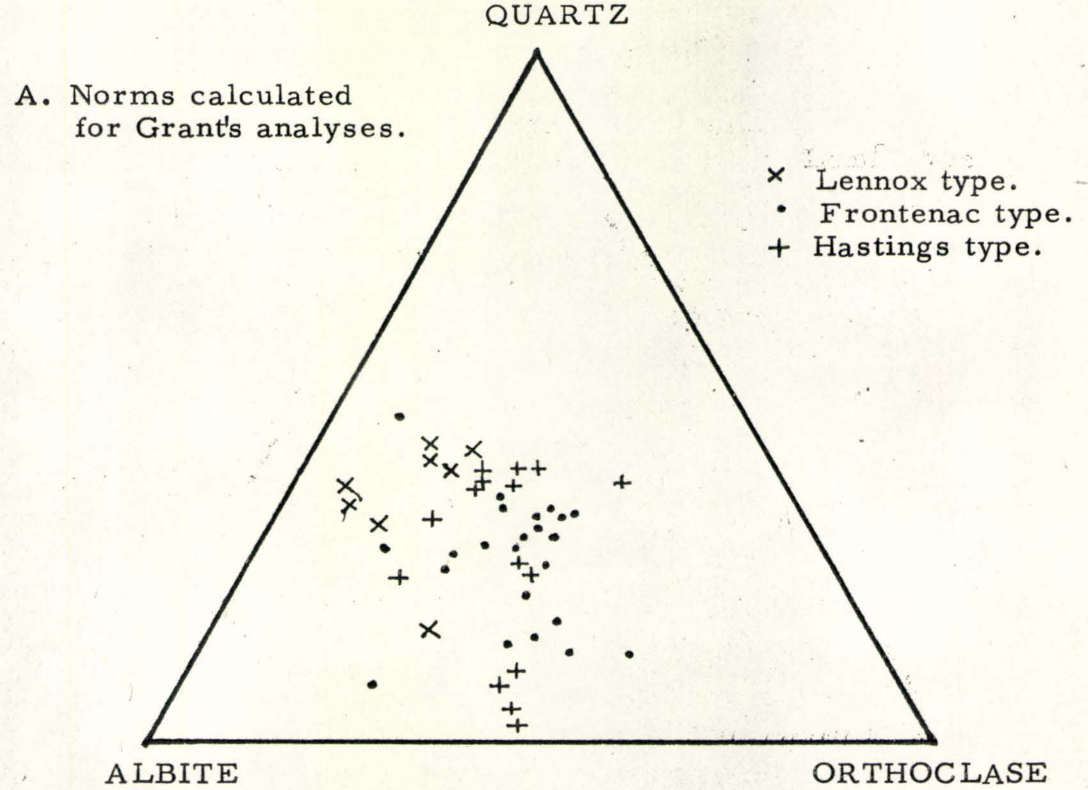
(a) migmatisation and granite emplacement are associated with high grade metamorphism,

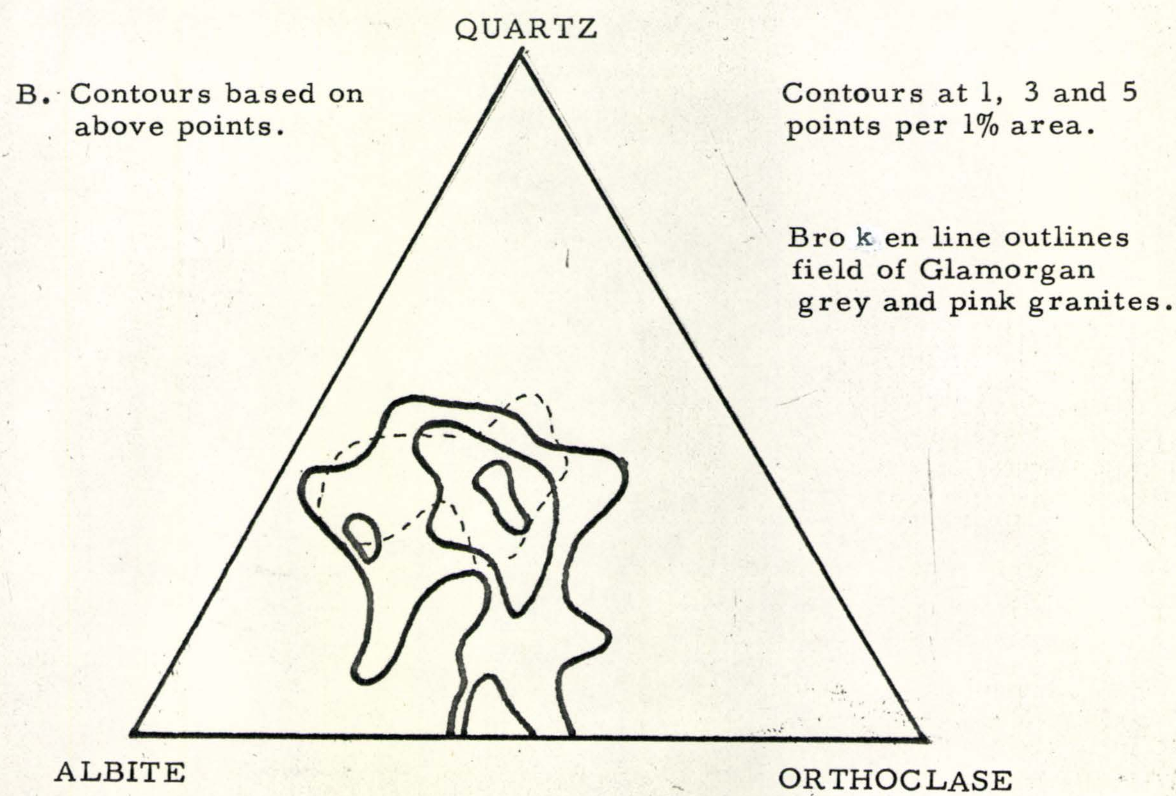
(b) a chemical and temporal contrast exists between early Na-rich and later K-rich granite rocks,

(c) the earlier Na-rich granites are spatially associated with a small volume of basic igneous rocks.

Observation (a) has been made many times by Read (1957), and also by Raguin (1965, p. 175). It is true of kyanite-sillimanite type (the Barrovian zones), of low-pressure intermediate type (Buchan) and andalusite-sillimanite type (Abukuma, Ryoke) metamorphism. It is not true for metamorphism of jadeite-glaucophane type, (Miyashiro, 1961).

FIGURE 9.1. COMPOSITIONS OF GRANITOID ROCKS OF S.E. ONTARIO. ANALYSES COLLECTED BY GRANT (1959).





Observation (b) is applicable to much of the Grenville province for which there is data. For example, in southeastern Ontario an older, grey oligoclase-granite gneiss (Lennox type) can be distinguished from later, more potassic granites (Frontenac and Hastings types) as Grant (1959) has shown. Grant's geographical terminology is probably ill-advised, since both Na- and K- rich granites can be found in the same regions, (e.g., according to Grant, Glamorgan township should contain only Hastings type granites). That the geographical division is not a rigorous one is shown when norms of Grant's analyses are plotted in the haplogranitic system (Figure 9.1). The marked preponderance of potassic granites in this plot, may not reflect a real frequency distribution so much as the samplers' bias as to what constitutes a good granite.

In the Grenville rocks of the N.W. Adironacks there is likewise a general sequence from less to more potassic granites with time, (e.g., Buddington, 1937). Similarly the Finnish granites are initially of sodic type and later more potassic, (Simonen, 1948, Niggli 1956, Figure 9.2). In Sweden, both Svecofennian and Karelian zones contain early granodiorites, and later more potassic ("eutectoid") granites, (Magnusson, 1965). West African granites too, show this same time-composition relationship, (Marmo, 1955).

Observation (c) is true in a general way, of the Grenville province of S.E. Ontario. Lumbers (1964) states that

> "the sodic group [of granites] is commonly spatially associated with the diorite-gabbro group and with metavolcanics."

In the northwest Adirondacks the Hermon type of hornblende-biotite granite is spatially associated with diorite, (Buddington, 1937, pp. 142-145, Plate 21). In Finland, oligoclase-granite gneiss surrounds a diorite-gabbro body at the classic locality of Orijärvi (Eskola, 1915). The Svecofennian and Karelian granodiorites of Sweden are associated with gabbros, (Magnusson, 1955).

From the foregoing it is clear that all three generalisations at the head of this chapter, must be important in formulating any theory of deep crustal (or "katazonal") petrogenesis. Two theories that have received much attention are the magmatectonic theory of Wahl (1936), and the idea of a granite series as expounded by Read (1949).

Scandinavian geologists in particular have sought to correlate granites with respect to a tectonic event. It is claimed that the more sodic granites are synkinematic and the more potassic are late kinematic, (Eskola, 1960 and Figure 9.2).

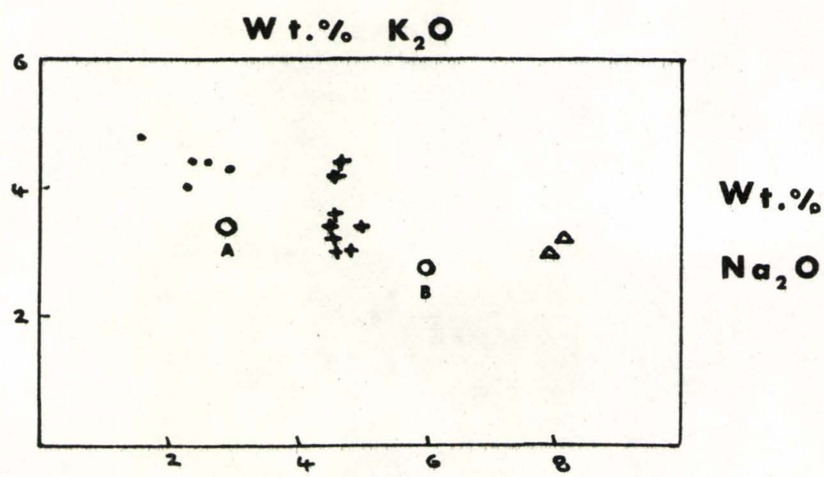
Observation (a) is incorporated into Read's granite series. The later diapiric granites are more potassium-rich than autochthonous and parautochthonous types, from which they are supposed to have developed. Bowes (unpublished) has demonstrated this relationship for Scottish granites.

Figure 9.3 summarises these general ideas.

In light of the present work, the following original model is proposed as a possible petrogenetic sequence in the crust.

a. After deposition, the Grenville series underwent induration and depression deep into the crust, possibly as a geosyncline, (Figure 9.4a).

b. A gradual elevation of isogeotherms caused crustal material to heat up and mantle material to melt, (Figure 9.4b).



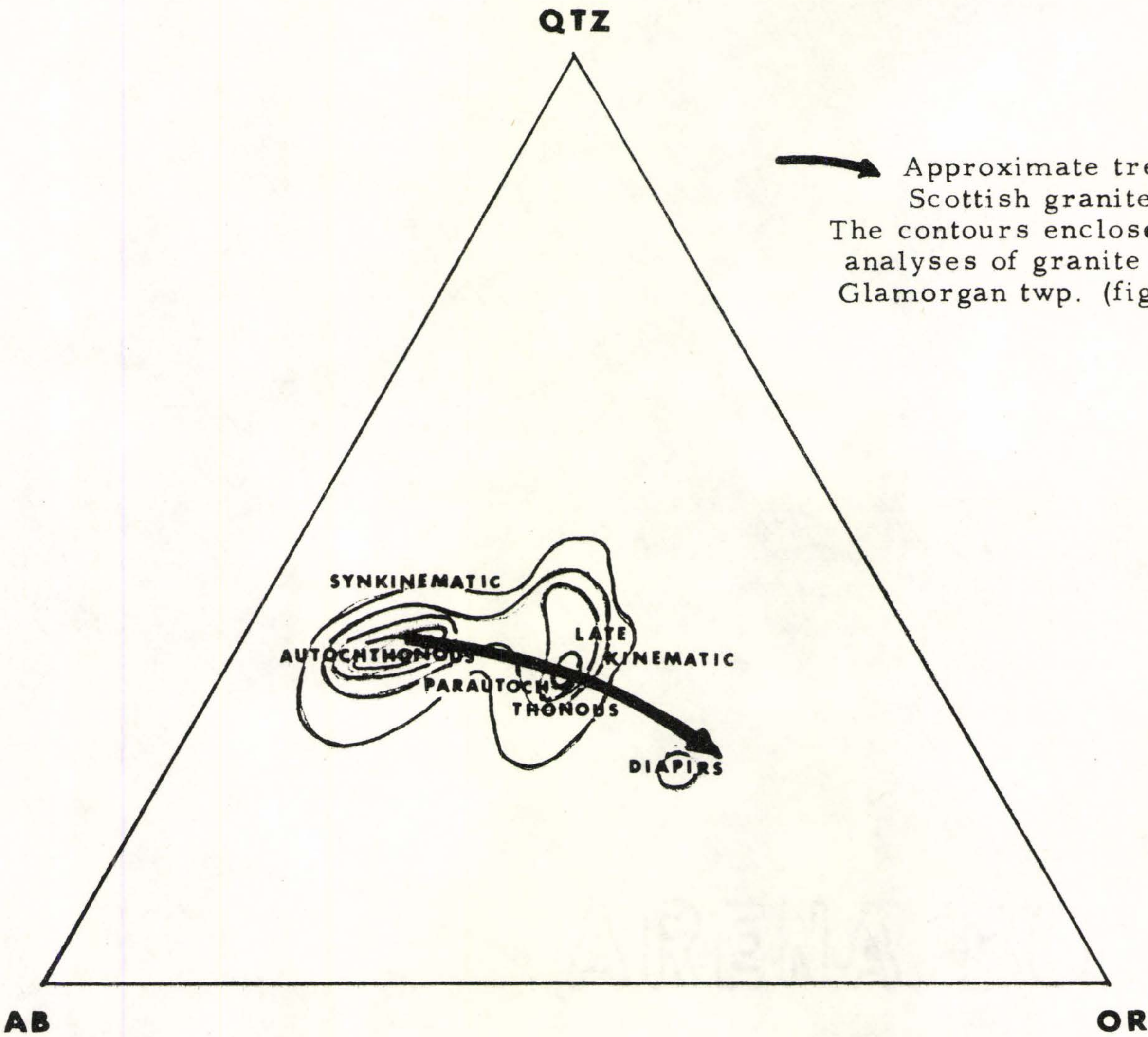
• Grey granite gneiss
+ Pink granite gneiss
△ Graphic granite/pegmatite

Gl. twp.

A average synkinematic granite, B average late kinematic granite, Finland (Simonen, 1948).

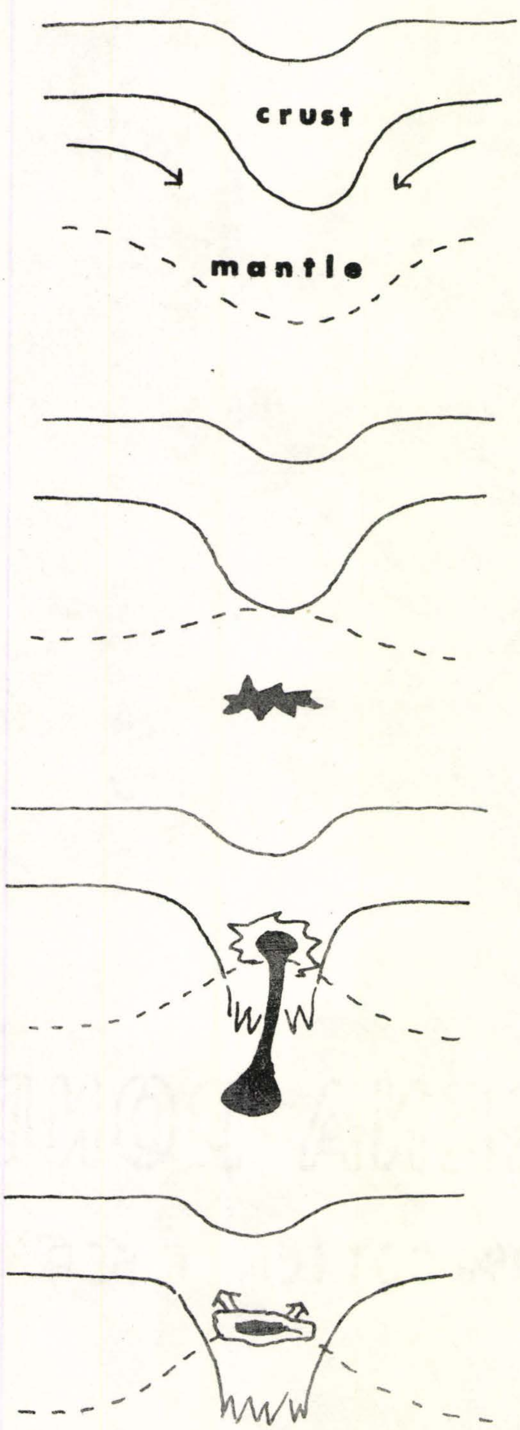
FIGURE 9.2. GLAMORGAN GRANITES COMPARED WITH TWO FINNISH AVERAGES.

FIGURE 9.3. Compositional variation of granite with respect to orogeny and to Read's granite series.



Approximate trend of Scottish granites, (Bowes).
The contours enclose 32 analyses of granite from Glamorgan twp. (fig. 5.9).

FIGURE 9.4. MODEL FOR THE PETROGENESIS OF THE GLAMORGAN ROCKS.



a Depression of crust and of isogeotherms (represented by dotted line).

b Rise of isogeotherms and formation of basic melt in mantle.

c Intrusion of basic magma into already hot crust, further raising isogeotherms and bringing on crustal melting.

d Intrusion of acid differentiates from crustal partial melt.

c. Gabbro and its differentiates intruded the already hot crust helping to raise the isogeotherms further. Sodium-rich granitoid magmas were formed in place, (Figure 9.4c)

d. The sodium-rich magma differentiated to a more potassium-rich one, which intruded surrounding rocks, (Figure 9.4d).

This simplified model provides an alternative reason for the spatial association of gabbro and granite, an association usually explained as a result of crystallization differentiation, (e.g., Buddington, 1937). It avoids a prominent difficulty of the latter hypothesis, mamely the scarcity of intermediate types. Furthermore the more mafic granitoids such as granodiorite, have been seldom reported as differentiates in sills and laccoliths, (Daly, 1933, p. 459).

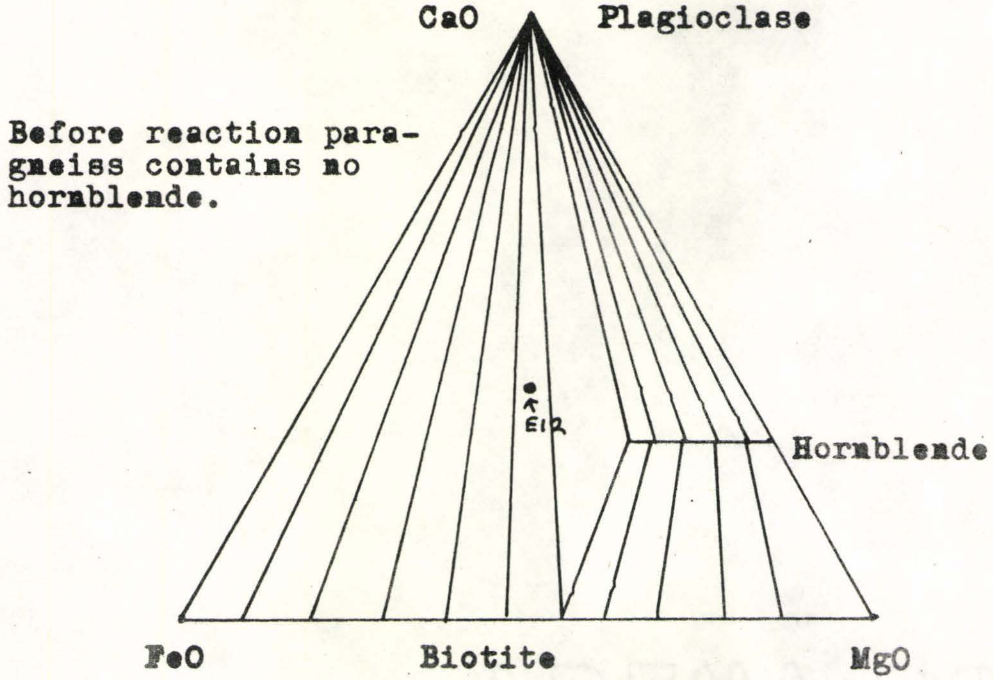
In view of the petrogenetic scheme elaborated in this work it is interesting to note the following quotation:

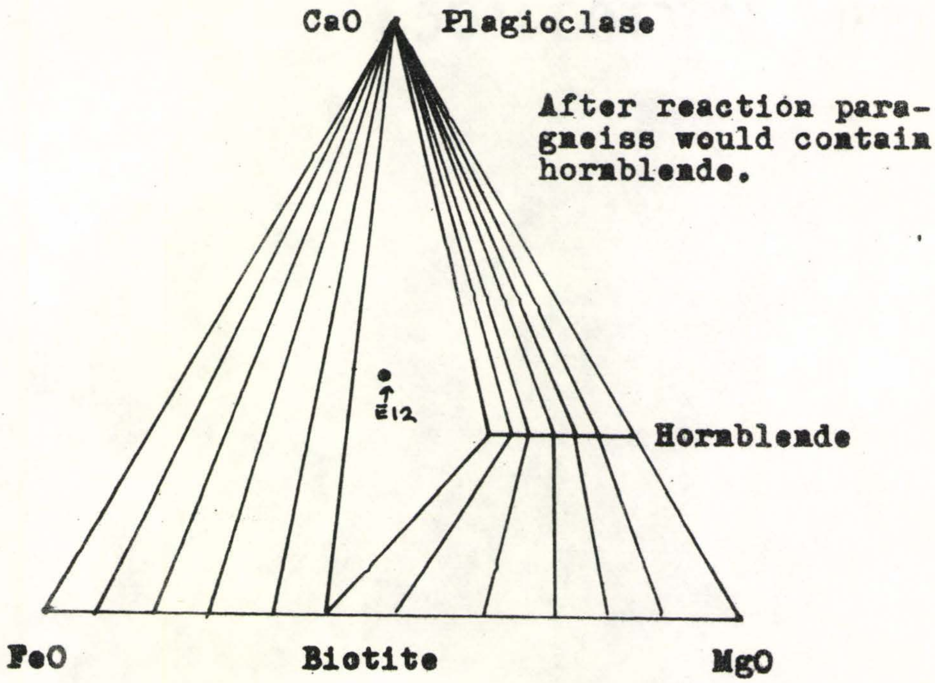
> "albite-oligoclase granite gneiss could ... be reasonably interpreted as formed from a sodium rich fluid ... sweated out of the biotite-quartz-plagioclase gneiss," (Buddington and Leonard, 1962).

It should also be noted that the idea of a basic intrusive providing heat to melt country rock is not new. Recently it has been suggested as one of the processes involved in the formation of tertiary granites in the inner Hebrides (Brown, 1962), and of the Needle Point granodiorite, Oregon, (Piwinski, 1964).

The problem of the origin of granodioritic rocks, and of the more mafic granitoids generally, is similar to that of the origin of andesites, for which the simple fractionation of basalt fails to provide a satisfactory genesis, (Tilley, 1950). Taylor and White (1965) prefer a hypothesis of partial fusion of deep crustal, or upper mantle

FIGURE 9.5. POSSIBLE CONGIGURATION OF TIE LINES BEFORE AND AFTER POSTULATED REACTION.





material to form andesitic magma. It is possible that the plutonic aspects of such volcanic processes are revealed in the deeply eroded, highly metamorphosed parts of precambrian shields, and a close comparison between rocks from such areas with a well documented series of calc-alkalic volcanic rocks, would form a worthwhile study.

9.3 SUGGESTIONS FOR FURTHER WORK

The next stage in this study should be the determination of mineral compositions. Knowing the latter a simple test is possible, of the feasibility of the proposed reaction:

biotite + plagioclase = microcline + hornblende $\pm$ other reactants

in paragneiss. As Figure 9.5 shows, biotite in the hornblende-paragneiss could become more iron rich than in the least altered rock.

This reaction, using natural samples as charges, could be investigated at high temperatures and pressures, in the kind of large volume pressure vessel, described by Burnham (1962). Also, such experiments could test directly the anatectic hypothesis developed in the foregoing pages.

Bibliography

Adams, F. D., and Barlow, A. E., 1910, Geology of the Haliburton and Bancroft areas, Province of Ontario: Geol. Surv. Canada, Mem. 6.

Adams, F. D., and Barlow, A. E., 1913, The Haliburton-Bancroft area of central Ontario: Guide Book No. 2, Excursions in the eastern townships of Quebec and the eastern part of Ontario, Geol. Surv. Canada.

Appleyard, E. C., 1965, The Grenville province and its tectonic significance - A discussion: Proc. Geol. Assoc. Can., v. 16, p. 51-57.

Armstrong, H. E., 1958, Preliminary geological map of Glamorgan township: Ontario Dept. Mines.

Backlund, H. G., 1946, The granitization problem: Geol. Mag., v. 83, p. 105-117.

Barker, F., 1964, Reaction between mafic magmas and pelitic schist, Cortlandt, New York: Amer. Jour. Sci., v. 262, p. 614-634.

Barlow, A. E., 1915, Corundum, its occurrence, distribution, exploitation, and uses: Geol. Surv. Canada Mem. 57.

Bell, P., 1963, Aluminum silicate system: Experimental determinations of the triple point: Science, v. 139, p. 1055-1056.

Best, M. G., 1966, Structural geology of precambrian rocks south of Bancroft, Ontario: Canadian Jour. of Earth Sciences, v. 3, p. 441-455.

Bowen, N. L., 1922, The reaction principle in petrogenesis: Jour. Geol., v. 30, p. 177-198.

Bowen, N. L., 1928, The evolution of the igneous rocks: Princeton University Press, Princeton, N. J.

Bowen, N. L., 1937, Recent high-temperature research on silicates and its significance in igneous geology: Amer. Jour. Sci., v. 33, p. 1-21.

Bowen, N. L., 1940, Progressive metamorphism of siliceous limestone and dolomite: Jour. Geol., v. 48, p. 225-274.

Bowen, N. L., 1948, The granite problem and the method of multiple prejudices: Geol. Soc. Amer. Mem. 28, p. 79-90.

Brown, G. M., 1963, Melting relationships of Tertiary granitic rocks in Skye and Rhum: Min. Mag., v. 33, p. 533-563.

Bruce, E. L., and Russell, G. A., 1939, Petrography of the crystalline limestones and quartzites of the Grenville series: Bull. Geol. Soc. Amer., v. 50, p. 515-528.

Buddington, A. F., 1939, Adirondack igneous rocks and their metamorphism: Geol. Soc. Amer. Mem. 7.

Buddington, A. F., 1959, Granite emplacement with special reference to North America: Bull. Geol. Soc. Amer., v. 70, p. 671-747.

Buddington, A. F., and Leonard, B. F., 1962, Regional geology of the St. Lawrence County magnetite district, northwest Adirondacks, New York: U. S. Geol. Surv. Prof. Paper 376.

Burnham, C. W., 1962, Large volume apparatus for high-temperature high-pressure experimentation (abstract): Amer. Cer. Soc. Meeting, Seattle.

Burnham, C. W., (in press); Hydrothermal solutions at the magmatic stage.

Carmichael, I. S. E., 1962, Pantelleritic liquids and their phenocrysts: Min. Mag., v. 33, p. 86-113.

Cochran, W. G., 1953, Sampling techniques: Wiley and Sons, New York.

Coombs, D. S., 1965, Sedimentary analcime rocks and sodium rich gneisses: Min. Mag., v. 34 (Tilley Vol.), p. 144-158.

Daly, R. A., 1933, Igneous rocks and the depths of the earth: McGraw-Hill, New York.

Davis, G. A., 1963, Structure and mode of emplacement of Caribou Mountain pluton, Klamath Mountains, California: Geol. Soc. Amer. Bull., v. 74, p. 331-348.

Deer, W. A., Howie, R. A., and Zussman, J., 1962, Rock forming minerals: v. 1, Ortho- and ring silicates: Wiley and Sons, New York.

Eckelmann, F. D., and Poldervaart, A., 1957, Geologic evolution of the Beartooth mountains, Montana and Wyoming: Geol. Soc. Amer. Bull., v. 68, p. 1225-1262.

Ells, R. W., 1901, Geology of part of Quebec and part of Ontario: Geol. Surv. Canada, Ann. Rept., v. 12, pt. J.

Engel, A. E. J., 1956, Apropos the Grenville: Royal Society of Canada, Special Publications no. 1, p. 74-96.

Engel, A. E. J., and Engel, C. G., 1953, Grenville series in the northwest Adirondack Mountains, New York: Geol. Soc. Amer. Bull., v. 64, p. 1013-1097.

Engel, A. E. J. and Engel, C. G., 1958, Progressive metamorphism and granitisation of the major paragneiss, northwest Adirondack Mountains, New York: Part 1, total rock: Geol. Soc. Amer. Bull., v. 69, p. 1369-1414.

Engel, A. E. J., and Engel, C. G., 1960, Migration of elements during metamorphism in the northwest Adirondack Mountains, New York: U. S. Geol. Surv. Prof. Paper 400 B, p. 465-470.

Engel, A. E. J., and Engel, C. G., 1962, Progressive metamorphism of amphibolite, northwest Adirondack Mountains, New York: in Buddington Volume, Geol. Soc. Amer., p. 37-82.

Eskola, P., 1914, On the petrology of the Orijarvi region in southwestern Finland: Comptes Rend. de la Comm. geol. de Finlande, v. 36.

Eskola, P., 1932, On the principles of metamorphic differentiation: Comptes Rend. de la Comm. geol. de Finlande, v. 97, p. 68-77.

Eskola, P., 1939, Die metamorphen Gesteine: in Barth, Correns and Eskola, 1939, p. 263-407.

Eskola, P., 1948, The problem of mantled gneiss domes: Geol. Soc. London, Quart. Jour., v. 104, p. 461-476.

Eskola, P., 1963, The precambrian of Finland: in the Precambrian, v. 1, p. 145-263, Interscience, New York.

Foye, W. G., 1916, The relation of the titaniferous magnetite ores of Glamorgan township, to the associated scapolitic gabbros, v. 11, p. 662-680.

Foye, W. G., 1916, Are the "batholiths" of the Haliburton-Bancroft area, Ontario, correctly named: Jour. Geol. v. 24, p. 783-791.

Francis, G. H., 1956, Facies boundaries in pelites at the middle grades of regional metamorphism: Geol. Mag., v. 93, p. 353-368.

Fyfe, W. S., and Turner, F. J., 1966, Reappraisal of the metamorphic facies concept: Contr. Mineral. and Petrol.,v. 12, p. 354-364.

Fyfe, W. S., Turner, F. J., and Verhoogen, J., 1958, Metamorphic reactions and metamorphic facies: Geol. Soc. Amer. Mem. 73.

Gilluly, J., 1945, Geologic map of the Gouverneur talc district, New York: U. S. Geol. Surv. Prelim. Map 3-163.

Gilluly, J., 1948, Origin of granite: Geol. Soc. Amer. Mem. 28.

Gittins, J., 1961, Nephelinization in the Haliburton-Bancroft district, Ontario, Canada: v. 69, p. 291-308.

Grant, J. A., 1959, M. A. thesis, Queens University, Kingston, Ontario.

Greenwood, H. J., 1962, Metamorphic reactions involving two volatile components: Ann. Rept. of the Director of the Geophysical Laboratory, Carnegie Institution of Washington, 1961-1962, p. 82-85.

Hamilton, D. L., Burnham, C. W., and Osborne, O. F., 1963, The solubility of water and effects of oxygen fugacity and water content on crystallization in mafic magmas: Jour. Petrology, v. 5, p. 21-39.

Harrison, W. D., 1953, A petrographic study of the gabbros of Glamorgan township, Ontario: M. S. thesis, McMaster University, Hamilton, Ontario.

Hewitt, D. F., 1952, Kyanite and sillimanite in Ontario, Ontario Dept. Mines publication.

Hewitt, D. F., 1956, The Grenville of Ontario: Royal Society of Canada, Special Publications no. 1, p. 221-41.

Hewitt, D. F., 1957, Geology of Cardiff and Faraday townships: Ontario Dept. Mines Ann. Rept., v. 64, pt. 3.

Hewitt, D. F., 1962, Some tectonic features of the Grenville province of ontario: Royal Society of Canada, Special Publications no. 4.

Hewitt, D. F., and Satterly, J., 1957, Haliburton-Bancroft area: Ontario Dept. Mines, Map No. 1957b.

Hinxman, L. W., et al., 1915, The geology of mid Strathspey and Strathdearn: Geol. Surv. Scotland, Mem. 74.

Holmquist, P. J., 1920, Om pegmatit-palingenes och ptygmatish veckning: F. F. F., v. 42, p. 191-213.

Jahns, R. H., and Tuttle, O. F., 1963, Layered pegmatite-aplite intrusives: Min. Soc. Amer. Sp. Paper 1, p. 78-92.

Jung, J., and Rogues, 1952, Introduction a l'étude zonéogeographique des formations cristallophylliennes: Bull. Serv. Cart. géol. de la France, v. 50, p. 1-62.

Korzhinskii, D. S., 1950, Phase rule and geochemical mobility of elements: Int. Geol. Congress, Great Britain.

Korzhinskii, D. S., 1959, Physicochemical basis of the analysis of minerals: Consultants Bureau, New York.

Korzhinskii, D. S., 1964, A theory of the processes of mineral formation: Int. Geol. Rev., v. 6, p. 387-399.

Krogh, T. E., 1964, Ph.D. thesis, M. I. T.

Krogh, T. E., 1966, Whole rock Rb/Sr studies in the northwest Grenville area of Ontario, (Abstract): Ann. Meeting A. G. U., Washington D. C.

Krumbein, W. C., 1934, The probable error of sampling sediments for mechanical analysis: Amer. Jour. Sci., v. 27, p. 204-214.

Krumbein, W. C., 1959, Trend surface analysis of contour-type maps with irregular control-point spacing: Jour. Geophys. Res., v. 64, p. 823-834.

Kuno, H. et al., 1957, Differentiation of Hawaiian magmas: Jap. Jour. Geol. and Geog., v. 28, p. 179-218.

Larsen, L. H., and Poldervaart, A., 1961, Petrologic study of Bald Rock batholith, near Bidwell Bar, California: Geol. Soc. Amer. Bull., v. 72, p. 69-91.

Loberg, B., 1963, The formation of a flecky gneiss and similar phenomena in relation to the migmatite and vein gneiss problem: G. F. F., v. 85, p. 3-109.

Lumbers, S. B., 1964, Preliminary report on the relationship of mineral deposits to intrusive rocks and metamorphism in part of the Grenville province of southeastern Ontario: Ontario Dept. Mines, P. F. 1964-4.

Lumbers, S. B., and Silver, L. T., 1965, Geochronologic studies in the Bancroft-Madoc area of the Grenville province, Ontario, Canada: G.S.A. program, Kansas City, p. 153.

Luth, W. C., Jahns, R. H., and Tuttle, O. F., 1964, The granite system at pressures of 4 to 10 kilobars: Jour. Geophys. Res., v. 69, p. 759-773.

Magnusson, N. H., 1965, The Pre-Cambrian history of Sweden: Geol. Soc. Lond., Quart. Jour., v. 121, p. 1-30.

Marmo, V., 1955, The petrochemistry of some precambrian granites of West Africa, and a petrochemical comparison with the Svecofennide granites of Finland: Amer. Jour. Sci., v. 253, p. 391-417.

McDougal, I., 1962, Differentiation of the Tasmanian dolerites; Red Hill dolerite - granophyre association: Geol. Soc. Amer. Bull., v. 73, p. 279-315.

Mehnert, K., 1959, Der geganwärtige Stand des Granitproblems: Fortschr. Mineral., v. 37, p. 117-206.

Mehnert, K., 1962, Petrographie und Abfolge der Granitisation im Schwarzwald III: N. Jb. Miner. Abh., v. 98, p. 208-249.

Merrin, S., 1964, Experimental investigations of epidote paragenesis: Ph.D. thesis, Penn. State Univ.

Miyashiro, A., 1958, Regional metamorphism of the Gosaisyo-Takanuki district in the central Abukuma plateau: J. Fac. Sci. Tokyo Univ., sec. II, v. 11, p. 219-272.

Miyashiro, A., 1961, Evolution of metamorphic belts: Jour. Petrology, v. 2, p. 277-311.

Moorhouse, W. W., 1959, The study of rocks in thin section: Harper and Row, New York.

Newton, R. C., 1966, Kyanite-andalusite equilibrium from 700° to 800°C: Science, v. 153, p. 170-172.

Niggli, P., 1946, Die leucogranitischen, trondhjemitischen und leucosyenitegranitischen Magmen und die Anatexis: Schweiz. Miner. Petr. Mitt. v. 26, p. 44-78.

Nockolds, S. R., 1934, The production of normal rock types by contamination and their bearing on petrogenesis: Geol. Mag., v. 71, p. 31-39.

Nockolds, S. R., 1954, Average chemical compositions of some igneous rocks: Geol. Soc. Amer. Bull., v. 65, p. 1007-1032.

Nockolds, G. R., and Allen, R., 1953, The geochemistry of some igneous rock series: Geochim. Cosmochim. Acta, v. 4, p. 105-142.

O'Connor, J. T., 1965, A classification for quartz-rich igneous rocks based on feldspar ratios: U. S. Geol. Surv. Prof. Paper 525-B, p. 79-84.

Orville, P. M., 1960, Alkali ion exchange between vapor and feldspar phases: Amer. Jour. Sci., v. 261, p. 201-237.

Osborne, E. F., 1959, Role of oxygen pressure in the crystallization and differentiation of basaltic magma: Amer. Jour. Sci., v. 257, p. 609-647.

Perrin, R., and Roubault, M., 1939, Le granite et les reactions à l'état solide: Bull. Serv. Carte géol. Algérie, 5 sér., Pétrographie, no. 4.

Pettijohn, F. J., 1957, Sedimentary rocks: 2nd ed., Harper & Bros., New York.

Pettijohn, F. J., 1963, Data of Geochemistry, Chapter 5, U. S. Geol. Surv. Prof. Paper.

Piwinskii, A. J., 1964, Experimental study of rocks from a zoned pluton: M.S. thesis, Penn. State Univ.

von Platen, H., 1965, Kristallisation granitischer Schmelzen: Beit. Miner. und Pet., v. 11, p. 334-381.

Quirke, T. T., and Collins, W. H., 1930, The disappearance of the Huronian: Geol. Surv. Canada, Mem. 160.

Raguin, E., 1965, Geology of granite: translation of 2nd French ed., Interscience, New York.

Ramberg, H., 1952, The origin of metamorphic and metasomatic rocks: University of Chicago Press.

Read, H. H., 1949, A contemplation of time in plutonism: Geol. Soc. London, Quart. Jour., v. 105, p. 101-156.

Read, H. H., 1957, The granite controversy: Murby, London.

Reynolds, D. L., 1946, The sequence of geochemical changes leading to granitization: Geol. Soc. London, Quart. Jour., v. 102, p. 389-446.

Roedder, P. L., Osborne, E. F., 1966, Experimental data for the system $MgO-FeO-Fe_2O_3-CaAl_2Si_2O_8-SiO_2$ and their petrologic implications: Amer. Jour., Sci., v. 264, p. 428-480.

Rosenquist, J. T., 1952, The metamorphic facies and the feldspar minerals: Univ. i Bergen Arbok, p. 1-108.

Saggerson, E. P., and Williams, L. A. J., 1964, Ngurumanite from southern Kenya and its bearing on the origin of rocks in the northern Tanganyika alkaline district: Jour. Petrol., v. 5, p. 40-81.

Satterly, J., 1943, Mineral occurrences in the Haliburton area: Ontario Dept. Mines, v. 52, pt. 2.

Satterly, J., 1944, Mineral occurrences in the Renfrew area: Ontario Dept. Mines, v. 53, pt. 3.

Satterly, J., 1956, Radioactive mineral occurrences in the Bancroft area: Ontario Dept. Mines, v. 65, pt. 6.

Schairer, J. F., and Yoder, H. S., 1960, The nature of residual liquids from crystallization, with data on the system nepheline-diopside-silica: Amer. Jour. Sci., v. 258, p. 273-283.

Schuiling, R. D., 1958, Kyanite-sillimanite equilibrium at high temperatures and pressures: Amer. Jour. Sci., v. 256, p. 680-682.

Sclar, C. B., 1965, Layered mylonites and the processes of metamorphic differentiation: Bull. Geol. Soc. Amer., v. 76, p. 611-612.

Sederholm, J. J., 1907, Om granit och gneiss: Camptes rend. de la Comm. geol. de Finlande, v. 23.

Sederholm, J. J., 1926, On migmatites and associated pre-Cambrian rocks of southwestern Finland, Part II: Comptes Rend. de la Comm. geol. de Finlande.

Shaw, D. M., 1962, Geology of Chandos township: Ontario Dept. Mines, Geol. Rept. No. 11, p.1-28.

Silver, L. T., 1964, Isotope investigations of zircons in precambrian igneous rocks of the Adirondack mountains, New York: G. S. A. Sp. Paper 76, p. 150-151.

Simonen, A., 1948, On the petrochemistry of the infracrustal rocks in the Svecofennidic territory of southwestern Finland: Comptes Rend. de la Comm. geol. de Finlande, v. 141.

Simony, P. S., 1960, Origin of the Apsley paragneiss: M.S. thesis, McMaster University.

Simpson, D. R., 1962, Graphic granite from the Romona pegmatite district, California: Amer. Min. v. 47, p. 1123-1138.

Smith, B. L., 1958, Geology of the Clarendon-Dalhousie area: Ontario Dept. Mines, v. 65, 1956, pt. 7.

Stockwell, C. H., 1962, A tectonic map of the Canadian Shield: Roy. Soc. Canada, Sp. Pub. 4, p. 6-15.

Taylor, S. R., and White, A. J. R., 1965, Geochemistry of andesites and the growth of continents: Nature, v. 208, p. 271-273.

Termier, P., 1912, Sur la genèse des terrains cristallophylliens: Int. Geol. Cong. Stockholm, p. 587-595.

Thompson, J. B., Jr., 1957, The graphical analysis of mineral assemblages in pelitic schists: Amer. Min., v. 42, p. 842-858.

Thornton, C. P., and Tuttle, O. F., 1960, Chemistry of igneous rocks, I.Differentiation index: Amer. Jour. Sci., v. 258, p. 664-684.

Tilley, C. E., 1950, Some aspects of magmatic evolution: Geol. Soc. London, Quart. Jour., v. 106, p. 37-61.

Tilley, C. E., and Gittins, J., 1961, Igneous nepheline-bearing rocks of the Haliburton-Bancroft region, province of Ontario: Jour. Petrol., v. 2, p. 38-48.

Tröger, W. E., 1963, Der geothermische gradient im pt-Feld der metamorphen Facies: Beit. Min. und Pet., v. 9, p. 1-12.

Turekian, K. K., 1963, The use of trace-element geochemistry in solving geologic problems: Royal Soc. Canada, Special Publications, no. 6, p. 3-24.

Turner, F. J., and Verhoogen, J., 1960, Igneous and metamorphic petrology: 2d ed., McGraw Hill, New York.

Tuttle, O. F., and Bowen, N. L., 1958, Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$Si-_2$-H_2O: Geol. Soc. Amer., Mem. 74.

Wahl, H., 1936, The granites of the Finnish part of the Svecofennian Archaen mountain chain: Comptes Rend. de la Comm. geol. de Finlande, v. 115, p. 489-505.

Walton, M., 1960, Granite problems: Science, v. 131, p. 635-645.

Walton, M., and de Waard, D., 1963, Orogenic and stratigraphic development of the precambrian in the Adirondack Highlands: G. S. A. Sp. Paper 73, p. 258.

Wegmann, C. E., 1935, Zur Deutung der Migmatite: Geol. Rund., v. 26, p. 305-350.

Weill, D. F., 1966, Stability relations in the Al_2O_3-SiO_2-Na_3AlF_6 system: Geochim. Cosmichim. Acta, v. 30, p. 223-237.

Wentworth, C. K., 1926, Methods of mechanical analysis of sediments: Univ. of Iowa Studies in Nat. Hist., v. 11.

Wilson, J. T., 1949, Some major structures of the Canadian Shield: Can. Min. Metal. Bull., v. 42, p. 547-554.

Winkler, H. G. F., 1961, Genesen von graniten und migmatiten auf grund neuer experimente: Geol. Rund., v. 51, p. 347-364.

Winkler, H. G. F., 1965, Petrogenesis of metamorphic rocks: Springer-Verlag, New York.

Winkler, H. G. F., and von Platen, 1961, Experimentelle Gesteins-metamorphose V Experimentelle anatektische Schmeltzen und ihre petrogenetische Bedeutung: Geochim. Cosmochim. Acta. v. 24, p. 250-259.

White, A. J. R., 1966, Genesis of migmatites from the Palmer region of south Australia: Chemical Geology, v. 1, p. 165-200.

Wyllie, P. J., 1963, Applications of high pressure studies to the earth sciences, in "High Pressure Physics and Chemistry," v. 2, ed. R. S. Bradley, Academic Press, London, p. 1-89.

Wyllie, P. J., and Tuttle, O. F., 1960, Melting in the earth's crust: Int. Geol. Cong. Copenhagen, pt. 18, p. 227-235.

Wyllie, P. J., and Tuttle, O. F., 1964, Experimental investigation of silicate systems containing two volatile components, Part III: Amer. Jour. Sci., v. 262, p. 930-939.

Wyllie, P. J., 1966, Experimental petrology: An indoor approach to an outdoor subject: Jour. Geol. Ed., v. 14, p. 93-97.

Wynne-Edwards, H. R., 1964, The Grenville province and its tectonic significance: Proc. Geol. Assoc. Can., v. 15, p. 53-67.

Yoder, H. S., and Tilley, C. E., 1962, Origin of basalt magmas: An experimental study of natural and synthetic rock systems: Jour. Petrol., v. 3, p. 342-532.

Addendum to Bibliography

Carmichael, I.S.E., 1964, The petrology of Thingmuli: J. Pet., v. 5, p. 435-460.

Fleuty, M.J., 1964, The description of folds: Proc. Geol. Assoc., v. 75, p. 461-492.

Langmyhr, F.J. and Graff, P.R., 1965, A contribution to the analytical chemistry of silicate rocks: Norges Geol. Unders. No. 230, 128 pp.

Mercy, E.L.P., 1956, The accuracy and precision of "rapid methods" of silicate analysis: G.C.A., v. 9, p. 161-173.

Shapiro, L. and Brannock, W.W., 1956, Rapid analysis of silicate rocks: U.S. Geol. Survey Bull., 1036-C, 56 pp.

Stevens, R.E. and Niles, W.W., 1960, Second report on a cooperative investigation of the composition of two silicate rocks. Part 1: U.S. Geol. Survey Bull. 1113, p. 3-43.

APPENDIX 1

Mapping was done on aerial photograph overlays, on a scale of four inches to the mile. A preliminary map (Armstrong, 1958), formed the basis of Map 1. The latter differs from Armstrong's map in two major respects and a number of minor ones.

The most important difference is that Armstrong's map unit 8 has been subdivided into pink granite gneiss, grey granite gneiss and migmatite (as well as subordinate units of granite-pegmatite and graphic granite). The field distinctions were based on criteria stated on page 33 of this thesis.

The other main difference between Map 1 and the preliminary map concerns Armstrong's map unit 2a. Armstrong gave this designation to rocks which he believed to be amphibolite. The latter term in the literature is generally restricted to amphibole-bearing, quartz-free rocks, and the fact that the 2a units of Glamorgan township are quartz-bearing (and differ from quartz-plagioclase-biotite paragneiss only in containing amphibole and potash feldspar), led the writer to use the symbol 2pa for these rocks - signifying amphibole bearing paragneiss.

Minor differences include the extent of the outcrop of diorite in the north-easterly corner of the map-sheet, of paragneiss in the Stormy Lake vicinity and of several minor bodies of marble and granite pegmatite. The structural data on the map is original to it.

APPENDIX 2

Rock analyses were made by the method of Shapiro and Brannock (1956), modified by John Muysson.

Data on precision, based on interlaboratory comparisons, of analyses of the granite G1 is supplied by Stevens and Niles (1960, p.31):

	Number of determinations	Arithmetic mean	Standard deviation
SiO_2	60	72.35	.48
Al_2O_3	60	14.32	.37
Fe_2O_3	57	.95	.30
FeO	57	.99	.11
MgO + 0.63 BaO	59	.40	.13
CaO + SrO	59	1.40	.12
Na_2O	59	3.31	.23
$K_2O + Rb_2O$	59	5.42	.39
H_2O-	48	.06	.05
H_2O+	51	.36	.18
TiO_2	60	.26	.04
P_2O_5	54	.10	.06
MnO	56	.03	.01
CO_2	9	.08	.01

Within a single laboratory, precision is likely to be greater than this. Unfortunately Stevens & Niles do not provide an analysis of single laboratory data. The only measure in this respect are the results of Langmyhr and Graff (1965, p.109) using a similar method for major constituents to Shapiro and Brannock:

	Number of determinations	Arithmetic mean	Standard deviation
SiO_2	10	72.73	.14
Al_2O_3	10	13.81	.42
Fe_2O_3	10	.66	.09
FeO	10	.96	.05
MgO	10	.39	.02
CaO	10	1.27	.01
Na_2O	10	3.27	.04
K_2O	10	5.05	.06

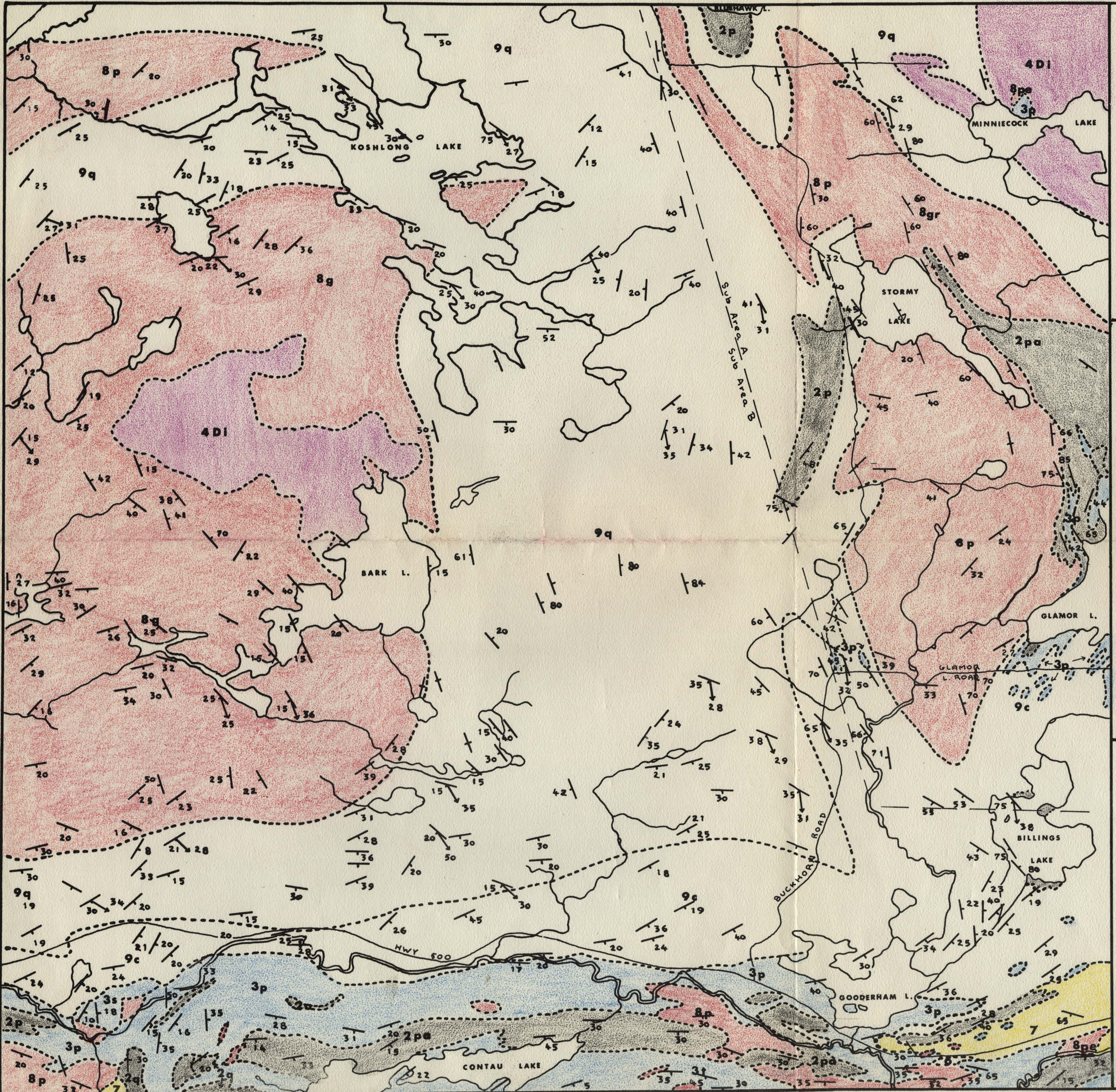
Mercy (1956) has proposed the following arbitrary limits for precision:

$C < 3.00$	-	precise
$3.00 < C < 10.00$	-	moderately precise
$10.00 < C$	-	not precise

where C is the relative deviation defined as the standard deviation expressed as a percentage of the arithmetic mean. By this criterion Langmyhr and Graff's results can be classified as:

a. Precise: SiO_2, Al_2O_3, FeO, CaO, K_2O.

b. Moderately precise: Fe_2O_3, MgO, Na_2O.



BEDROCK GEOLOGY of part of GLAMORGAN township.

PRECAMBRIAN

PLUTONIC ROCKS

9 — MIGMATITE: Alternating granitic and nongranitic layers. Latter contain quartz but no calcite in 9q; and calcite, generally but not invariably without quartz in 9c.

8 — GRANITE: (in the broad sense). 8g grey granodioritic gneiss; 8p pink leucogranite gneiss; 8pe microcline rich granite pegmatite; 8gr graphic granite closely associated with 8p.

7 — SYENITE: pink gneiss with little or no quartz.

6 — NEPHELINE ROCKS: light grey nepheline syenite gneiss, in places interbanded with calcite-bearing layers.

4 — BASIC ROCKS: 4di diorite, gneissic at borders, massive internally

METASEDIMENTS

3 — MARBLE: well bedded calcite bearing rock, with some interbedded amphibolite. 3p phlogopite-bearing, 3t tremolite bearing, 3s scapolite-bearing marble.

2 — PARAGNEISS-AMPHIBOLITE GROUP: 2a quartz-free hornblende-plagioclase gneiss; 2p quartz-plagioclase-biotite paragneiss; 2pa amphibole-bearing paragneiss.

Symbols

N

Lithological boundary (inferred)

Attitude of foliation in gneisses and bedding in marble. (Dip in degrees).

Lineation. (Plunge in degrees).

Scale

0 ½ 1 MILE

Base map by Ontario Dept. of Lands and Forests. Geology by H. S. Armstrong (1958) and Ward Chesworth (1961-4).