K-Rb-Tl RELATIONSHIP IN SOME GNEISSIC ROCKS

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By

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SCOPE AND CONTENTS: On the basis of K, Rb and Tl data Chesworth's (1967) hypothesis of the origin of certain granitic rocks in Glamorgan township, southeastern Ontario, Canada was confirmed.

It was found that the distribution of Rb and Tl during partial melting depends mainly on mineralogical composition of the residuum which remains after partial melting. During magmatogenic and metasomatic processes an important role is played by the high mobility of thallium.

ABSTRACT

Granitic and associated metamorphic rocks of Precambrian age in southeastern Ontario, Canada have been studied in order to determine the relationship of K, Rb and Tl and their behaviour during the process of partial melting and magmatic differentiation and metasomatism.

Analytical results for major elements and rubidium and thallium abundances for 52 samples are given.

From the present data, it appears possible that the series of migmatite and granodiorite gneiss originated by partial melting of paragneiss, together with pink granite which developed by late magmatic processes from a granodiorite melt, as was proposed by Chesworth (1967).

Consideration of the geochemical data shows that the principal aspects of the distribution of Rb and Tl during partial melting are controlled by the mineralogical composition of the residuum which remains after partial melting. If mica is present in the residuum a newly-formed melt could have higher or the same K/Rb, K/Tl and Rb/Tl ratios as the parent rock and thus the "classical rule" of lower K/Rb and K/Tl in the anatectic melt is not valid.

Enrichment of Tl in rocks affected by metasomatic processes is demonstrated. The marked decrease of K/Tl and Rb/Tl

in the contact rocks (calc-silicate marbles) is caused by stronger migration of Tl, relative to K and Rb, from the intruded pink granite.

The high mobility of thallium compounds is an important factor in the distribution of Tl during metasomatic and magmatogenic processes.

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1. INTRODUCTION

This study was carried out on a granitoid complex and associated marbles in Glamorgan township, Haliburton County, Ontario.

It was undertaken to determine the relationship of the elements K, Rb and Tl in the granitoid rocks and the marble, and the behaviour of the ratios K/Rb, K/Tl and Rb/Tl in the metasomatic contact rocks.

The area studied is part of the Grenville province of the Canadian Precambrian Shield, which comprises rocks dated at 900-1400 m.y.

The rocks of southern Glamorgan township consist essentially of a series of migmatites and granodiorite gneiss believed to have originated by partial melting of a paragneiss, together with a pink granite which possibly developed as a later stage of fractional crystallization of the anatectic melt (Chesworth, 1967). In the southern part of the township this series is bordered mainly by marbles.

Previous studies have suggested a distribution of the K/Rb ratios which may be expected in rocks which originated by partial melting or by late magmatic processes: it was decided to test these hypotheses, and extend them to see whether a similar distribution of K/Tl and Rb/Tl ratios may have been produced.

2. REVIEW OF K, Rb and Tl RELATIONSHIPS

From a chemical point of view, the ions K^{1+}, Rb^{1+} and Tl^{1+} have very similar properties. Major physicochemical features considered to control geochemical behaviour of these elements are listed in Table 1.

Table 1.

Physicochemical properties of K, Rb and Tl

Properties	K	Rb	Tl
Atomic number	19	37	81
Atomic weight	39.102	85.47	204.37
Valence	1+	1+	1+, 3+
Ionic radius, Å	1.33	1.47	1.47 (1+) 0.95 (3+)
Electronegativity, eV	0.8	0.8	1.5 (1+) 1.9 (3+)
Ionization potential, eV	4.339	4.176	6.106 (1+) 29.8 (3+)
Relative total bonding energy (Kcal/g-atom)	K-O 90	Rb-O 85	Tl^{1+}-O 74

Data from: Ahrens (1952), Heydemann (1969), Nockolds (1966)

Although thallium belongs to the 3a subgroup of the periodical system it can be seen that its crystallochemical properties in the 1+ valence state are very similar to those of the alkalies.

In natural processes all three elements form a coherent group. Since isomorphic replacement largely depends on: (1) ionic radius, (2) valence, (3) bond type, it can be expected that Rb^{1+} and Tl^{1+} will readily enter the monovalent positions in most potassium bearing minerals. Rubidium is always incorporated in K-minerals and forms no minerals of its own.

The Tl minerals are very rare in nature and are only formed under supergene conditions (Vlasov, 1966). However the bulk of Tl is found in K-minerals and sulphides.

The main concentrators of alkali metals and Tl in silicate rocks are micas and feldspars. The Rb and Tl contents of these minerals increases with increasing "differentiation" of the host rock and is at a maximum in late-stage pegmatite K-minerals.

The Rb^{1+} and Tl^{1+} ions are larger than K^{1+} and are preferentially incorporated in 12-coordination in micas relative to K-feldspars and other K-minerals (8-10 coordination). This is demonstrated by the K/Rb and K/Tl ratios of coexisting K-feldspars and micas, which are always lower in the latter (Heier and Adams, 1964; Tauson and Buzayev, 1957; Kolbe, 1966).

The Rb/Tl ratios on the other hand are similar for coexisting biotite and feldspar (Voskresenskaya, 1959).

Since the regional geology of the area under study indicates that magmatic, hydrothermal and metamorphic processes have been active, a short review of the behaviour of K, Rb and Tl during these processes will be given.

For several years many authors maintained that the K/Rb ratio is fairly constant for most igneous rock series (e.g. Ahrens, Pinson and Kearns, 1952; Ahrens and Taylor, 1961; Heier and Adams, 1964; Taylor, 1965). These authors and others, have also pointed out that the K/Rb ratio only decreases in rocks such as pegmatites which are usually produced by extreme fractionation. In recent years however the correctness of this hypothesis has been disputed. It is generally agreed now that in rocks formed in the initial and final stages of magmatic differentiation the K/Rb ratios may differ significantly from the "normal" value of 230 (commonly accepted average for continental crust). Values as high as 2000 are found for tholeiitic basalts (Gast, 1965) and are as low as 80 for pegmatites and late-stage granites. It therefore follows that Rb is enriched relative to K during increasing differentiation. The main reason for this relative concentration of Rb is the difference between the ionic radii Rb^{1+} and K^{1+} (Taylor and Heier, 1960) and the trend which leads to the crystallization of micas (calc-alkalic trend) (Shaw, 1968).

The behaviour of Tl during magmatic processes is not very well known, because of the lack and generally doubtful quality of the data. From the few existing data it seems that Tl largely shows the same behaviour as Rb during the magmatic process, which is to be expected since Tl has the same ionic radius as Rb. K/Tl ratios seem to have the same characteristic as K/Rb ratios; they only decrease in the ultimate stages of differentiation.

The Rb/Tl covariance is more strongly developed than either K/Rb or K/Tl. Rb/Tl ratios appear to be very constant throughout magmatic fractionation, although relative enrichment of Tl in the last stages seems to occur. This effect was explained by several authors (Ahrens 1952; Kogarko, 1959; Voskresenskaya, 1959; Heier and Adams, 1964) as being due to difference in bond type between Rb-O and Tl-O bond, the latter being more covalent. This is reflected in the ionization potential and electronegativity for Rb and Tl (see Table 1). Since K-feldspars and micas tend to accumulate the elements with a stronger polar bonding, Rb will preferably enter into those structures, and later differentiates will be relatively enriched in Tl.

By contrast, an increase of K/Rb and Rb/Tl ratios during fractionation has been noted in some alkalic complexes (Payne and Shaw, 1967) as well as erratic behaviour (Gerasimovskii and Lebedev, 1959; Butler, 1962; White, 1966).

The chalcophile properties of Tl and its characteristic duality (occurrence in K-silicates on the one hand, and in various sulphides on the other) are the most pronounced during hydrothermal processes. Sometimes iron sulphides containing large amounts of thallium (tenths of a per cent!) have been observed in USSR and Yugoslavia (Vlasov, 1966).

The Rb content of potassium minerals from hydrothermal deposits is substantially lower than in those formed during magmatic processes. Hydrothermal alteration of pre-existing rock leads frequently to a relative enrichment in Tl with comparison with Rb and K. Three-fold enrichment in Tl is reported by Voskresenskaya et al. (1962) for the pyritized and limonitized porphyries of the Greater Caucasus and slight enrichment in kaolinized and opalized granosyenite porphyries than in unaltered rock. A particularly striking example is found in Tyrny-Auz (Voskresenskaya, 1959) where marmorized limestone adjacent to a granite body shows a thousand-fold enrichment in Tl.

Potassium metasomatism is accompanied by enrichment in Tl (Ivanov et al., 1969; Sitnin, 1960; Voskresenskaya, 1961), and during albitization K and Tl are removed more intensively than Rb (Voskresenskaya, 1959).

There is no indication of systematic variation in K and Rb concentrations during regional metamorphism until the level of granulite facies is reached, where due to the breakdown of biotite the K/Rb ratio increases (Heier, 1960; Lambert and Heier, 1968; Whitney, 1969; Sighinolfi, 1969). The distribution of Tl in metamorphic rocks has not yet been thoroughly investigated but a few figures indicate that Tl might be depleted in granulite facies rocks (Shaw, 1952; Heier, 1960).

3. ANALYTICAL METHODS

Thallium was determined spectrographically, following pre-enrichment by anion-exchange. The method, described by R.R. Brooks, L.H. Ahrens and S.R. Taylor (1960) was modified for the determination of Tl by J. Muysson and C.A.R. de Albuquerque.

The procedure is based on the fact that several elements (e.g. Tl, Au, Bi, Cd, Zn, ...) form chloro-complexes in hydrochloric acid. These may be absorbed on a basic anion exchanger. Since abundant elements (O, Al, Si, Na, K, Ca, Mg, Ti) do not form complexes, separation and concentration of the complex-forming elements can be achieved. Iron forms a weak complex and does not present a problem, as very little is absorbed when 1N HCl is used. Tl^{+3} forms a strong chlorocomplex at this normality and is completely retained by the resin at low concentrations. Absorbed elements were eluted from the ion-exchange column, concentrated by evaporation, and the residue was analyzed spectrographically for thallium.

3.1. Preparation of samples and chemical procedure

About 250 g of rock chips were crushed in a tungsten carbide rock-pulverizer and sieved through a 100 mesh sieve. The amount of sample taken for analysis varied, depending on the expected contents of K, Rb and Tl. One gram portions were taken for the analysis of granites, 2-5 g for amphibolites, and 5-10 g for marbles. Dissolution of the sample was achieved by a preliminary treatment with a mixture of concentrated hydrofluoric and perchloric acids (3:1), followed by treatment with hydrofluoric acid alone and then perchloric acid alone, each added after an intervening step of evaporation. After evaporation of acids and fuming off the perchloric acid, the cake was taken up with HCl and diluted to 1N HCl concentration. The final volume for ion exchange was 50 ml per gram of sample. A small quantity (1 ml) of bromine water was added as an oxidizing agent, because Tl forms a strong chloro-complex only in its highest valency state (Tl^{3+}).

The prepared solution was passed through a 0.9 x 10 cm column of basic anion exchanger DOWEX-1-X8 at a rate not exceeding 50 ml per hour. The flow rate was controlled by stop-cocks.

Atomic absorption spectroscopy was employed for the determination of Rb and K in the effluent, collected from the column (for conditions see page 13).

Elution of Tl from the resin required 600 ml of 0.25 N HNO_3 containing H_2O_2 1% ($^v/_v$). Most of the Tl was released in the first 200 ml.

The eluate was evaporated to low volume, transferred to a weighed porcelain evaporating dish, evaporated and weighed. Approximately 5 mg of residue was thus obtained from granite and 10 mg from amphibolite and marble. The residue was taken up with HCl, and a solution of LiCl (containing In) was added, to aid in collecting the residue and to serve as an internal standard for the subsequent spectrographic analysis. Careful handling of the evaporated residue was necessary to prevent water absorption due to the hygroscopic properties of LiCl.

3.2. Spectrographic procedure

3.2.1. Choice of an internal standard

The factors concerning the choice of an internal standard are listed by Ahrens and Taylor (1961, p. 91):

"(I) If the internal standard is to be added, its concentration in the analysis specimens should be negligibly low.

(II) The rates at which internal standard and analysis element volatilize should be very similar.

(III) Internal standard and analysis lines should have similar excitation potentials.

(IV) The internal standard line should be free from self-absorption.

(V) Analysis and internal standard lines should be roughly the same wavelength, so as to reduce errors that occur in the photographic measurement of radiant energy.

(VI) If the internal standard is added, it should be in a very high state of purity with respect to the elements sought.

(VII) The ionization potential of the internal standard element should be similar to that of the analysis element.

(VIII) The atomic weight of the internal standard element should preferably not differ very greatly from that of the analysis element if either is a light element.

(IX) Finally, if a large variety of samples is to be analyzed, the internal standard line should, if possible, behave in such a way that the intensity ratio of the analysis pair is comparatively insensitive to changes of matrix and composition."

Data from the literature and preliminary work indicated that indium would be a suitable internal standard, because of the similarity in the configuration of the outer electrons of the In and Tl atoms.

The points discussed by Ahrens and Taylor may be answered as follows:

(I) Since the In content of the analyzed rocks should be approximately the same as their Tl content, it would be expected that the In content of the analyzed residue would be negligibly low, since In is retained in the resin at a level $\sim 10^{-6}$ Tl.

(II) The volatilities of Tl and In compounds present are high.

(III) Excitation potential of Tl (5350.46 Å) is 3.27 eV and In (4511.325 Å) is 3.01 eV.

(IV) Tests at different concentrations of indium gave no indication of self-absorption for In (4511.325 Å).

(V) Wavelength of Tl line is 5350.46 Å and In line is 4511.325 Å.

(VI) Johnson-Matthey "specpure" chemicals were used.

(VII) The ionization potential of Tl is 6.12 eV and In is 5.79 eV.

(VIII) Both are heavy elements; at. w. of Tl is 204.37 and In is 114.82.

(IX) Since the matrix usually makes up 90 weight per cent of the analyzed powder and the matrix used is always the same the internal standard line is not expected to be affected by different starting materials.

3.2.2. Choice of a matrix

In view of the high volatility of In and Tl an alkali metal compound can be used as a suitable matrix. Initially NaCl matrix was used but this was later rejected because a Na line (4668.60 Å) affected the In line (4511.325 Å) and its background. The LiCl matrix was finally chosen as showing no inference effects at all, and was found to be a very good carrier since its volatility is very close to those of $TlCl_3$

and $InCl_3$.

3.2.3. Spectrographic determination

To the sample residues from ion exchange extraction were added 43 mg of LiCl containing In to give a final concentration of 3 ppm in solution. Artificial thallium standards were prepared in concentrations of 1, 2, 5, 10, 25, 50 ppm Tl, each containing the same amount of LiCl and In as the samples. Standards and samples were arced in triplicate in graphite electrodes.

Complete spectrographic parameters are given in Table 2.

3.3. Atomic absorption spectrometry

Potassium and rubidium were determined with a model 303 Perkin-Elmer atomic absorption spectrometer. Instrumental parameters used are given in the Perkin-Elmer reference manual: Revision of Analytical Method for Atomic Absorption Spectroscopy (1968). Standard solutions were prepared from specpure substances. Sampling of the solutions was done automatically and the readings were processed by computer.

Rubidium was determined on the effluent from the anion exchange column. To minimize the effect of other alkali metals an

Table 2

Spectrographic analysis parameters

Spectrograph	Jarrell-Ash, 21 ft grating instrument. Wadsworth mount, first order dispersion, 5.2 Å/mm
Electrodes	anode - Ultra Carbon Co. cat. no. 1677, grade U-2 cathode - Ultra Carbon Co. graphite rod, 3.05 mm diameter
Slit width and length	30 microns; 10 mm
Intensity control	7-step sector, log intensity ratio = 0.2 per step, 1 screen
Arc gap	4.5 mm
Diaphragm	with 3 mm aperture
Current	6.5 amps D.C.
Exposure	45 sec.[1]
Wavelength	4300 - 5600 Å
Plate	Eastman Kodak, type 103 a - G
Processing	3 minutes in Kodak D 19 developer at 20°C, 15 seconds in stop bath, 4 minutes in Kodak rapid fixer
Photometry	Jarrell-Ash recording microphotometer
Calibration	4-step method, using transmission values obtained on each analytical line from sample and standard spectra. Results checked by computer calibration

[1] By moving plate exposure it was found that no Tl and In were recorded after 30 second exposure. A longer exposure was chosen in order to provide a slight general background to the spectra

ionization buffer (= 1% $^w/_v$ solution of Na as NaCl) was added to give a final concentration of 10,000 ppm Na. A vapor-discharge lamp was used as the light source.

Potassium was determined after appropriate dilution (1:10, 1:20, 1:50) according to the content of K_2O expected. Enough Na buffer was added to give 5000 ppm Na in the final volume. A hollow-cathode lamp was used as the light source.

3.4. Sensitivity, precision and accuracy

All determinations for K_2O were made at least in duplicate, but not all for Rb and Tl. Precision of the data, expressed as relative standard deviation C (%), was calculated from all duplicate determinations. If there are n pairs of duplicate values x_{1i} and x_{2i}, and if the coefficient of variation is c, then

$$c^2 = 2n \frac{\Sigma(x_{1i} - x_{2i})^2}{[\Sigma x_{1i} + x_{2i}]^2}$$

(see Bennett and Franklin, 1954, p.168)

The results are in Table 3, together with the sensitivity limit and detection limit for each element. The sensitivity limit is the level below which a signal or intensity of spectral line cannot be profitably corrected for background. The detection limit (n.d.) is the point below which no signal or line can be detected. Observations between the sensitivity limit and detection limit have poor precision.

Accuracy was tested against the rock standards G-1, G-2, W-1 and GSP-1 (they were not used in calibration). Results are listed in Table 4. G-2 and W-1 were done in duplicate. Table 5 shows a comparison of results for K_2O for samples analyzed both by atomic absorption spectrometry and by flame photometry.

Table 3

Precision, sensitivity and detection limits
for K, Rb and Tl

Element	Precision C (%)	Sensitivity limit (ppm in rock)	Detection limit (ppm in rock)
K	1.3	10[1]	5[1]
Rb	4.5	3	0.4
Tl	6.9	0.014	0.007

[1] Usual values. All concentrations determined for K were higher than these limits

Table 4

Results on some standard reference samples

	K_2O (%)		Rb (ppm)		Tl (ppm)	
Standard rock	This paper	Recommended value[1]	This paper	Recommended value[1]	This paper	Recommended value[1]
G-1	5.51	5.48	216	220	1.31	1.3
G-2	4.56 4.55	4.51[2]	162 163	174[4] 108-513	0.89 0.94	0.85 1.3[5]
W-1	0.62 0.64	0.64	19 20	22	0.098	0.13
GSP-1	5.53	5.48[3]	245	260 200-692	1.22	0.71 1.6[5]

[1] Flanagan, 1969; Fleischer, 1969

[2] Average of 22 reported values (Flanagan, 1969; Fleischer, 1969)

[3] Average of 20 reported values (Flanagan, 1969; Fleischer, 1969)

[4] Median and range of 19 reported values (Flanagan, 1969; Fleischer, 1969)

[5] Only 2 values were reported; not yet recommended (Flanagan, 1969; Fleischer, 1969)

Table 5

Comparison of atomic absorption spectroscopy (AAS) and flame photometry (FP) analyses of K_2O (wt.%)

Sample n	I AAS[1]	AAS[2]	Sample n	II AAS[1]	FP[3]
1	5.19	5.12	5	4.56	4.31
2	4.69	4.64	11	1.77	1.74
3	5.07	5.06	12	1.41	1.36
6	5.11	5.12	13	1.46	1.42
8	5.72	5.78	14	3.33	3.36
9	3.91	4.03	25	2.30	2.28
32	8.41	8.45	26	3.06	3.06
10	4.17	4.21	27	2.47	2.45
15	0.08	0.09	29	8.28	7.84
17	0.26	0.25	30	7.03	6.76
24	1.42	1.43	31	6.68	6.40
16	0.14	0.13	33	1.57	1.54
18	0.20	0.20	34	1.89	1.83
20	0.44	0.44	41	4.76	5.19
19	0.44	0.42	42	2.87	2.86
21	1.70	1.74	43	1.95	1.57
23	2.19	2.16			

[1] Analyses by M. Pacesova

[2] Analyses by J.R. Muysson

[3] Flame photometry analyses by J.R. Muysson (1963), in Chesworth (1967)

Analyses made on the same powder by each method, except for samples 5 and 43

4. GEOLOGICAL SETTING

This study covers an area of Glamorgan Township, the Haliburton Highlands, situated about 100 miles north of Toronto (Ontario, Canada) (Fig. 1). The rocks in Glamorgan Township are dominantly granitoid (90%). Minor amounts of diorite, gabbro and syenite also occur in the metamorphic terrane. This complex forms part of the Grenville province, which is the southeastern-most part of the Canadian Precambrian Shield.

Age relations in the Haliburton Highlands and distribution of rocks in the studied area are shown in Table 6.

Works by several authors confirm that these rocks have been affected by upper amphibolite facies metamorphism and form part of a low pressure intermediate facies series (as defined by Miyashiro, 1962).

Figure 1

General location map (Ontario, Canada)

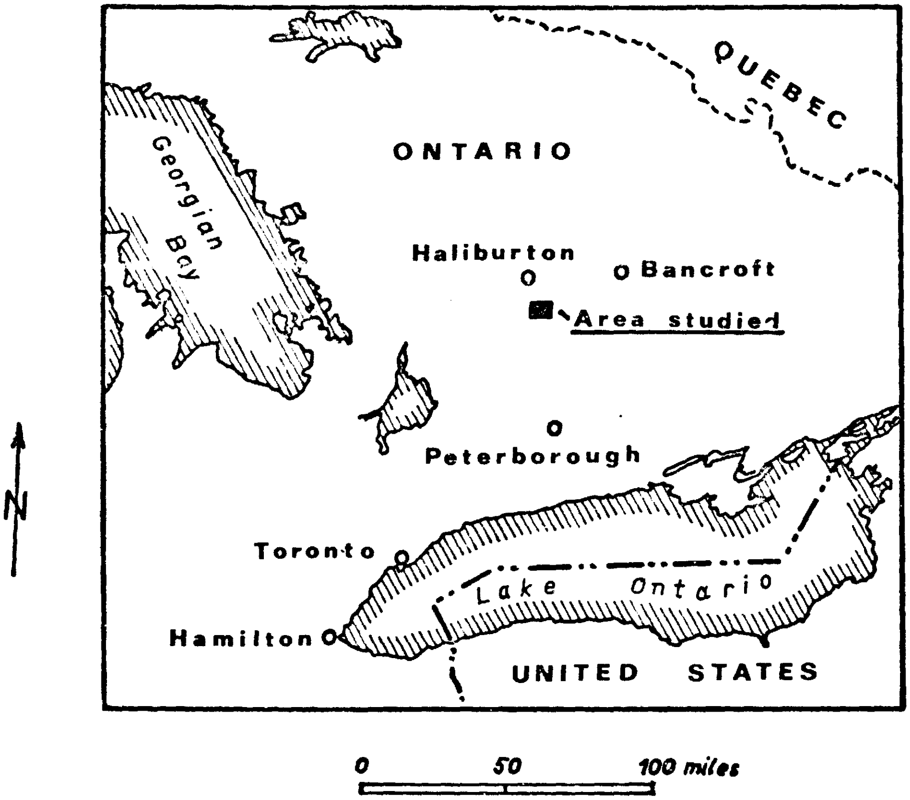

QUEBEC
ONTARIO
Georgian Bay
Haliburton
Bancroft
Area studied
Peterborough
Toronto
Hamilton
Lake Ontario
UNITED STATES
N
0
50
100 miles

Table 6

Age relations in the Haliburton Highlands and distribution of the rocks in the studied area (after Chesworth, 1967, 1971)

Age in m.y.	Dominant events	Lithological proportions in the studied area		
1300-1400	Grenville group sedimentary and volcanic rocks laid down	Grenville series	Marble	5%
			Paragneiss	2%
			Amphibolites and quartzite	1%
1200-1300	Pre-metamorphic intrusions (neph. syenite, gabbro, diorite)		Diorite	2%
1000-1200	Metamorphism with formation of granite, pegmatite and migmatite	Granitoid rocks	Pink granite	10%
			Granodiorite gneiss	17%
			Migmatite	62%
			Pegmatite	1%
900	Post-metamorphic intrusions (pegmatite)			

5. PETROLOGY AND CHEMISTRY

The rock samples were collected from an area of about 50 square miles.

Two series of samples were analyzed for K, Rb and Tl. The first series comprises samples collected by W. Chesworth, who analyzed them for major elements. The powdered rock samples were available in the Department of Geology, McMaster University, and K, Rb and Tl determinations were performed by me on 32 of them. Values of major elements and modes are taken from Chesworth (1967): these samples are designated in the tables by WCH.

The second series of rock samples was collected by me. In these samples major elements were determined by J.R. Muysson, and norms, modes and K, Rb, Tl analyses were done by the author (these samples are designated in the tables by index MP). Additional rocks analysed by Chesworth are referred to in the discussion, although not analysed for Rb, Tl.

Chesworth made a systematic sampling according to a pre-arranged grid pattern (see Chesworth, 1967, pp. 64-68). My samples were chosen chiefly with regard to distance from the contacts.

Geologic and petrologic information on rocks in Glamorgan township has been obtained during several investigations (e.g. Adams and Barlow, 1910, 1913; Foye, 1916; Hewitt and Satterly, 1957; Armstrong, 1958; van de Kamp, 1968; Chesworth, 1967, 1968, 1970a,b, 1971). Therefore the petrological details will be summarized only briefly and supplemented by my own observations. The rocks will be described in approximate order of decreasing age.

5.1. Paragneiss

The paragneiss is a fine-grained grey gneiss. Two types were found in the region studied. The least-altered paragneiss is composed dominantly of biotite, plagioclase and quartz, with microcline, pyrite, magnetite, apatite, calcite and graphite as accessory minerals. The rock contains no granitoid bands (distant from granite and migmatite) and is sometimes interbedded with marble.

The second type is more altered paragneiss, called by Chesworth amphibolitic paragneiss. Hornblende and microcline accompany plagioclase, biotite and quartz. Sphene is an additional accessory mineral, while calcite is absent. This rock appears to be intermediate between the least altered paragneiss and migmatite. It occurs in the field with sparse conformable granitic veins and is found also on edges of the least-altered paragneiss bodies.

Chemical analyses, norms and modes are given in Table 7.

Table 7

Chemical analyses of paragneiss (wt.%)

Sample no.	Least-altered 11 WCH	12 WCH	Amphibolitic* 13 WCH	14 WCH
SiO_2	64.80	66.86	65.50	65.40
TiO_2	0.95	0.70	0.94	0.53
Al_2O_3	16.10	15.09	15.20	15.30
Fe_2O_3	2.30	1.97	3.01	1.21
FeO	3.03	2.69	2.77	2.71
MnO	0.07	0.08	0.15	0.06
MgO	1.75	1.72	1.50	2.43
CaO	3.40	3.92	3.80	3.03
Na_2O	4.92	4.43	4.93	4.38
K_2O	1.74	1.36	1.42	3.36
P_2O_5	0.29	0.16	0.29	0.09
H_2O+	0.64	0.69	0.29	0.56
H_2O-	0.06	0.18	0.02	0.08
CO_2	0.22	0.16	0.02	0.31
Sum	100.27	100.01	99.84	99.45
K (%)	1.47	1.17	1.21	2.76
Rb (ppm)	57	60	32	68
Tl (ppm)	0.43	0.48	0.27	0.28
K/Rb	258	195	378	406
$K/Tl.10^{-2}$	342	244	448	986
Rb/Tl	133	125	119	243

*Amphibolitic paragneiss relicts in migmatite. Sample 14 is contaminated by a little micropegmatite, occurring in a fine veinlet in the rock (Chesworth, 1967)

Table 7 (continued)

	Norms			
	11	12	13	14
Quartz	18.7	23.3	20.3	15.5
Corundum	1.3	-	-	-
Orthoclase	10.3	8.2	8.5	20.0
Albite	44.4	40.4	44.8	39.7
Anorthite	13.7	17.5	15.3	12.3
Enstatite	4.9	4.8	3.7	6.7
Ferrosilite	1.9	2.0	1.0	2.7
Magnetite	2.4	2.1	3.2	1.3
Ilmenite	1.3	1.0	1.3	0.7
Calcite	0.6	0.4	0.05	0.8
Apatite	0.6	0.3	0.6	0.2
Diopside	-	-	1.1	0.2
Hedenbergite	-	-	0.3	0.1
	Modes			
Microcline	-	tr.	8.0	11.4
Plagioclase	46.8	53.1	55.8	45.6
Quartz	32.3	27.6	22.1	25.7
Biotite	18.6	19.0	4.6	5.2
Hornblende	-	-	8.9	11.0
Accessories	1.3	0.3	0.6	1.1
Plag. comp.	An_{22}	An_{24}	An_{25}	An_{22}

Equivalent cation norms were calculated on a CDC-6400 computer using a programme prepared by D.M. Shaw

5.2 Marble

Several types of marble are found in Glamorgan township. All are coarsely crystalline (2-10 mm). Nearly pure marble is found away from the contact with granite. The closer to the granite, the more silicated the marble becomes. This altered marble is rich in scapolite and diopsidic clinopyroxene besides calcite, with subordinate quartz, common hornblende, phlogopite and tremolite. Accessory minerals are graphite, sphene, apatite, epidote, magnetite, pyrite. Mosaic texture is common in thin section with fine layering due to concentration of silicates. Close to the contact a marble-granite migmatite is found. Directly adjacent to the granite, a selvedge of pyroxene with grains of amphibole is usually present.

Chemical analyses are given in Table 8.

5.3. Para-amphibolite

Para-amphibolite occurs as layers from 0.5 cm - 1 m or more in thickness, in the scapolite marbles and scapolite-diopside gneiss. The major minerals are common hornblende (brown-green), plagioclase (An_{26-35}), scapolite (Me 30-55) and green diopsidic clinopyroxene: sphene, phlogopite, apatite, zircon, pyrite, magnetite, calcite and microcline form additional minor phase. The rock has granonematoblastic texture.

Chemical analyses are given in Table 9.

Table 8

Chemical analyses of marbles (wt.%)

Sample No.	15 MP	16 MP	17 MP	18 MP	19 MP	20 MP
Variety	Pure marble	Altered marble			Contact skarn	
SiO_2	0.87	24.44	21.16	23.12	53.09	50.06
TiO_2	0.00	0.33	0.22	0.20	0.76	0.81
Al_2O_3	-	6.30	5.70	5.41	10.77	10.89
Fe_2O_3	0.03	0.69	0.64	0.41	2.95	2.98
FeO	0.10	1.88	1.79	2.50	6.34	6.06
MnO	0.02	0.07	0.08	0.10	0.20	0.20
MgO	3.89	3.43	3.43	2.88	5.67	5.79
CaO	51.58	37.87	39.29	38.50	13.70	16.75
Na_2O	-	1.44	1.33	1.72	3.19	3.08
K_2O	0.09	0.13	0.25	0.20	0.42	0.44
P_2O_5	0.03	0.07	0.05	0.05	0.13	0.16
H_2O+	0.19	0.35	0.41	0.32	1.24	0.74
H_2O-	0.05	0.12	0.22	0.14	0.76	0.49
CO_2	43.24	22.68	24.88	23.85	0.74	0.40
S					0.32	0.34
Cl					0.29	0.76
Sum	100.09	99.80	99.45	99.40	100.57	99.85
Less (O≡Cl,S)					0.19	0.30
Total					100.38	99.55
K (%)	0.065	0.11	0.21	0.17	0.36	0.36
Rb (ppm)	(0.5)	(0.6)	4.5	3	5.5	5.5
Tl (ppm)	tr.	0.051	0.089	0.083	0.13	0.14
K/Rb	very high		471	567	654	654
$K/Tl.10^{-2}$	v.h.	216	236	205	277	257
Rb/Tl	v.h.		50	36	42	39

Sample 19 is adjacent to sample no. 9 of pink granite

Sample 20 is adjacent to sample no. 32 of pink granite

Table 9

Chemical analyses of para-amphibolite (wt.%)

Sample No.	21* MP	22 MP	23 MP	24 MP
SiO_2	49.48		42.68	50.67
TiO_2	0.62		1.23	1.01
Al_2O_3	13.77		16.40	16.28
Fe_2O_3	1.58		3.58	2.70
FeO	5.41		8.04	7.13
MnO	0.12		0.14	0.15
MgO	4.29		7.30	5.62
CaO	16.00		11.02	8.83
Na_2O	3.45		3.10	4.29
K_2O	1.74		2.16	1.43
P_2O_5	0.15		0.10	0.20
H_2O+	0.49		1.24	0.96
H_2O-	0.13		0.11	0.09
CO_2	1.99		0.31	0.18
S	0.06		0.38	
Cl	0.41		0.40	
Sum	99.69		98.19	99.54
Less (O≡S,Cl)	0.12		0.23	
Total	99.57		97.96	
K (%)	1.41	1.04	1.82	1.18
Rb (ppm)	44	27	85	25
Tl (ppm)	0.43	0.30	0.65	0.36
K/Rb	321	385	213	472
$K/Tl.10^{-2}$	326	347	280	328
Rb/Tl	102	90	133	68

*Sample 21 is a calc-silicate rock with thin layers of amphibolite

5.4. Granitoid rocks

Four types of granitoid rocks are found in Glamorgan township:

granodiorite gneiss (GG)
pink granite (PG)
pegmatitic veins
migmatite

Modal analyses of these granitic rocks (except pegmatite veins, which are too coarse to determine the mode from a thin section) are plotted in Figure 2, along with classifications of granitic rocks after Johannsen (1939) and Streckeisen (1967). The composition of the rocks is seen to range from granodiorite to granite. The content of biotite increases from granite to granodiorite.

Samples of pink granite introduced by Adams and Barlow (1910) fall into the field of adamellite (Johannsen) or granite (Streckeisen).

The granodiorite gneiss and granodiorite bands of migmatite were called by Adams and Barlow and Chesworth (1967, 1968, 1971) "grey granite gneiss". Chesworth (1970b) also used the name "trondhjemite gneiss".

In the field migmatite is observed to grade into paragneiss on the one hand and into granodiorite gneiss or pink granite on the other. The granodiorite gneiss is, however, older than pink granite and pegmatites, which cross-cut it.

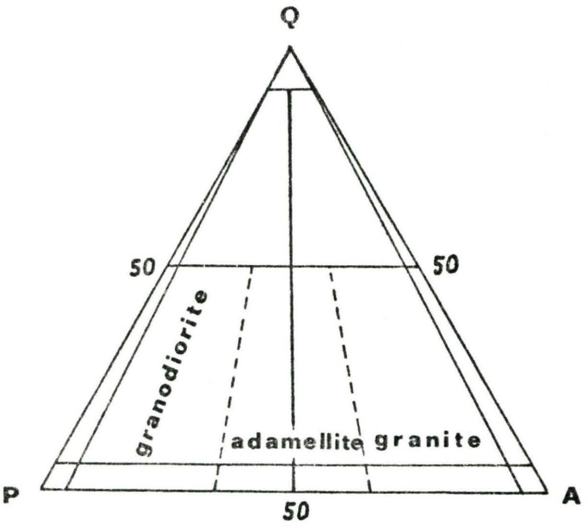
Figure 2

Classification of modal composition of the granitic rocks from Glamorgan township

(a) Classification according to A. Johannsen (1939)

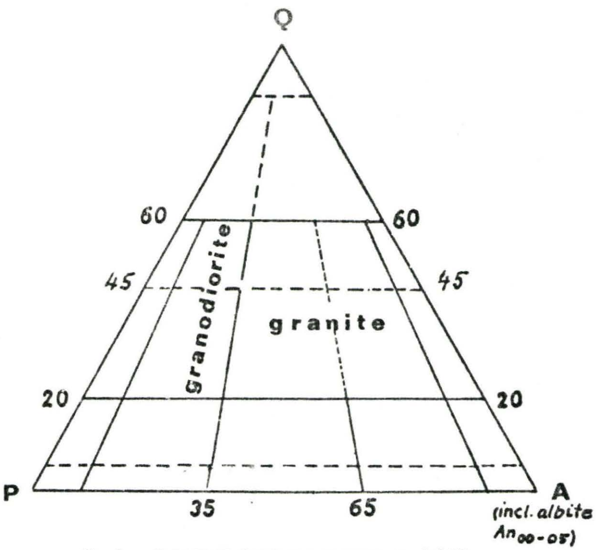
(b) Classification according to A.L. Streckeisen (1967)

(c) Granitic rocks from Glamorgan township. Solid circles - pink granite and pink granite bands of migmatite. Open circles - granodiorite gneiss and equivalent bands of migmatite. Top of line through each point marks the percentage of plagioclase + alkali feldspar; bottom of line marks percentage of quartz. Vertical distance between ends of line marks percentage of ferromagnesian + accessory minerals.



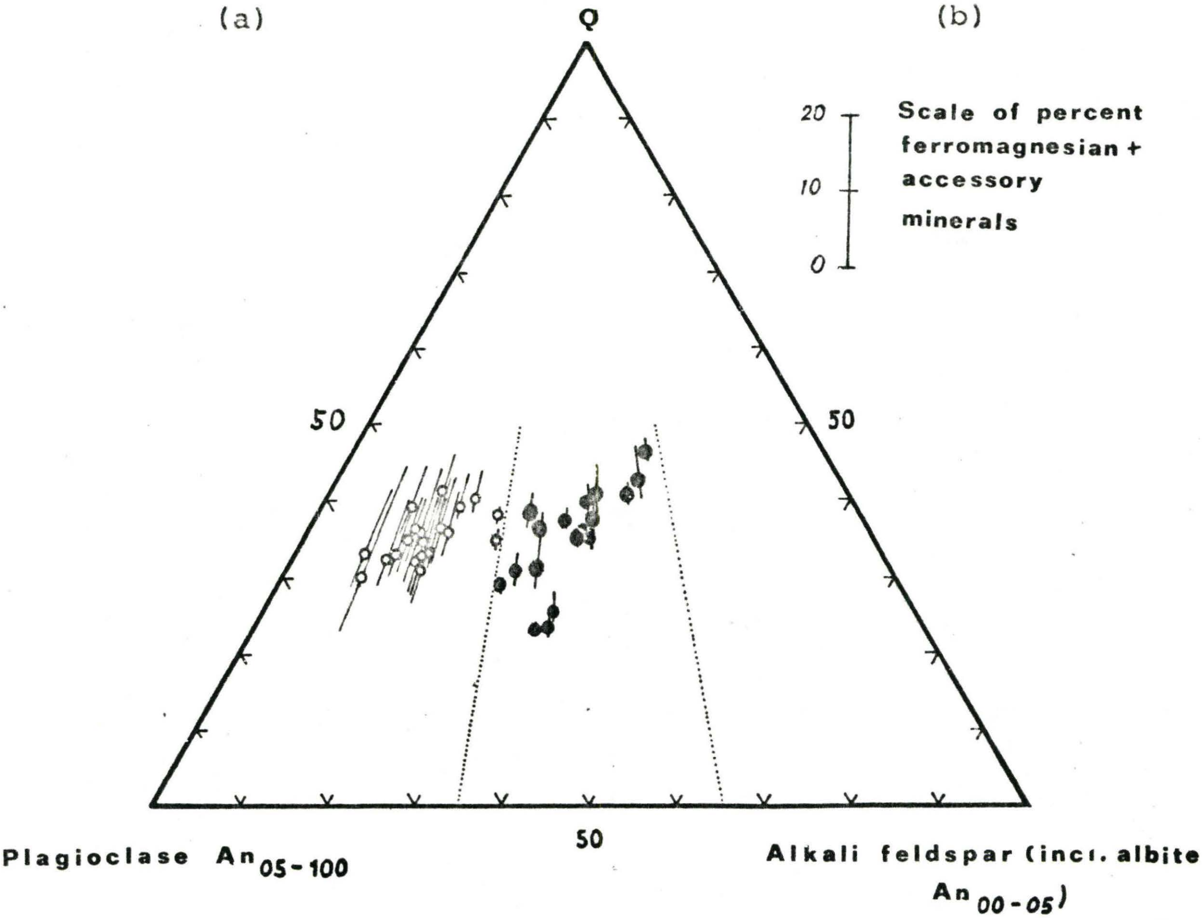
A. JOHANNSEN (1939)

(a)



A.L. STRECKEISEN (1967)

(b)



(c)

The age relations of the pink granite and pegmatite cannot be unambiguously determined from field evidence. At some outcrops pink granite appears to be older than pegmatite, elsewhere the relationship seems to be reversed.

5.4.1. Granodiorite gneiss

Granodiorite gneiss is grey and well-foliated. It forms intrusive bodies, as well as leucocratic layers in migmatite, and dikes which discordantly cut the paragneiss.

The granodiorite gneiss consists chiefly of quartz, microcline, plagioclase and biotite, with minor hornblende and magnetite: apatite, sphene and zircon are accessories.

Chemical analyses, modes and norms are given in Table 10.

5.4.2. Pink granite

Pink granite is a fine- to medium-grained, weakly to well-foliated rock. Mineralogically it is remarkably uniform and quartz, plagioclase and microcline make up more than 95 per cent of the rock. Biotite is the chief dark mineral, and accessory minerals include tourmaline, zircon, apatite, sphene, muscovite, fluorite, and hematite. Myrmekite and perthite are common. The texture is hypidiomorphic granular.

The pink granite occurs in intrusive bodies (the biggest one being south of Stormy Lake), discordant lenses,

Table 10

Chemical analyses of granodiorite gneiss (wt.%)

Sample No.	25 WCH	26 WCH	27 WCH
SiO_2	69.71	72.00	70.60
TiO_2	0.67	0.44	0.46
Al_2O_3	14.08	14.20	14.00
Fe_2O_3	2.33	1.59	1.86
FeO	1.92	1.57	1.78
MnO	0.11	0.03	0.05
MgO	0.87	0.81	0.72
CaO	2.37	1.86	1.80
Na_2O	4.45	4.25	4.47
K_2O	2.28	3.06	2.45
P_2O_5	0.21	0.12	0.14
H_2O+	0.36	0.36	0.39
H_2O-	0.11	0.05	0.03
CO_2	0.04	0.00	0.02
Sum	99.51	100.34	98.77
K (%)	1.91	2.54	2.05
Rb (ppm)	61	79	65
Tl (ppm)	0.38	0.50	0.39
K/Rb	313	322	315
$K/Tl.10^{-2}$	503	508	526
Rb/Tl	161	158	167

Table 10 continued

	Norms		
	25	26	27
Quartz	27.5	28.3	28.7
Corundum	0.6	0.9	1.2
Orthoclase	13.7	18.2	14.8
Albite	40.7	38.5	41.1
Anorthite	10.3	8.5	8.1
Enstatite	2.5	2.3	2.0
Ferrosilite	0.6	0.8	0.9
Magnetite	2.5	1.7	2.0
Ilmenite	1.0	0.6	0.7
Calcite	0.1	-	0.05
Apatite	0.5	0.3	0.3
		Modes	
Microcline	10.6	14.8	11.9
Plagioclase	51.1	44.4	48.2
Quartz	30.2	32.3	32.1
Biotite	6.7	7.4	6.8
Hornblende	tr.	-	tr.
Accessories	1.4	1.1	1.0
Plag. comp.	An_{19}	An_{21}	An_{21}

dikes and veins. It also forms layers in migmatites.

Chemical analyses, norms and modes are given in Tables 11 and 12.

5.4.3. Pegmatitic veins

Pegmatitic veins are coarse to very coarse. They range from a few centimeters to several metres wide. Pegmatite also appears in lenses and patches. Pegmatites have a simple mineralogy: microcline (60%), plagioclase (albite) (20%) and quartz (20%). Biotite, tourmaline and scapolite occur in some samples.

Chemical analyses are norms are given in Table 13.

5.4.4. Migmatite

The migmatite nomenclature used here follows the definitions recommended by Mehnert (1968):

(1) The paleosome, i.e. the unaltered or only slightly modified parent rock or country rock.

(2) The neosome, i.e. the newly formed rock portion. Here again two rock types are distinguishable as a rule, viz:

  a. The leucosome containing more light minerals (quartz and/or feldspar) with respect to the paleosome;

Table 11

Chemical analyses of pink granite (wt.%)

Sample No.	1 MP	2 MP	3 MP	4 MP	5 WCH
Location within the granite body	Core	Core	Margin	Margin	Margin
SiO_2	76.84	77.42	77.60		77.90
TiO_2	0.14	0.14	0.18		0.15
Al_2O_3	12.00	11.76	11.81		12.70
Fe_2O_3	0.83	0.76	0.78		1.10
FeO	0.56	0.54	0.43		0.52
MnO	0.02	0.02	0.02		-
MgO	0.12	0.14	0.13		0.22
CaO	0.42	0.50	0.36		0.43
Na_2O	3.30	3.58	3.40		3.09
K_2O	5.12	4.64	5.06		4.31
P_2O_5	0.02	0.01	0.01		-
H_2O+	0.29	0.30	0.25		0.22
H_2O-	0.03	0.01	0.04		
CO_2	0.05	0.06	0.06		-
Sum	99.74	99.88	100.13		100.6
K (%)	4.31	3.89	4.21	3.47	3.79
Rb (ppm)	132	115	112	82	85
Tl (ppm)	0.52	0.44	0.66	0.64	0.59
K/Rb	326	338	376	422	446
$K/Tl.10^{-2}$	829	884	638	542	642
Rb/Tl	254	260	169	128	144

Table 11 continued

	Norms				
	1	2	3	4	5
Quartz	35.1	35.5	35.4		39.6
Corundum	0.5	0.1	0.3		2.4
Orthoclase	30.9	27.9	30.4		25.8
Albite	30.2	32.7	31.0		28.1
Anorthite	1.7	2.1	1.4		2.2
Enstatite	0.4	0.4	0.4		0.6
Ferrosilite	0.1	0.1	-		-
Magnetite	0.9	0.8	0.7		0.9
Ilmenite	0.2	0.2	0.3		0.2
Calcite	0.1	0.2	0.2		-
Apatite	0.04	0.02	0.02		-
Hematite	-	-	0.1		0.2
	Modes				
Microcline	19.9	15.0	17.1	22.2	16.0
Perthite	8.1	14.3	15.2	8.7	15.1
Plagioclase	33.0	29.2	31.5	31.7	32.5
Quartz	36.2	38.8	33.2	34.6	34.5
Biotite	2.1	1.4	1.6	1.1	1.0
Muscovite	0.1	0.3	0.3	0.7	-
Accessories	0.6	1.0	1.1	1.0	0.9
Plag. comp.	An_{12}	An_{10}	An_{16}	An_{11}	An_{10}

Table 12

Chemical analyses of pink granite veins (wt.%)

Sample No.	6 MP	7 MP	8 MP	9 MP	10 MP	32 MP
Distance from contact granite-marble	160 cm	60 cm	15 cm	0-5 cm	composite sample	3 cm thick vein
SiO_2	72.02		73.01	73.69	73.79	69.89
TiO_2	0.09		0.06	0.05	0.09	0.10
Al_2O_3	15.65		14.97	14.60	14.29	15.18
Fe_2O_3	0.30		0.27	0.20	0.33	0.25
FeO	0.34		0.24	0.31	0.40	0.50
MnO	0.01		0.01	0.01	0.01	0.02
MgO	0.13		0.08	0.08	0.12	0.24
CaO	1.02		0.93	1.65	1.25	1.88
Na_2O	4.84		4.21	4.86	4.58	2.60
K_2O	5.12		5.78	4.03	4.21	8.45
P_2O_5	0.02		0.01	0.01	0.02	0.03
H_2O+	0.30		0.32	0.23	0.30	0.19
H_2O-	0.03		0.03	0.06	0.08	0.05
CO_2	0.10		0.13	0.39	0.24	0.54
S				0.00		0.00
Cl				0.03		0.07
Sum	99.97		100.05	100.20	99.71	99.99
Less (O≡Cl)				0.01		0.02
Total				100.19		99.97
K (%)	4.24	4.39	4.75	3.25	3.46	6.98
Rb (ppm)	115	107	142	99	99	277
Tl (ppm)	0.87	0.93	1.2	0.96	0.83	3.5
K/Rb	369	412	333	328	349	252
$K/Tl.10^{-2}$	487	472	399	339	417	199
Rb/Tl	132	115	118	103	119	79

Table 12 continued

			Norms			
	6	7	8	9	10	32
Quartz	20.4		22.8	25.2	26.4	18.2
Corundum	0.6		0.5	0.2	0.6	0.0
Orthoclase	30.1		34.2	23.7	25.0	50.2
Albite	43.3		37.8	43.5	41.3	23.5
Anorthite	4.3		3.7	5.6	4.6	4.8
Enstatite	0.4		0.2	0.2	0.3	0.5
Ferrosilite	0.1		0.1	0.3	1.0	0.3
Magnetite	0.3		0.3	0.2	-	0.3
Ilmenite	0.1		0.1	0.07	0.1	0.1
Calcite	0.3		0.3	1.0	0.6	1.4
Diopside	0.0		0.0	0.0	0.0	0.4
Hedenbergite	0.0		0.0	0.0	0.0	0.3
Apatite	0.04		0.02	0.02	0.04	0.06
			Modes			
Microcline	25.2	22.3	30.5	24.9	25.8	52.0
Perthite	6.8	10.1	1.4	-	-	-
Plagioclase	42.1	39.6	43.7	45.4	41.4	tr.
Quartz	22.3	24.3	23.3	28.2	29.2	19.9
Biotite	1.8	2.0	0.6	0.6	1.5	3.9
Muscovite	1.0	0.5	0.1	tr.	0.8	tr.
Accessories	0.8	1.2	0.5	0.8	1.3	0.6
Scapolite						17.1
Hornblende						3.2
Pyroxene						2.1
Calcite						1.2
Plag. comp.	An_{13}	An_{12}	An_{12}	An_{14}	An_{16}	

Table 13

Chemical analyses of pegmatite (wt.%)

Sample No.	29 WCH	30 WCH	31 WCH
SiO_2	68.70	63.49	73.50
TiO_2	0.12	0.61	0.09
Al_2O_3	16.00	17.05	15.60
Fe_2O_3	1.00	1.43	0.13
FeO	0.78	1.17	0.23
MnO	0.04	0.07	-
MgO	0.68	0.80	0.25
CaO	0.18	2.96	1.20
Na_2O	3.73	4.85	2.89
K_2O	7.84	6.76	6.40
P_2O_5	-	0.13	-
H_2O+	0.32	0.25	0.11
H_2O-		0.21	
CO_2	0.01	0.07	0.01
Sum	99.40	99.85	100.41
K (%)	6.87	5.84	5.55
Rb (ppm)	250	202	190
Tl (ppm)	0.77	1.10	0.63
K/Rb	274	289	285
$K/Tl.10^{-2}$	892	531	881
Rb/Tl	325	200	302

Table 13 continued

	Norms 29	 30	 31
Quartz	14.3	3.9	27.1
Corundum	1.2	0.0	1.9
Orthoclase	46.5	39.6	37.9
Albite	33.6	43.2	26.0
Anorthite	0.8	4.8	5.9
Enstatite	1.9	0.0	0.7
Ferrosilite	0.4	0.0	0.1
Magnetite	1.0	1.5	0.1
Ilmenite	0.2	0.8	0.1
Calcite	0.03	0.2	0.03
Diopside	0.0	4.9	0.0
Hedenbergite	0.0	0.2	0.0
Wollastonite	0.0	1.1	0.0
Apatite	0.0	0.3	0.0

b. The melanosome containing mainly dark (mafic) minerals, such as biotite, hornblende, cordierite, and others.

About 60% of the area studied consists of migmatite - a mixture of light-coloured granitic rock and darker gneiss or marble. For mapping purposes (following Chesworth, 1967), granitic rocks containing more than 10 per cent of a non-granitic component are considered to be migmatite. The bands of migmatite range from milimetres to metres in thickness. For chemical analyses only samples from bands at least 1.5 m wide were chosen.

The melanosome consists of calc-silicate rock at some localities, i.e. near the contact of granitic rocks and marble. More often, however, it is a gneiss similar in composition to the amphibolitic paragneiss, but containing less microcline.

The leucosomes are mostly medium- to fine-grained granodiorite gneiss, but pink granite and pegmatite also occur.

Chemical analyses, norms and modes are given in Tables 14 and 15. Data for calc-silicate melanosome are in Tables 8 and 9.

Table 14

Chemical analyses of migmatite light bands - leucosome (wt.%)

Sample No.	41 WCH	42 WCH	43 WCH	44 WCH	45 WCH	46 WCH	47 WCH	48 WCH	49 WCH	50 WCH	51 WCH	52 WCH
	pink granite type	granodiorite type										
SiO_2	75.42	75.80	63.38	75.84	75.70	74.16	69.65	74.00	73.50	69.57	70.78	73.24
TiO_2	0.27	0.17	0.68	0.20	0.18	0.30	0.54	0.24	0.33	0.61	0.66	0.44
Al_2O_3	13.01	12.60	16.33	12.46	13.50	13.82	14.37	14.80	13.40	15.13	14.56	13.53
Fe_2O_3	0.77	1.37	1.91	1.30	0.71	0.74	1.56	1.00	1.65	2.04	2.08	1.71
FeO	0.46	0.71	3.27	0.80	0.84	1.08	2.28	0.99	1.09	1.76	1.48	1.18
MnO	0.00	0.04	0.10	0.03	0.02	0.02	0.06	0.02	0.05	0.10	0.08	0.03
MgO	0.22	0.28	2.25	0.21	0.39	0.41	1.27	0.39	0.48	0.78	0.58	0.66
CaO	0.60	0.57	4.39	0.93	1.14	1.50	2.00	0.99	1.60	1.99	2.00	1.52
Na_2O	3.39	5.21	4.53	4.38	4.72	3.96	4.31	4.83	4.90	5.47	5.64	4.96
K_2O	5.19	2.86	1.57	3.08	2.65	3.18	2.82	2.21	1.83	1.92	1.89	2.31
P_2O_5	0.04	0.02	0.16	0.04	0.02	0.05	0.13	0.00	0.10	0.13	0.12	0.11
H_2O+	0.63	0.15	0.72	0.21	0.22	0.36	0.60	0.21	0.22	0.36	0.35	0.38
H_2O-	0.09	0.05	0.19	0.15	0.03	0.11	0.25	-	0.02	0.15	0.11	0.07
CO_2	0.00	0.02	0.02	0.01	0.03	0.01	0.03	0.00	0.02	0.04	0.00	0.01
Sum	100.09	99.85	99.50	99.64	100.05	99.70	99.87	99.68	99.19	100.05	100.33	100.15

Table 14 continued

Sample No.	41	42	43	44	45	46	47	48	49	50	51	52
K (%)	3.95	2.38	1.62					2.37*				
Rb (ppm)	121	41	31					57				
Tl (ppm)	0.55	0.13	0.14					0.39				
K/Rb	326	580	523					404				
K/Tl.10^{-2}	718	1830	1157					582				
Rb/Tl	321	328	221					147				

*Concentrations of K, Rb and Tl were determined in a composite sample consisting of equal amounts of samples 44-52

Table 14 continued

Sample No.	Norms											
	41	42	43	44	45	46	47	48	49	50	51	52
Quartz	32.40	30.80	16.40	34.30	32.40	32.80	25.50	32.20	32.10	23.50	24.10	29.50
Orthoclase	31.20	17.00	9.40	18.50	15.80	19.10	16.90	13.20	11.00	11.40	11.20	13.80
Albite	31.00	47.10	41.30	40.00	42.60	36.20	39.30	43.70	44.80	49.40	50.70	44.90
Anorthite	2.70	2.60	19.90	4.40	5.40	7.20	9.00	5.00	7.30	8.80	8.90	6.80
Diopside	0.00	0.01	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00
Hedenbergite	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Enstatite	0.60	0.80	6.00	0.60	1.10	1.20	3.60	1.10	1.30	2.20	1.50	1.80
Ferrosilite	0.00	0.00	2.90	0.10	0.60	0.80	1.80	0.05	0.20	0.50	0.05	0.10
Magnetite	0.50	1.40	2.00	1.40	0.70	0.80	1.70	1.10	1.80	2.10	2.20	1.80
Ilmenite	0.40	0.20	1.00	0.30	0.30	0.40	0.80	0.30	0.50	0.90	0.90	0.60
Calcite	0.03	0.05	0.05	0.03	0.08	0.03	0.08	0.00	0.05	0.10	0.00	0.03
Hematite	0.20	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Apatite	0.09	0.04	0.34	0.09	0.04	0.11	0.28	0.00	0.20	0.27	0.25	0.20
Corundum	0.90	0.00	0.00	0.40	1.00	1.40	1.10	2.90	0.80	0.90	0.00	0.40

Table 14 continued

Sample No.	Modes											
	41	42	43	44	45	46	47	48	49	50	51	52
Microcline	30.8	21.7	11.2	11.8	15.7	14.6	12.7	11.0	19.8	9.9	12.2	13.3
Plagioclase	29.3	42.3	48.5	42.1	41.4	42.0	46.9	48.6	40.6	49.8	43.8	44.0
Quartz	36.9	34.0	32.1	38.6	38.2	37.5	28.2	31.3	36.8	28.7	29.1	32.1
Biotite	1.8	1.2	7.1	6.0	3.5	4.1	11.0	6.3	1.9	10.2	13.8	10.1
Muscovite	-	tr.	-	-	-	-	-	1.1	-	-	tr.	-
Hornblende	-	-	-	-	-	-	-	-	-	tr.	tr.	-
Accessories	1.2	0.8	1.1	1.5	1.2	1.4	1.2	1.2	0.9	1.4	1.1	0.5
Plag. comp.	An_9	An_6	An_{10}	An_9	An_{15}	An_{18}	An_{21}	An_{14}	An_{13}	An_{20}	An_{18}	An_{20}

Table 15

Chemical analyses of migmatite dark bands - melanosome (wt.%)

Sample No.	33 WCH	34 WCH	35 WCH	36 WCH	37 WCH	38 WCH	39 WCH	40 WCH
SiO_2	63.20	63.50	61.90	61.50	62.89	61.42	62.50	63.30
TiO_2	0.75	0.69	0.90	0.90	0.71	0.79	1.24	0.83
Al_2O_3	16.60	15.90	16.30	15.90	15.89	15.89	15.50	15.02
Fe_2O_3	2.25	1.71	2.81	2.47	1.98	2.08	2.99	1.84
FeO	3.08	3.56	3.73	3.62	3.76	4.30	3.44	3.66
MnO	0.13	0.10	0.12	0.13	0.12	0.11	0.17	0.06
MgO	1.80	2.35	2.32	2.48	2.54	3.07	1.92	2.94
CaO	4.10	4.53	4.78	4.90	4.96	5.71	4.16	4.90
Na_2O	5.43	4.47	4.65	4.29	4.31	4.05	5.83	3.75
K_2O	1.54	1.83	1.51	2.27	1.57	1.54	1.32	2.53
P_2O_5	0.22	0.15	0.28	0.26	0.17	0.18	0.43	0.17
H_2O+	0.65	0.70	0.34	0.73	0.62	1.08	0.59	0.72
H_2O-	0.05	0.06	0.11	0.06	0.16	0.16	0.11	0.14
CO_2	0.02	0.03	0.01	0.06	0.16	0.02	0.01	0.00
Sum	99.82	99.58	99.76	99.57	99.84	100.40	100.21	99.86
K (%)	1.30	1.57			1.51*			
Rb (ppm)	44	66			44			
Tl (ppm)	0.29	0.52			0.31			
K/Rb	295	238			343			
$K/Tl.10^{-2}$	448	302			487			
Rb/Tl	152	127			142			

*Concentrations of K, Rb and Tl were determined in a composite sample consisting of equal amounts of samples 35 - 40

Table 15 continued

Sample No.	Norms 33	34	35	36	37	38	39	40
Quartz	13.2	15.6	14.3	13.2	16.0	13.9	12.3	16.0
Orthoclase	9.1	10.9	9.0	13.6	9.4	9.2	7.8	15.2
Albite	49.0	40.6	42.2	39.1	39.2	36.8	52.5	34.2
Anorthite	16.5	18.2	19.3	17.7	19.6	20.9	12.3	17.0
Diopside	1.3	1.8	1.5	2.8	1.7	3.4	3.3	3.7
Hedenbergite	0.5	1.0	0.6	1.1	0.9	1.7	1.1	1.5
Enstatite	4.3	5.7	5.7	5.6	6.3	6.9	3.7	6.4
Ferrosilite	2.1	3.1	2.5	2.3	3.3	3.5	1.2	2.6
Magnetite	2.4	1.8	3.0	2.6	2.1	2.2	3.1	2.0
Ilmenite	1.0	1.0	1.3	1.3	1.0	1.1	1.7	1.2
Calcite	0.05	0.08	0.03	0.2	0.5	0.1	0.03	0.0
Apatite	0.5	0.3	0.6	0.6	0.4	0.4	0.9	0.4
	Modes							
Microcline	10.7	7.6	8.2	7.3	8.4	tr.	6.6	7.9
Plagioclase	47.7	49.8	49.9	47.5	44.0	48.4	49.3	45.4
Quartz	17.1	21.6	16.9	20.5	15.3	11.2	24.9	10.3
Biotite	6.5	7.1	7.7	5.2	10.6	9.0	6.1	8.0
Hornblende	16.9	12.6	15.7	18.1	20.3	29.7	11.3	27.2
Accessories	1.1	1.2	1.6	1.4	1.4	1.7	1.8	1.2
Plag. comp.	An_{25}	An_{25}	An_{28}	An_{28}	An_{29}	An_{30}	An_{28}	An_{30}

6. DISCUSSION

The series of migmatites and granodiorite gneiss is believed to have originated by partial melting of a paragneiss; the pink granite developed as a later stage of fractional crystallization of the anatectic melt (Chesworth, 1967, 1970b). K/Rb/Tl ratios can help to test this hypothesis.

6.1. Paragneiss - migmatite - granodiorite gneiss

Chesworth (1967, 1971) showed that the gneiss complex was produced by high grade metamorphism. He summarized 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 with tentative conditions of formation - temperature 580-700°C, load pressure 3.5-7 kb.

The pre-metamorphic material was probably biotite-rich paragneiss consisting of biotite (20 volume per cent), quartz (30%) and plagioclase (50%).

6.1.1. Application of experimental data

In order to understand the anatexis of the Glamorgan paragneiss experimental anatexis was reviewed, mainly from the point of view of K-bearing minerals.

For example, in experimental investigations by Winkler and von Platen (1961) a paragneiss containing K-feldspar-cordierite-plagioclase-quartz and little biotite and sillimanite was melted (Ab/An ratio = 5). At 685°C (P_{H_2O} = 2000 bars) a melt was produced. At 700°C the melt had still the "minimum melt" granite composition, and all the alkali feldspar had melted, together with corresponding amounts of plagioclase and quartz. As the temperature was increased the melt composition changed to granodiorite. At 770°C about 80 weight per cent of the original paragneiss had been melted. The crystalline residue consisted of 8% quartz, 8% cordierite and 4% opaque minerals.

According to the investigation of von Platen and Höller (1966), anatectic melts produced from quartz-plagioclase-muscovite-biotite gneiss had the same minimum melt composition as the example described above. Similar variation of the melt composition in response to rising temperature occurred (at pressure 2000 bars the melt had the same Ab/An ratio = 5).

In another experiment (Winkler, 1967), anatexis of a muscovite-plagioclase-quartz gneiss was examined. At P_{H_2O} = 5000 bars and 680°C, an anatectic melt begins to form.

At this stage, it was observed that muscovite disappeared and produced a melt containing the K-feldspar component.

However, the reactions during anatexis are different if the metamorphic rock consists of biotite, plagioclase and quartz only, where muscovite or K-feldspar is absent. In such a rock all the K_2O is contained in biotite, as is the case of the Glamorgan least-altered paragneiss.

Knabe (1966, in Winkler, 1967) investigated the anatexis, at P_{H_2O} = 2000 bars, of biotite + quartz + plagioclase (An_{25}) mixtures and of metamorphic greywacke schists of corresponding composition. He found that in such a rock not all the biotite disappears at the beginning of anatexis (715°C), unlike muscovite and K-feldspar in the previously described examples. Therefore, the amount of K-feldspar component in the melt is generally small, relative to the amount of plagioclase and quartz components, and a granodioritic melt is formed. As the temperature increases more biotite reacts to give K-feldspar component. Contemporaneously certain amounts of plagioclase and quartz enter the melt increasing its amount, without appreciably changing its composition. As the temperature is further increased (by 70-100°C) some biotite still remains. As a rule, a portion of the biotite forms part of the crystalline residue.

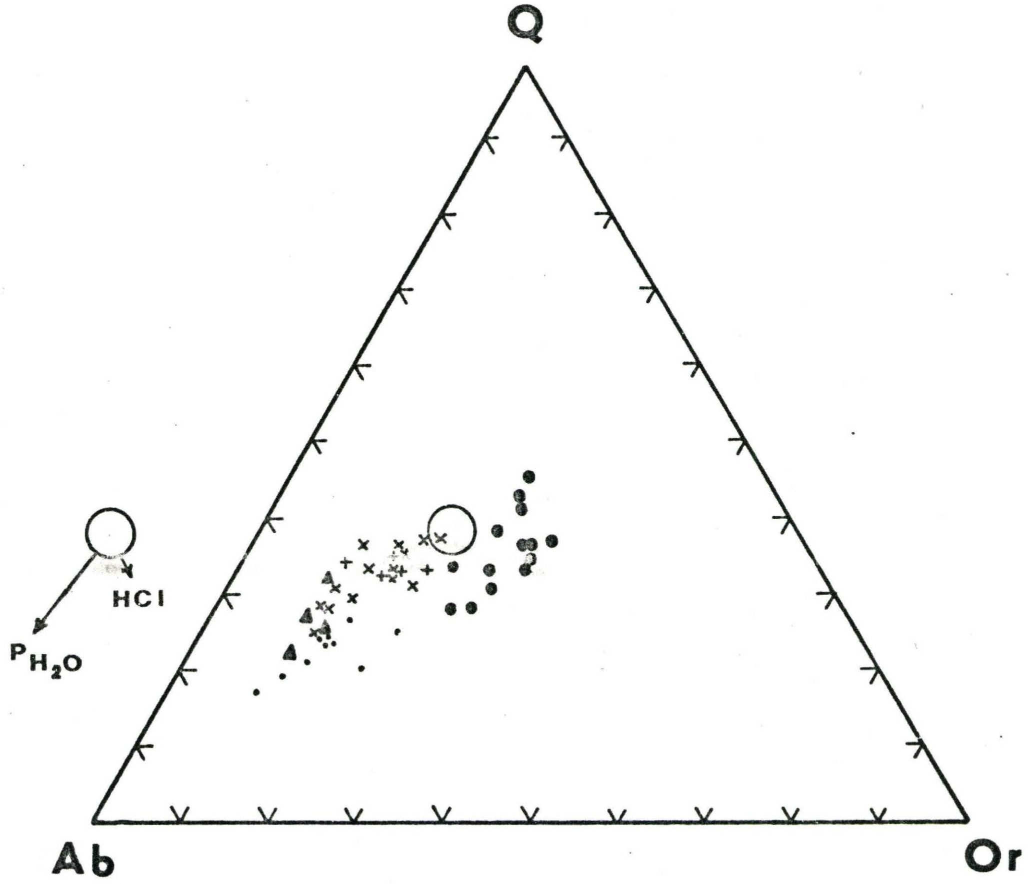
In Figure 3 the normative percentages of quartz, albite and orthoclase of the Glamorgan rocks have been plotted

Figure 3

Normative composition of rocks from Glamorgan township projected onto the Ab-Or-Q triangle

The large open circle is the minimum melt composition in the system Q-Ab-An-Or-H_2O, with Ab/An = 3 at P_{H_2O} = 2kbar, produced by experimental anatexis of rock composed of quartz, biotite and plagioclase (taken from Knabe, 1966, _in_ Winkler, 1967).

The arrows indicate the direction and extent to which the composition of the melt changes during the rising water pressure (from 2 kbars to 7 kbars) and in the presence of HCl (0.05 moles/litre). The arrows are drawn on the basis of data by von Platen and Höller (1966) and von Platen (1965).



▲ paragneiss
+ granodiorite gneiss
× granodiorite bands of migmatite
· dark bands of migmatite
● pink granite and equivalent bands of migmatite

in the Q-Ab-Or triangle. The circle represents the minimum melt composition in the system Q-Ab-An-Or-H_2O taken from Knabe (in Winkler, 1967). The anatexis started at 715±10°C, and the circle represents the composition at 720°C.

In Figure 3 the anorthite component is not considered. The experimentally melted gneiss had an Ab/An ratio of 3 and the least-altered Glamorgan paragneiss (samples 11 and 12) had ratios of 2.5 and 3.2, respectively. In the experiments, the composition of the minimum melt depends markedly on the pressure and on the ratio Ab/An in the plagioclase. Moreover, it must be taken into account that the gaseous phase, composed essentially of H_2O may, in nature, contain other components such as HCl and HF.

The minimum melt composition shifts towards the Ab corner in response to an increase of pressure. The change of the components Q:Ab:Or when P_{H_2O} increases from 2000 to 7000 bars (for a gneiss of Ab/An ratio 2.9) is shown by the arrow on the circle in the left part of Figure 3. The second arrow shows the change in composition of the minimum melt in the presence of HCl (von Platen and Höller, 1966; von Platen, 1965) (for a gneiss of Ab/An ratio 3) at 2000 bars and HCl concentration of 0.05 moles/litre. The pressure given by Chesworth (1967, 1971) for the Glamorgan rocks is 3500-7000 bars.

Figure 3 shows that granodiorite gneiss samples fall in a rather limited region of the compositional triangle. The granodiorite bands of migmatite fall close to them, but are somewhat more scattered. The close coincidence in major element chemistry and mineralogy of the granodiorite bands of migmatite and the larger bodies of granodiorite gneiss indicates their genetic relationship, as might be expected in regional metamorphic terrains, where migmatites produced by partial melting occur, together with magma segregations formed by a process such as filter-pressing.

Figure 3 further shows that granodiorite gneiss and equivalent migmatite bands plot near the minimum melt composition produced in the laboratory (for P_{H_2O} = 3500-700 bars).

The experimentally observed melt reaction:

biotite+plagioclase+quartz→K-feldspar+quartz+albite-bearing melt+
hornblende

might be supported by the mineralogy of the Glamorgan rocks. Chesworth (1967) found a positive correlation between modal microcline and hornblende and a negative one between these minerals and biotite in a paragneiss and in both portions (light and dark) of migmatites and granodiorite gneiss. Also, as a consequence of fractional melting, the residual plagioclase is slightly enriched in An (average An 28) with respect to that of the gneiss before anatexis (average An 23). The light bands of migmatite have an average plagioclase composition of An 14.

Another important point with regard to the anatectic origin of migmatite is the quantitative relationship of its light and dark bands and the parent rock. When the light part of migmatite was formed by partial melting of paragneiss, the dark bands represent the residuum of the parent rock: then by adding both components of migmatite, the primary composition of the parent rock should be obtained. Chesworth (1967) compared these rocks graphically in various ways. A better way to study the quantitative relationships of the minerals (using modal composition) was shown by Mehnert (1968) and was applied in this study and extended to the trace elements. The mineral composition of migmatite, granodiorite gneiss and paragneiss is plotted in Figure 4. It can be seen that the average values lie close to a straight line. Mehnert (1968) shows that this is an argument in favor of an anatectic differentiation of parent rock. The two end-members resulted from partial melting of a paragneiss in the ratio 1:1 (estimated according to the ratios of distances from the paragneiss).

The average chemical analyses (Table 16) show that by adding granodiorite to dark bands in the ratio 1:1, the composition of paragneiss can be obtained in a relatively accurate fashion, using both major and trace elements. This supports the view that the process took place without addition or subtraction of material.

All these facts support Chesworth's (1967, 1970b) view

Figure 4

Relative mineral composition of migmatites,
granodiorite gneiss and paragneiss

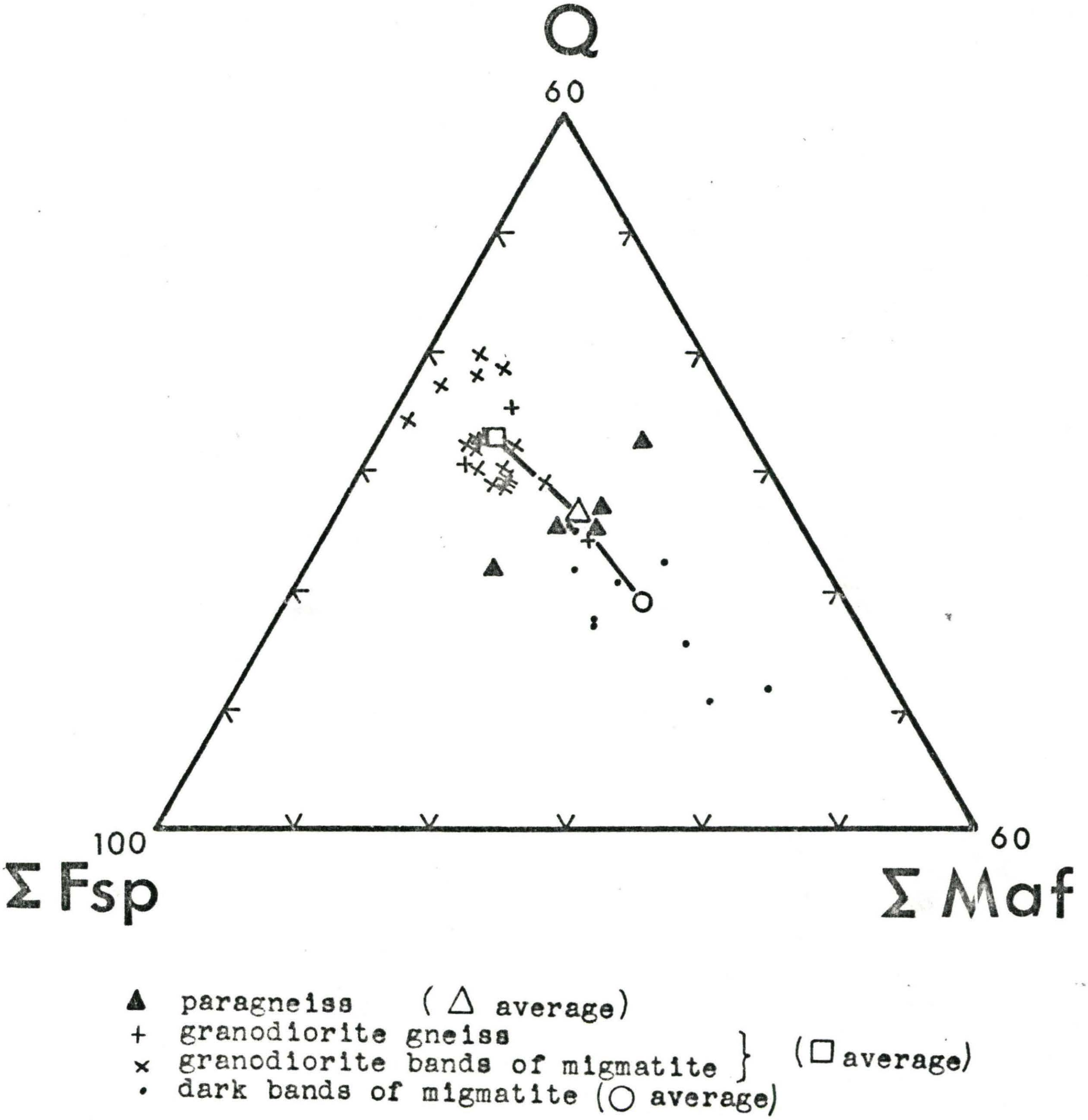

Q
60
100
ΣFsp
60
ΣMaf
▲ paragneiss (△ average)
+ granodiorite gneiss
× granodiorite bands of migmatite } (□ average)
• dark bands of migmatite (○ average)

Table 16

Chemical analyses of migmatite compared with parent rock

No.		wt. % recalculated to 100%											Σ	Rb	Tl
		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O		(ppm)	
1	Granodiorite (migmatite bands + granodiorite gneiss*	71.8	0.4	14.3	1.5	1.6	0.1	0.9	2.0	4.7	2.3	0.4	100.0	56	0.36
2	Dark bands of migmatite**	63.1	0.8	15.9	2.2	3.6	0.1	2.4	4.7	4.6	1.8	0.8	100.0	47	0.33
3	Bulk composition of migmatite (no. 1+2 in the ratio 1:1)	67.45	0.6	15.1	1.85	2.6	0.1	1.65	3.35	4.65	2.05	0.6	100.0	51.5	0.345
4	Parent rock: paragneiss***	65.8	0.8	15.7	2.1	2.8	0.1	1.8	3.6	4.8	1.9	0.6	100.0	54	0.36
	Difference between migmatite (no.3) and parent rock (no.4)	+1.65	-0.2	-0.6	-0.25	-0.2	0	-0.15	-0.25	-.15	+0.15	0	0.0	-2.5	-0.025

* Average of 20 samples; Rb, Tl average of 14 samples

** Average of 10 samples; Rb, Tl average of 8 samples

*** Average of 5 samples; Rb, Tl average of 4 samples

Averages of major element oxides include additional samples from the thesis of Chesworth (1967); Rb, Tl averages include also composite samples that a mechanism of partial melting of paragneiss was responsible for formation of the migmatites and granodiorites.

6.1.2. Trace elements and partial melting

Trace element contents, if related to appropriate major elements, can be useful tools for suggesting the process of rock formation. When the process of anatexis and partial melting is involved, K/Rb, Rb/Sr, Ba/Sr, K/Ba, Ba/Rb, K/Tl and Rb/Tl ratios are of special importance. I determined K, Rb and Tl only, therefore K/Rb, K/Tl and Rb/Tl can be applied in this study. Variation of these ratios during partial melting were discussed by several authors (e.g. White, 1965; Siedner, 1968; Gast, 1968; Shaw, 1968, 1970; Condie, 1969; Sighinolfi, 1969; Whitney, 1969), but there is no experimental work to verify their hypotheses.

Generally, the trace elements concentrated in late differentiates should be concentrated in early-formed melts. Rubidium and especially Tl should be enriched relative to potassium in the liquid phase when a rock is partially melted.

Shaw (1968) suggested an evolution scheme of crustal blocks at the highest grades of metamorphism with respect to the K/Rb ratio: when biotite-rich gneiss is involved in a process of anatexis, the principal reaction to occur would be the breakdown of mica yielding an aqueous fluid, an Al silicate and K-feldspar. This reaction together with the partial melting of the quartzo-feldspathic material would produce the following three phases with expected K/Rb ratios:

	aqueous fluid	low K/Rb
biotite gneiss	silicate melt	normal K/Rb
	residual gneiss	higher (?) K/Rb

According to Shaw's proposal the variation of K/Rb in the three phases is due to a lower K/Rb ratio in biotite in comparison to K-feldspar. Such a transformation should enrich the fluid phase in Rb. The absolute change of ratios should depend on the relative amounts of the three phases formed and on their evolution during anatexis.

In order to test this proposal Table 17 was constructed, using the four samples of paragneiss, fourteen of granodiorite gneiss and equivalent bands of migmatite and eight of dark bands of migmatite which have been analyzed for K, Rb and Tl. Chesworth (1967) considered the amphibolitic paragneiss a transition rock between the least-altered paragneiss and migmatite. It is believed that the mineralogical changes (e.g. amphibole and biotite-bearing parageneses) result from metamorphic-anatectic processes and not from original composition. If we compare then the amphibolitic paragneiss with the least-altered paragneiss (in Tables 7 and 17), some loss of Tl in amphibolitic paragneiss is observed. K/Tl ratio increases as a consequence. All other changes are not significant regarding small number of samples analyzed.

Table 17

Average K, Rb and Tl contents and average K/Rb, K/Tl and Rb/Tl ratios in paragneiss, granodiorite gneiss and migmatite

	least-altered paragneiss ②		amphibolitic paragneiss ②	silica melt ⑭ = granodior. gneiss ③ + equivalent bands of migmatite ⑪	residual gneiss ⑧ = dark bands of migmatite	
K (%)	1.32	⟶	1.98	2.27	1.49	(2.17 + 2.30)
Rb (ppm)	58	⟶	50	56	47	(68 + 53)
Tl (ppm)	0.46	⟶	0.28	0.36	0.33	(0.42 + 0.34)
K/Rb	226	⟶	392	406	324	(317 + 431)
$K/Tl.10^{-2}$	293	⟶	717	697	459	(512 + 748)
Rb/Tl	129	⟶	181	168	141	(162 + 170)

Numbers in circles represent number of samples analyzed including composite samples

The three ratios in the dark portions of the migmatite are lower than in the light bands, which contradicts the scheme given by Shaw (1968). This can be explained by analogy with matrix-phenocryst distribution coefficients. Thus Philpotts and Schnetzler (1970) have shown that the K/Rb ratio of a mica phenocryst is lower or the same as the K/Rb ratio of coexisting melt (matrix). Similar conclusions can be drawn using data given by Higuchi and Nagasawa (1969). This indicates that liquid coexisting in equilibrium with mica phase does not have lower K/Rb (and probably K/Tl) than the residuum, but has higher values. This can also apply to the anatectic process when an anatectic melt coexists in equilibrium with mica phase and has higher K/Rb and K/Tl than the residuum. For the equilibrium between mica-bearing residue and new anatectic melt there is support from experimental work (Knabe, 1966, *in* Winkler, 1967) as well as geological evidence.

The distribution of K, Rb and Tl seems to be thus the result of the partitioning of these elements between K-feldspar and biotite. The K/Rb, K/Tl and Rb/Tl ratios of paragneiss as well as both dark and light bands of migmatite, increase significantly with decreasing biotite content and increasing K-feldspar content of the rocks. This is indicated by the ratios of the distribution coefficients for K, Rb and Tl between biotite and K-feldspar (in non-pegmatitic rocks)

$$D_K/D_{Rb} = \frac{K/Rb^{\text{biotite}}}{K/Rb^{\text{K-feldspar}}} \simeq 0.25$$

$$D_K/D_{Tl} = \frac{K/Tl^{\text{biotite}}}{K/Tl^{\text{K-feldspar}}} \simeq 0.1$$

$$D_{Rb}/D_{Tl} = \frac{Rb/Tl^{\text{biotite}}}{Rb/Tl^{\text{K-feldspar}}} \simeq 0.4 - 1$$

(Sources: Voskresenskaya 1959; Kolbe, 1966; White, 1966; Sighinolfi, 1969; Whitney, 1969)

These indicate that the mineralogical composition affects most strongly the K/Tl ratio.

As a test of mineralogical control of the total rock ratios, the K/Tl ratio was chosen and plotted against the ratio (volume %) $\frac{\text{biotite}}{\text{K-feldspar + biotite}}$ (Figure 5). This shows a negative correlation, indicating the relative concentration of Tl in rocks where biotite is the dominant K-bearing phase.

Since no mineral analyses were made, another way to see the degree of dependence of K/Tl on mineralogical composition was investigated. In the following calculations the rocks are treated as a simple two-phase system: this is possible because biotite and K-feldspar are the only minerals containing K, Rb and Tl in substantial quantity. Slight inaccuracy may arise

Figure 5

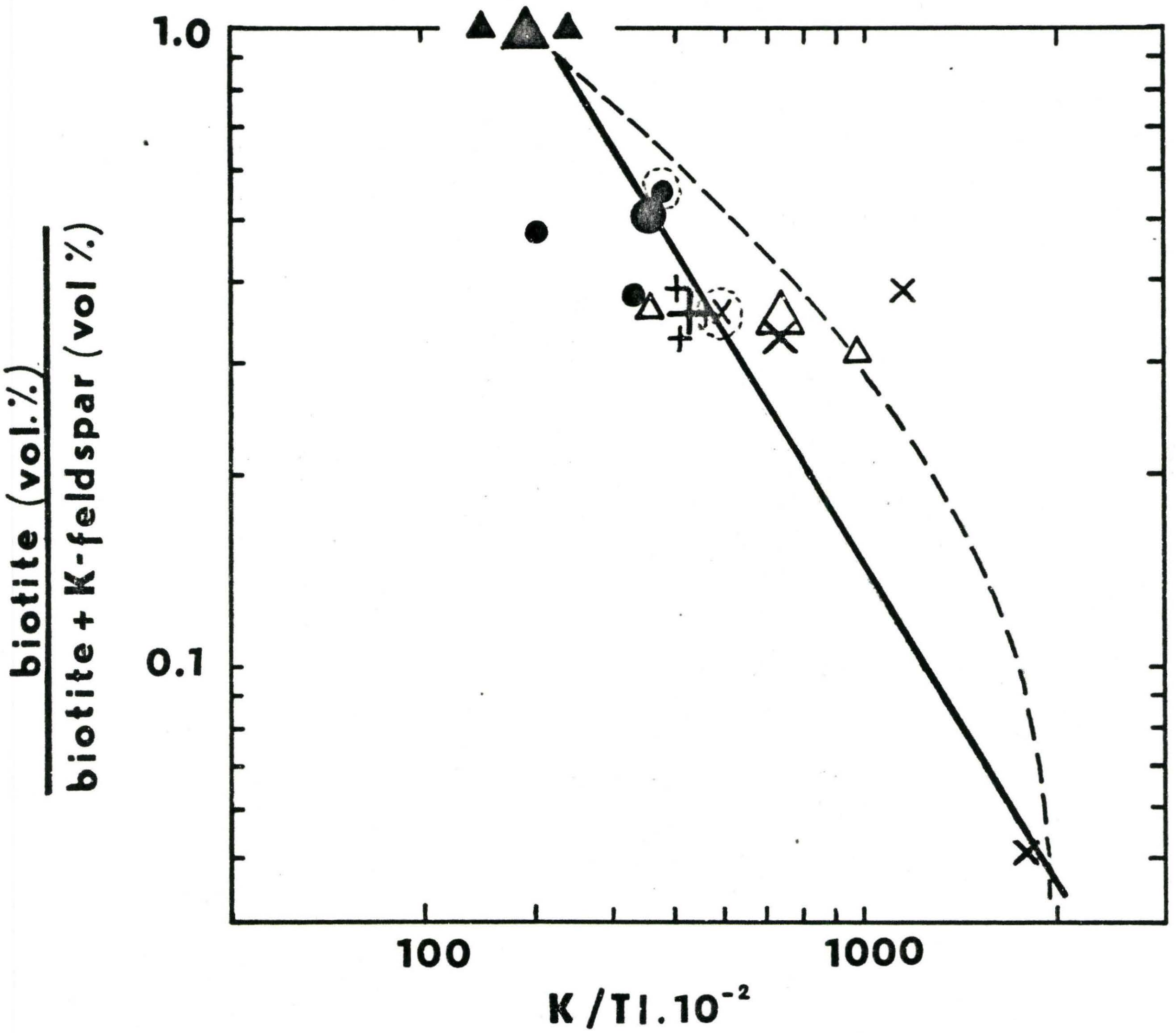
Log-log plot of the K/Tl.10^{-2} ratio against the ratio (volume %)

$$\frac{\text{biotite}}{\text{K-feldspar + biotite}}$$

in paragneiss, migmatite and granodiorite gneiss

Dashed line - represents the K/Tl ratio as a function of varying proportion of biotite and K-feldspar, calculated from data of the least-altered paragneiss;

Solid line - is a weighted regression line (K/Tl = dependent variable) calculated from data for individual samples (small symbols). Averages for rock types, marked with large symbols were not included.



▲ the least-altered paragneiss (▲ average)
△ the amphibolitic paragneiss (△ average)
\+ granodiorite gneiss (+ average)
× granodiorite bands of migmatite (× average)
● dark bands of migmatite (● average)
symbols in circles represent composite samples

from the presence of plagioclase, however, the amounts of K, Rb and Tl in plagioclase are only about 0.5 wt.%, 20 ppm and <0.5 ppm. Moreover, the similar proportion of plagioclase in all the rocks in question is favourable for the calculation.

Using the rearranged formula given by Hart (1968)

$$(K/Tl)^{\alpha} = (K/Tl)^{t} \frac{(D_K - D_K/D_{Tl})f + D_K/D_{Tl}}{(D_K - 1)f + 1}$$

where $D_K = K^{\alpha}/K^{\beta}$ is the partition coefficient of potassium between the two phases α (biotite) and β (K-feldspar),

$D_{Tl} = Tl^{\alpha}/Tl^{\beta}$ is the partition coefficient of thallium between the two phases α (biotite) and β (K-feldspar),

f represents the fraction of the rock which is phase α (biotite).

The K/Tl in the total (t) rock for varying proportions of biotite and K-feldspar in the rock was calculated. As the amount of biotite in a rock approaches 100% (no K-feldspar present) and $f \to 1$, the K/Tl of the total rock approaches the biotite value: this is the case for 2 samples of least-altered paragneiss, where biotite is the only substantial K and Tl bearing phase. The following values were used for the calculations:

$$D_K/D_{Tl} = \frac{(K/Tl)^{biotite}}{(K/Tl)^{K\text{-feldspar}}} = 0.1^*$$

$K/Tl^{biotite}$ = 28700 (the average K/Tl value of 2 samples of the least-altered paragneiss)

$$D_K = K^{biotite}/K^{K\text{-feldspar}} = 0.64^{**}$$

Sources: *Kolbe, 1966

**Kolbe, 1966; White, 1966; Whitney, 1969.

The dashed line in Figure 5 was constructed according to these calculations. It shows the K/Tl ratio as a function of varying proportions of biotite and K-feldspar; the system is assumed to have been closed and at equilibrium. The solid line in Figure 5 is a weighted regression line (K/Tl = dependent variable) calculated from data for individual samples (averages for rock types were not included). The present data are in good agreement with the calculated line (dashed line) and show that partition coefficient can explain the observed variation in K/Tl. Similar pattern of theoretical and observed distribution may indicate the condition close to equilibrium.

The influence of the mineralogical composition also explains the fluctuation of ratios in the light migmatite bands and granodiorite gneiss, i.e. as a function of the variation of the modal proportion of biotite (from 1.2-13 vol. %).

Another important point concerning fractionation of elements during partial melting (Sighinolfi, 1971) is whether the liquid phase generated remains within the solid residue until the system reaches equilibrium at the maximum temperature and pressure, as is normally assumed in experimental partial melting, or alternatively, begins to be separated from the system before.

Several authors have discussed the role of element diffusion in metamorphism (e.g. Grant, 1968; Makrygina et al., 1969; Whitney, 1969; Sighinolfi, 1971). The result of diffusion would be the redistribution of trace elements within the rocks. In a study of K/Rb ratios in magmatic paragneiss, Whitney (1969) explains higher K/Rb ratios in granite veins than in the biotite-rich host rocks either by metamorphic differentiation (direct diffusion of ions of K and Rb to preferred mineralogical environments, K being relatively concentrated in K-feldspar and Rb in biotite) or by anatectic melting. He suggests the possibility that even if anatexis resulted in a relative concentration of Rb in the melt (i.e. the veins), re-equilibration between feldspars in the veins and biotite in the gneiss, perhaps through the agency of an aqueous fluid phase, during or after solidification could take place.

Summarizing the problem, the K/Rb, K/Tl and Rb/Tl ratios are not alone sufficient to distinguish the mechanism of origin of migmatites. However, the distribution of K, Rb and Tl does not exclude the process of partial melting (proposed by Chesworth, 1967, 1970b) to be responsible for the origin of migmatites and granodiorite gneiss.

6.2. Pink granite

To study the distribution of elements in pink granite, the samples collected at the contact and the core of the pluton (located around Stormy Lake) were analyzed. Pink granite from marble migmatite was also analyzed.

Mineralogically, the rock samples collected from the contact zones of the pink granite body are not significantly different from those collected within the body and migmatite.

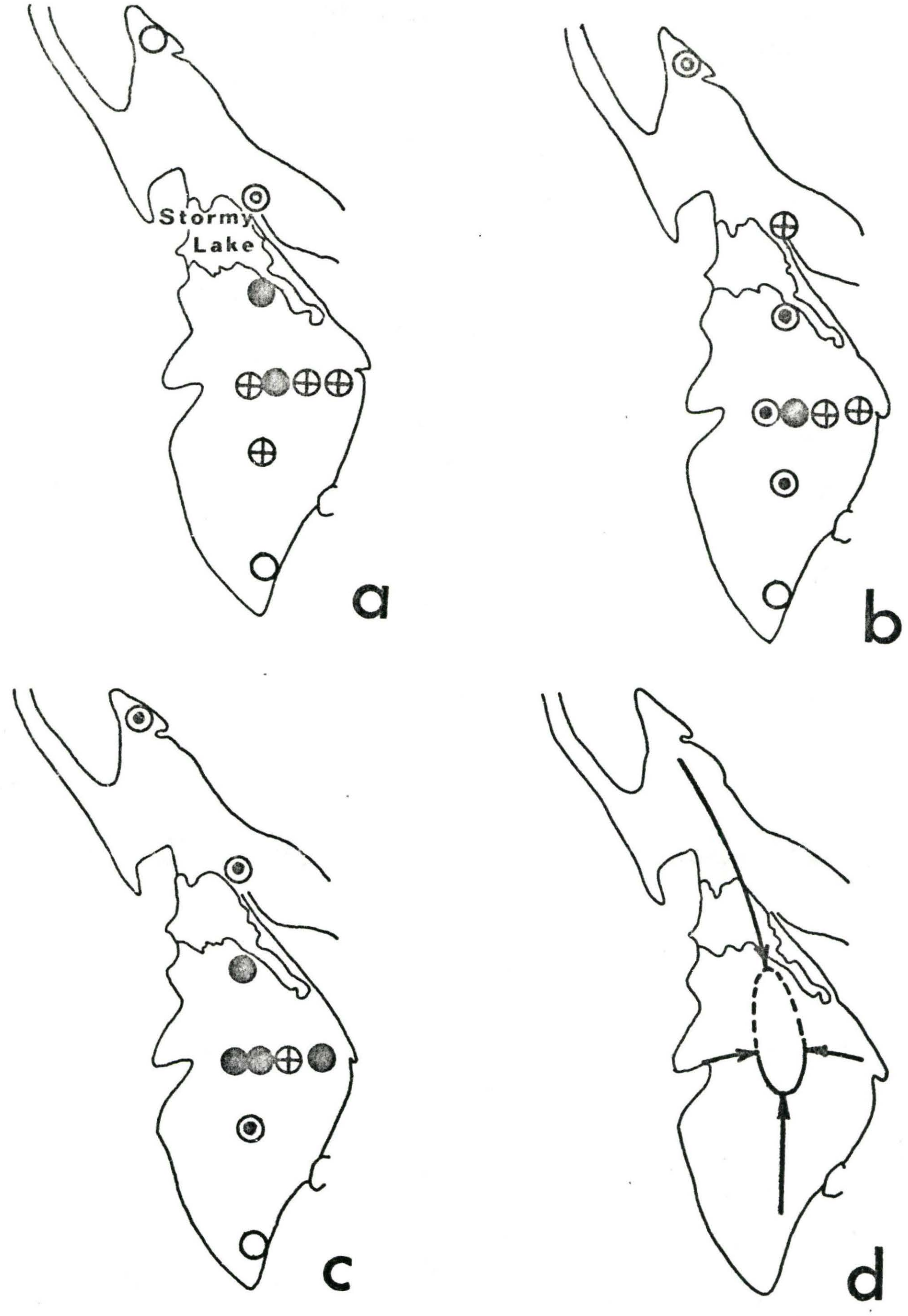
Only a relatively small number of samples were analyzed from the pluton. However, certain differences in chemical composition of the core and the border zone of the pluton were found. Areal distribution of weight per cent ratios of oxides K_2O/Na_2O, Fe_2O_3 + FeO/MgO and Larsen index [$SiO_2/3$ + K_2O] - [CaO + MgO] (Figure 6, a,b,c) gives grounds for the interpretation of a differentiation sequence (Figure 6d), center seems more differentiated and border less differentiated. This is also suggested in the geological section of the Stormy Lake pluton (Figure 7).

6.2.1. Trace element data

The content of Rb and the K/Rb ratio also support the interpretation of a differentiation sequence (Figure 8). The Rb content increases towards the centre of the body, while K content varies irregularly and the K/Rb ratio decreases towards the centre. Similar variation was found by Heier and Taylor (1959) in feldspars in a profile across a granite intrusion in

Figure 6

Area distribution of some element ratios characteristic for differentiation in the Stormy Lake granite body (includes sample D13, E13, G13, H13, J13 from Chesworth, 1967).



a - K_2O/Na_2O ○ 1.0-1.1, ◎ 1.1-1.2, ⊙ 1.2-1.3, ⦶ 1.3-1.4,
⊕ 1.4-1.5, ● 1.5-1.6

b - $(Fe_2O_3+FeO)/MgO$ ○ 0-2, ◎ 2-4, ⊙ 4-6, ⦶ 6-8,
⊕ 8-10, ● 10-12

c - Larsen index ○ 28-28.5, ◎ 28.5-29, ⊙ 29-29.5,
⊕ 29.5-30, ● 30.-30.5

d - possible interpretation of sequence of differentiation

Figure 7

Cross-section along A-A through the rocks of Glamorgan township (see Map 1) according to Chesworth (1967)

The arrows show the direction of increasing differentiation in the Stormy Lake body.

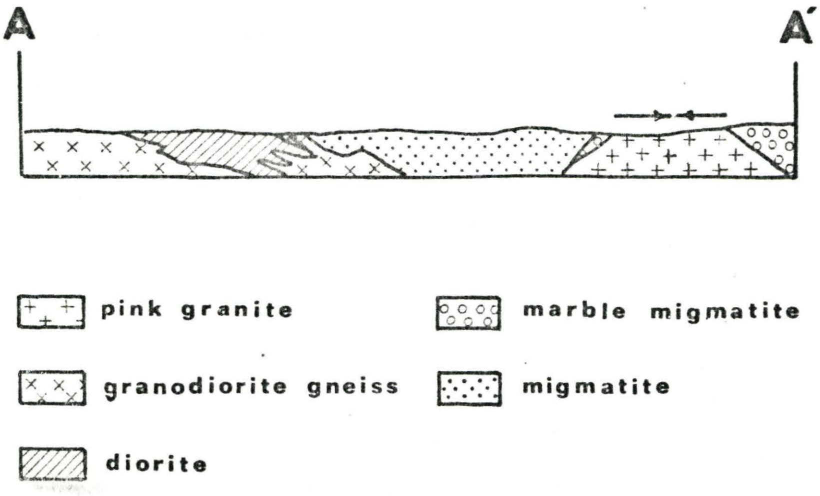
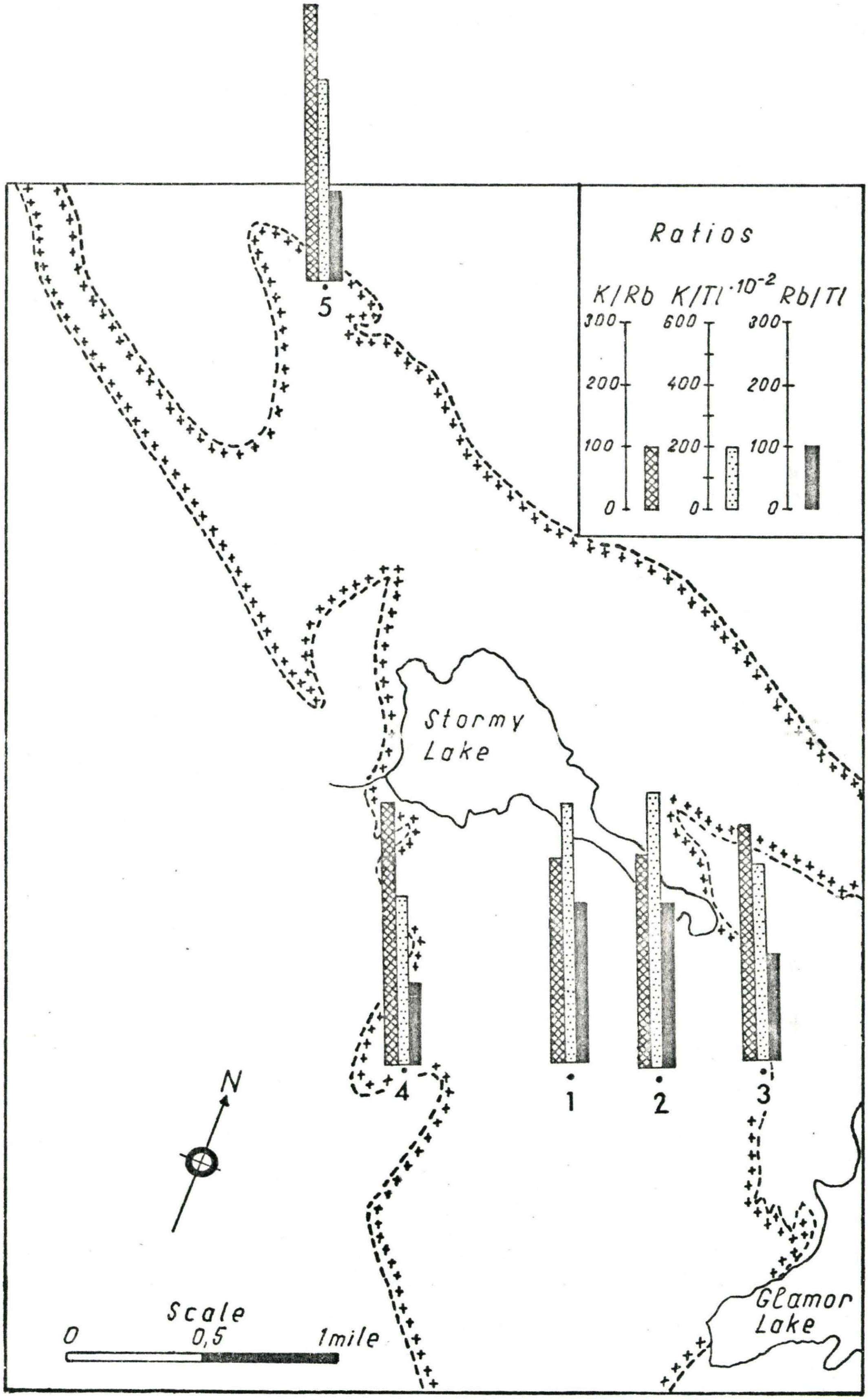

A
A′
pink granite
marble migmatite
granodiorite gneiss
migmatite
diorite

Figure 8

Map of the Stormy Lake pink granite body with block diagrams of K/Rb, K/Tl and Rb/Tl ratios in the samples from the indicated localities


Ratios
K/Rb
K/Tl·10-2
Rb/Tl
300
200
100
0
600
400
200
0
300
200
100
0
5
Stormy
Lake
4
1
2
3
N
Glamor
Lake
Scale
0
0,5
1mile

South Norway, by Kogarko (1959) in granitoids in the Turgoyarsky massif and by Hahn-Weinheimer and Ackermann (1967) in a granite pluton of the Southern Black Forest. All these authors suppose the granite crystallized from outside towards the centre and Heier and Taylor state "here we have a clearly established enrichment in Rb as differentiation proceeds".

K/Tl and Rb/Tl ratios show an opposite variation to K/Rb ratio, although according to theory Tl might be expected to become enriched relative to K and in later stages also to Rb. The data in Tables 11 and 19 show enrichment of Tl towards the margin in the Stormy Lake pluton. The same behaviour was found by Voskresenskaya (1959) and Kogarko (1959). Heier and Taylor (1959) made analyses of Tl, Rb and K in samples collected in profile across a granite pluton; however they did not calculate and discuss the K/Tl and Rb/Tl ratios. The ratios can be calculated from their data and show again the enrichment in Tl in peripheral parts of the pluton.

The different behaviour of Tl from Rb and K in granitic bodies has not yet been satisfactorily explained.

Many authorities believe that late-stage magmatic and hydrothermal solutions can transport metallic elements in the form of halides. Voskresenskaya (1959) suggested that Tl migrates as halide. The volatilities of K, Rb and Tl halides are compared in Table 18.

Much higher volatility of Tl halides is clearly

Table 18

Volatility of potassium, rubidium and thallium halides

K halides	M.P.	B.P.	Rb halides	M.P.	B.P.	Tl halides	M.P.	B.P.
KF	846	1505	RbF	755	1410	TlF	327	655
KCl	776	1500*	RbCl	715	1390	TlCl	430	720
KBr	730	1435	RbBr	682	1340	TlBr	480	815
KI	686	1330	Rbl	642	1300	TlI	440	823

Temperatures in °C

Data from The Handbook of Chemistry and Physics, 49th edition, 1968-1969

*Sublimation

Table 19

Average K, Rb, Tl contents and average K/Rb, K/Tl and Rb/Tl ratios in pink granites

	Pink granite body		Pink granite vein	
	Core (2)	Margin (3)	Core (2)	Margin (3)
K (%)	4.10	3.82	4.32	4.00
Rb (ppm)	124	93	111	121
Tl (ppm)	0.48	0.63	0.90	1.08
K/Rb	332	415	391	331
$K/Tl.10^{-2}$	857	607	480	369
Rb/Tl	257	147	124	111

Numbers in parentheses represent number of samples analyzed demonstrated by the boiling points.

If it is true that Tl migrates in the form of halides, this might explain the distribution of Tl. However the only evidence supporting this is the occurrence of scapolite at contacts with marble.

The mobility of Tl is supported in Figure 8 and Table 19. The rocks near the contact appear enriched in Tl in comparison with core samples in the pink granite body as well as in veins.

The pink granite veins in silicated marble have K/Rb, K/Tl and Rb/Tl ratios lower than in the granite body. This may indicate that the veins are more differentiated. There is a regular decrease in the ratios towards the contact of the vein (samples 6,7,8,9), especially in the K/Tl ratio ($K/Tl.10^{-2}$ from 487 through 472, 399-339).

Sample no. 10 (Table 12) is a composite sample from another pink granite vein. Its K, Rb, Tl content and ratios correspond to the average values for pink granite vein.

Sample no. 32 (Table 12) is from a pink granite vein (about 3 cm thick) cutting both altered marble and a bigger vein of pink granite, where samples 6-9 were collected. The ratios of sample no. 32 are the lowest among all the rocks studies ($K/Rb = 252$, $K/Tl.10^{-2} = 199$ and $Rb/Tl = 79$) and indicate the late origin of the vein. The vein is slightly enriched in Tl.

Figure 9

K-Rb-Tl relations in pink granite

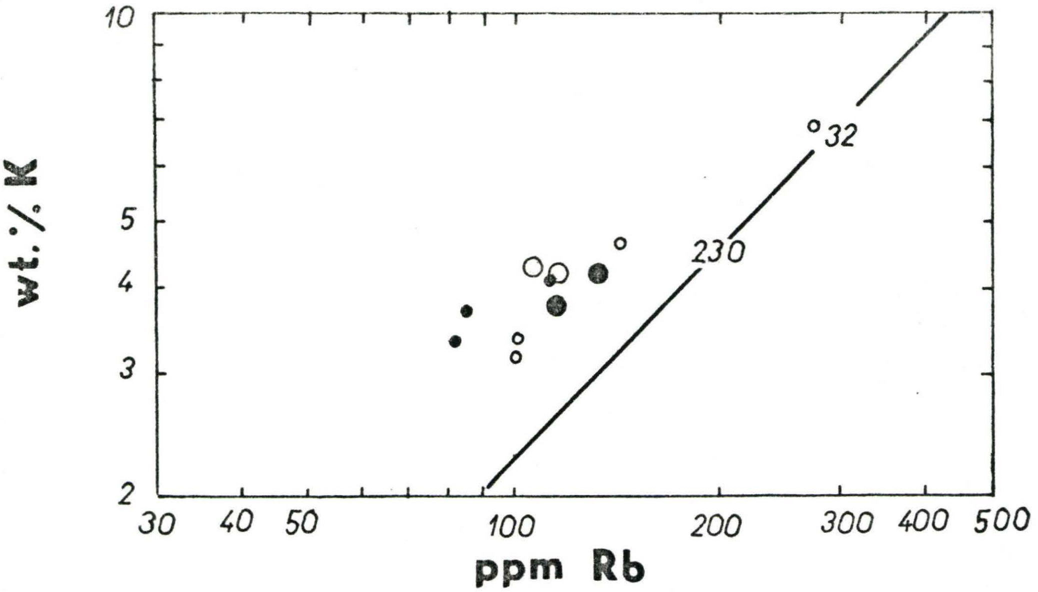
Solid circles - pink granite body

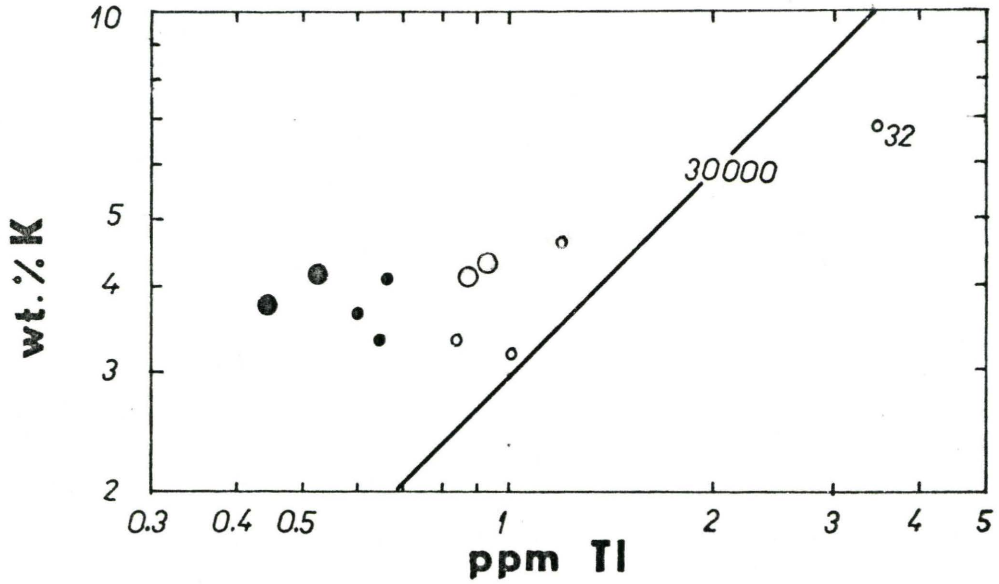
Open circles - pink granite veins

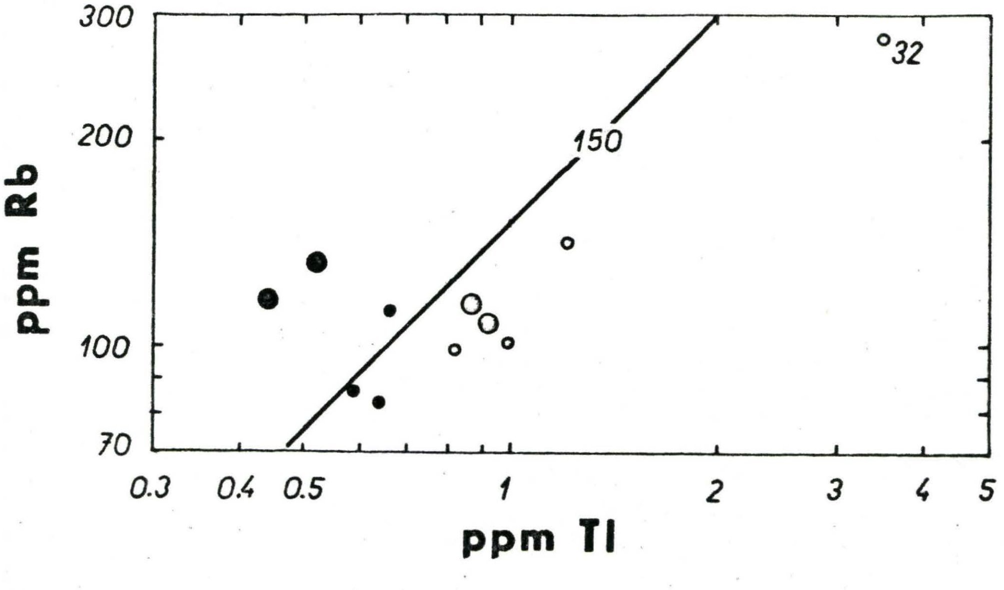
The centre of the body or vein is marked with large symbols

Sample 32 is a late-stage pink granite vein

Lines show average ratios in igneous rocks


wt.% K
10
5
4
3
2
30
40
50
100
200
300
400
500
ppm Rb
230
32


wt.% K
10
5
4
3
2
0.3
0.4
0.5
1
2
3
4
5
ppm Tl
30000
32


ppm Rb
300
200
100
70
0.3
0.4
0.5
1
2
3
4
5
ppm Tl
150
32

The pegmatite veins (samples 29,30,31, Table 13) show a considerable range in K/Tl and Rb/Tl ratios, indicating that no simple explanation will account for their origin. The pegmatites contain higher amounts of K, Rb and Tl; however their ratios do not show any evidence of fractionation. Field relationship and modal composition of individual samples were not known to the author. From K/Rb/Tl relationships nothing certain can be said as to their origin.

6.3. Granodiorite gneiss and pink granite relationship

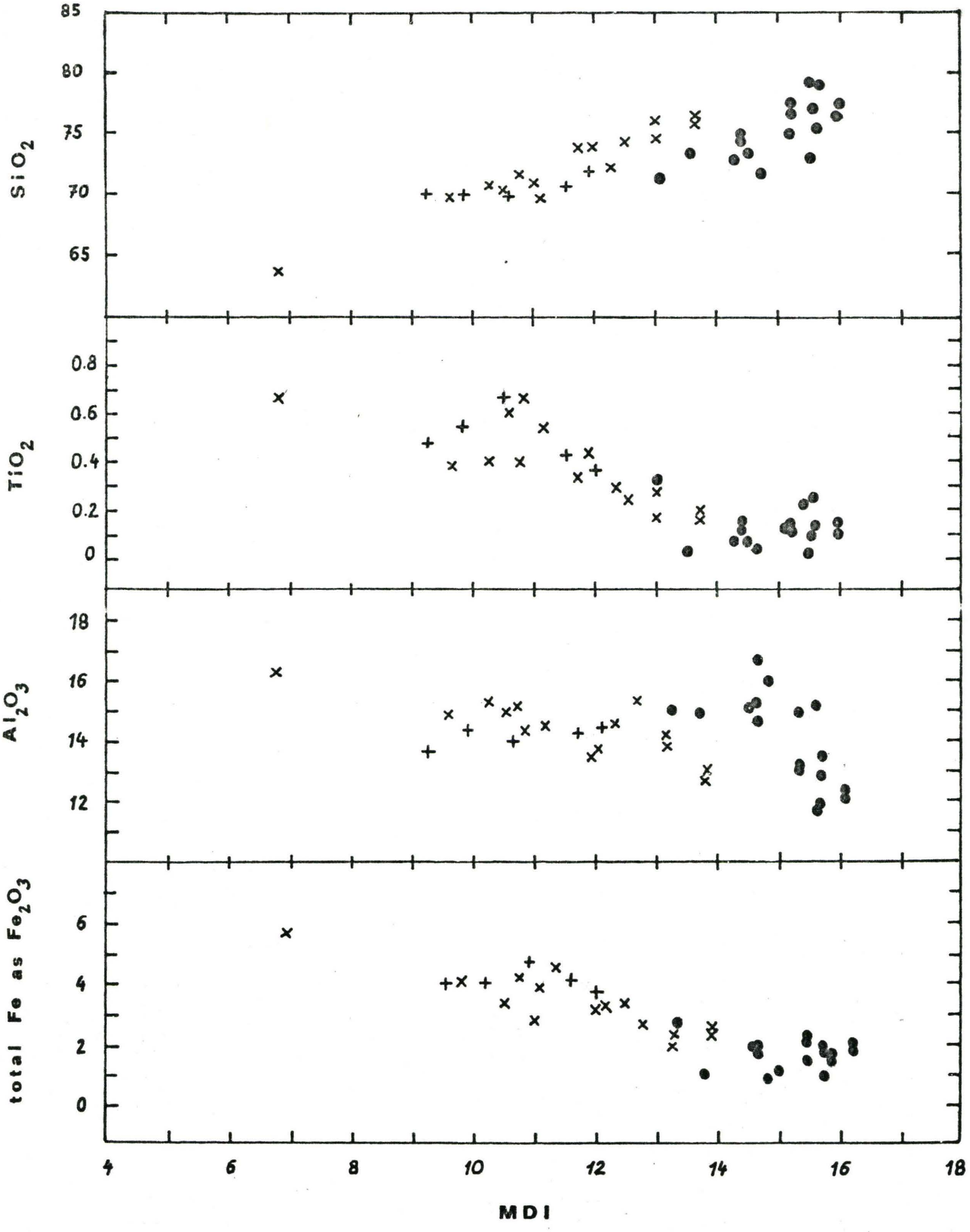
Chesworth (1967) proposed the theory that the pink granite may be a later differentiate of the granodiorite gneiss.

It is possible to see from Tables 10, 11 and 12 that these two rock types differ petrologically and chemically. Pink granite is richer in SiO_2 and K_2O, granodiorite gneiss in all other oxides. In order to compare these two rock series on the same basis, a modified Larsen index (MDI) [1/3 Si + K] - [Ca + Mg] (Nockolds and Allen, 1953) was used. Figure 10a,b illustrate the relationship of major element oxides in the granodiorite gneiss and pink granite and show the trend usually associated with magmatic differentiation. Except for Al_2O_3 it seems that granodiorite gneiss and pink granite form a continuous series.

Using the same criteria as Hopson (1964), the content of K was plotted versus total Fe plus Mg (Figure 11). There

Figure 10a

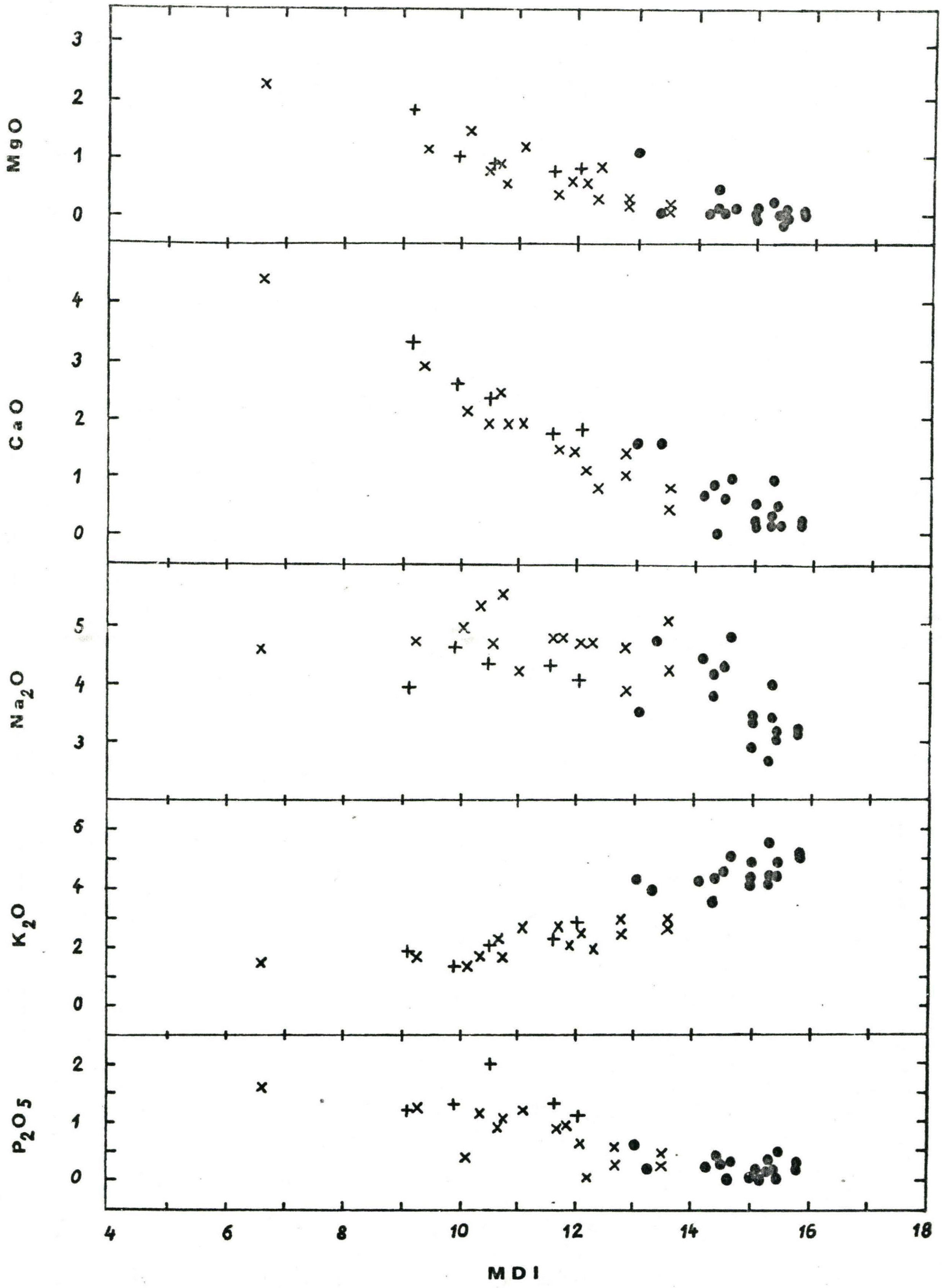
Variation diagram of major element oxides (wt.%) and modified Larsen differentiation index MDI = (1/3 Si + K) - (Ca + Mg)



+ granodiorite gneiss
× granodiorite bands of migmatite
● pink granite

Figure 10b

Variation diagram of major element oxides (wt.%) and modified Larsen differentiation index MDI = (1/3 Si + K) - (Ca + Mg)

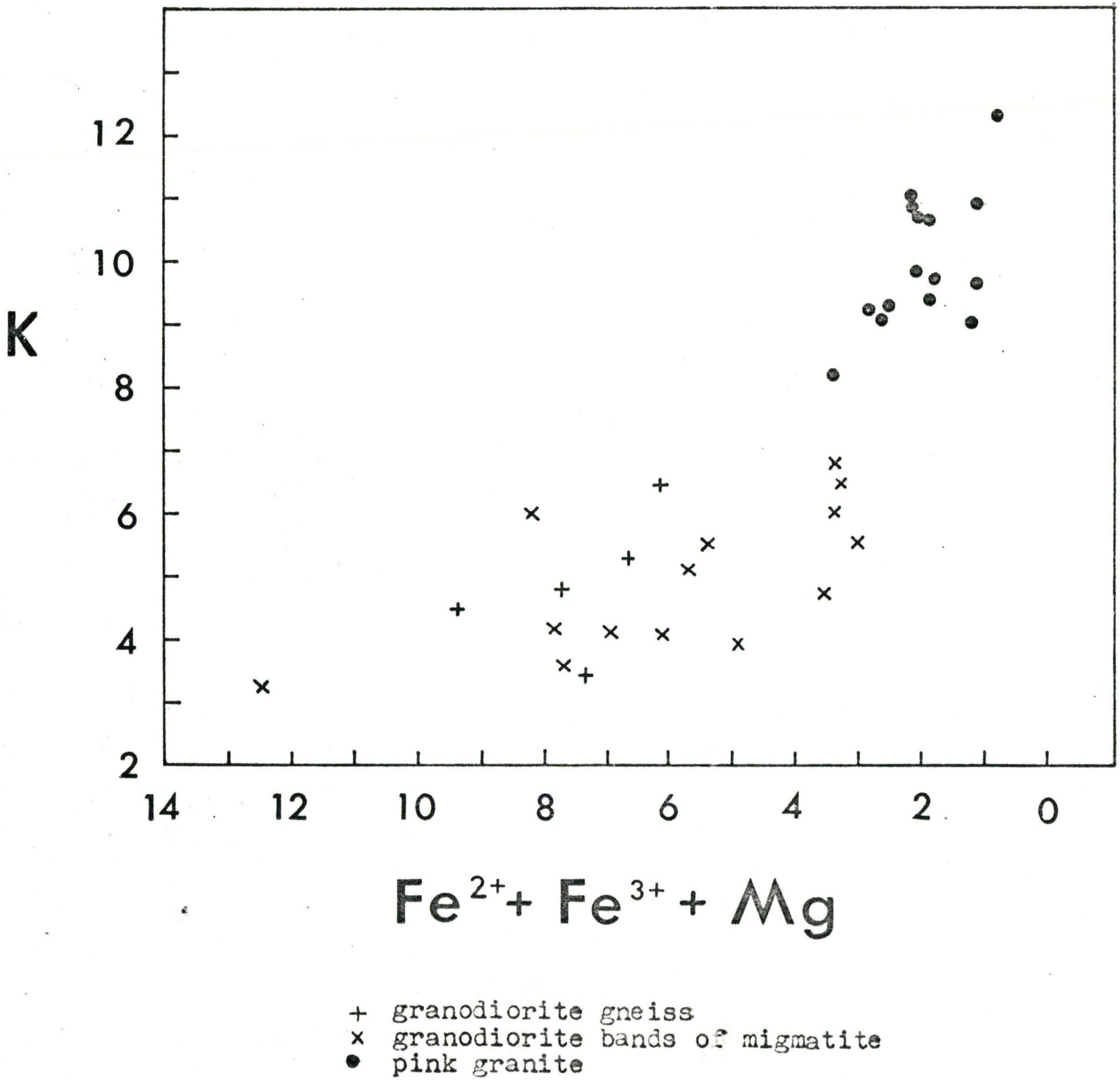


\+ granodiorite gneiss
× granodiorite bands of migmatite
● pink granite

Figure 11

Chemical variation diagram, with K plotted against total ferromagnesian constituents, comparing the trends of the pink granite and granodiorite gneiss series

Data in cation proportions x 100


K
12
10
8
6
4
2
14
12
10
8
6
4
2
0
$Fe^{2+} + Fe^{3+} + Mg$
+ granodiorite gneiss
× granodiorite bands of migmatite
● pink granite

are seen some differences between the two series (the pink granites are more potassic) but the chemical trend of both series is again continuous.

Turning to the trace elements, the pink granite has higher abundances of K, Rb and Tl than granodiorite gneiss, but there is no significant differences in the average K/Rb, K/Tl and Rb/Tl ratios between these two rocks (Table 20). The presence of the biotite-rich phase (e.g. granodiorite gneiss or dark bands of migmatite) which have coexisted with the melt at the time of pink granite formation provides a plausible explanation why the ratios are not lower in pink granite.

Table 20

Average K, Rb, Tl contents and average K/Rb, K/Tl and Rb/Tl ratios in granodiorite gneiss and pink granite

	Granodiorite gneiss (14 samples*)	Pink granite (12 samples**)
K (wt.%)	2.27	4.22
Rb (ppm)	56	124
Tl (ppm)	0.36	0.97
K/Rb	406	356
$K/Tl.10^{-2}$	697	547
Rb/Tl	168	162

* Sample nos. 25-27, 42-52

** Sample nos. 1-10, 32 and 41

6.4. Marbles and para-amphibolites

A complete gradational transition from pure marble to calc-silicate rock is found at the southern contact of the Glamorgan granitic rocks. A metasomatic origin for these rocks and the para-amphibolites brought about by the action of granitic intrusions on limestone was proposed by Adams and Barlow (1910).

From marble to granitic rock the sequence is: pure marble → marble with minor calc-silicate mineral → calc-silicate rock consisting largely of diopside → thin amphibolitic layer. The same sequence is found on a small scale in the altered marble layers of migmatite.

To follow the exchange reactions, samples of marbles, calc-silicate rock and granite were compared.

To simplify the problem, only volume-for-volume exchanges are regarded. The replacement of substances in a unit volume is shown in Table 21, where chemical analysis of pink granite and marble (at different distances from the contact) recalculated to the percentage of various cations associated with 160 oxygen anions, using Barth's standard cell method (Barth,1948, 1952). In Figure 12 a diagrammatic comparison of altered with unaltered rocks is given.

The metasomatism here involves redistribution of material within a relatively restricted volume of rocks. The

Table 21

Comparison of the number of ions in a Barth standard cell of pink granites and marbles. The samples are arranged according to the distance from contact

			Barth standard cell											
		Sample no.	K	Na	Ca	Mg	Fe	Al	Si	Ti	P	C	(O	OH)
pink granite	body	1	5.6	5.5	0.4	0.2	1.0	13.2	66.4	0.1	0.0	0.1	158.4	1.6
		2	5.1	6.0	0.5	0.2	1.0	12.0	66.6	0.1	0.0	0.1	158.2	1.8
		3	5.4	5.6	0.3	0.2	0.8	12.0	66.9	0.1	0.0	0.1	158.5	1.5
		5	4.6	5.1	0.5	0.3	1.1	12.6	66.1	0.1	0.0	-	158.7	1.3
		I average	5.2	5.5	0.4	0.2	1.0	12.5	66.5	0.1	0.0	0.1	158.5	1.5
	veins	10	4.7	7.7	1.1	0.3	0.5	14.6	64.1	0.1	0.0	0.3	158.1	1.9
		6	5.7	8.1	0.9	0.2	0.5	16.1	63.0	0.1	0.0	0.1	158.3	1.7
		8	6.4	7.1	0.9	0.1	0.4	15.4	63.5	0.1	0.0	0.2	158.1	1.9
		II average	5.6	7.6	1.0	0.2	0.5	15.4	63.5	0.1	0.0	0.2	158.2	1.8
		III 9	4.5	8.5	1.6	0.1	0.4	14.9	64.8	0.1	0.0	0.5	158.7	1.3
contact														
marble		19	0.5	5.9	13.9	8.2	7.1	12.1	50.6	0.6	0.1	1.0	152.2	7.8
		20	0.6	5.9	17.5	8.6	7.1	12.6	49.2	0.6	0.1	0.5	155.3	4.7
		IV average	0.6	5.9	15.7	8.5	7.1	12.4	49.9	0.6	0.1	0.8	153.8	6.2
		17	0.3	2.3	39.3	4.8	1.8	6.3	19.7	0.2	0.1	31.7	157.5	2.5
		18	0.2	3.1	38.2	4.0	2.2	5.9	21.4	0.2	0.1	20.2	157.9	2.1
		19	0.2	2.6	37.3	4.8	2.0	6.8	22.6	0.2	0.1	28.5	157.9	2.1
		V average	0.2	2.7	38.3	4.5	2.0	6.3	21.2	0.2	0.1	30.1	157.8	2.2
		VI 15	0.1	0.0	48.7	5.1	0.2	0.0	0.8	0.0	0.0	52.0	158.7	1.3

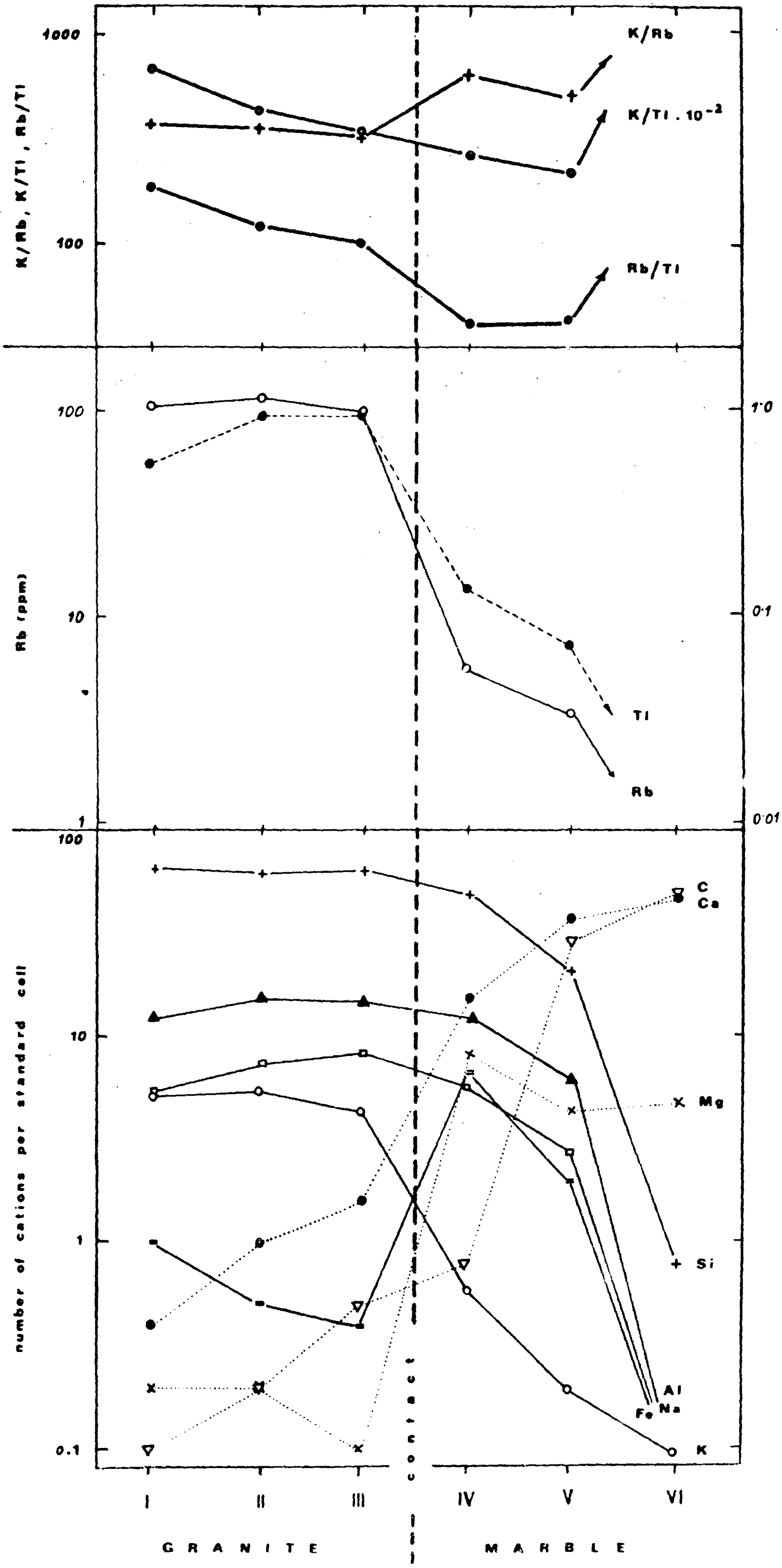
Figure 12

Number of cations in Barth standard cell, Rb, Tl contents and K/Rb, K/Tl and Rb/Tl ratios of pink granites and marbles

I - pink granite body (samples 1,2,3,4*,5)
II - pink granite veins in altered marble (samples 6,7*,8, 10)
III - contact sample of pink granite vein (sample 9)
IV - contact samples of altered marble (samples 19, 20)
V - contact aureole samples of altered marble (samples 16**, 17, 18)
VI - pure marble (sample 15)

*Samples which were analyzed for K, Rb, Tl only

**Plotted without Rb abundance (value near the detection limit) and K/Rb, Rb/Tl ratios


1000
100
K/Rb, K/Tl, Rb/Tl
K/Rb
K/Tl . 10^{-2}
Rb/Tl
100
10
1
Rb (ppm)
1·0
0·1
0·01
Tl (ppm)
Tl
Rb
100
10
1
0.1
number of cations per standard cell
C
Ca
Mg
Si
Al
Na
Fe
K
contact
I
II
III
IV
V
VI
GRANITE
MARBLE

systematic addition of certain constituents and loss of others on both sides of the contact is found. The reciprocal exchange of elements Si, Al, K, Na from the granite side and Ca and C from marble is rather continuous. Fe, Ti, Mg and H_2O are concentrated in samples of calc-silicate rock at the contact; diopside, hornblende, epidote, sphene and scapolite account for the element abundances.

Kroner (1971) expresses the chemical changes during transformation of one rock to another by comparison of a number of cations in the Barth standard cell of both rocks. Such a comparison is shown in Table 22, where the impression of the extent of chemical changes in the contact aureole to pure marble is given.

6.4.1. Trace elements

The upper part of Figure 12 illustrates the behaviour of Rb, Tl, K/Rb, K/Tl and Rb/Tl ratios in granite and marble. A relative enrichment of Tl to K and Rb is seen in the contact calc-silicate rock. The K/Tl and Rb/Tl ratios decrease continuously through the granite to the calc-silicate rock at the contact and are the lowest in samples of altered marble. This may demonstrate preferential intake of Tl relative to K and Rb into marble. The altered contact marble (sample no. 19 and 20) contains 0.32% S and 0.34% S probably due to content of pyrite which could be one of the main Tl-bearing phase in these rocks.

Table 22

Comparison of the number of cations in the Barth standard cell to be moved during transformation of pure marble to contact metamorphosed marble

	Cations which have to be moved			
	between the pure marble (no. 15) and contact aureole samples (no. 16,17,18)		between the pure marble (no. 15) and contact samples (no. 19,20)	
	Introduced	Removed	Introduced	Removed
Si	+19.4		+49.1	
Al	+ 6.3		+12.4	
Fe	+ 2.0		+ 7.1	
Mg (+Mn)		- 0.6	+ 3.3	
Ca		-10.4		-33.0
Na	+ 2.7		+ 5.9	
K	+ 0.1		+ 0.5	
Ti	+ 0.2		+ 0.6	
P	+ 0.1		+ 0.1	
C		-21.9		-51.2
Sum of removed or added cations	+30.8	-32.9	+78.9	-84.2

The enrichment in Tl in the country rock near the contact with magmatic rock was observed also by Dunin-Barkovskaya (1961), Voskresenskaya (1959) and Voskresenskaya et al. (1962). They found that the degree of enrichment in Tl depends on the mineralogical assemblage of the country rock. Contact limestone usually shows a marked enrichment in Tl.

Amphibolite layers are found in calc-silicate rocks near the contact with granite, and show some variation in mineralogy (e.g. sample 21 has thin layers rich in scapolite, others in hornblende or pyroxene). There is a corresponding variation in K, Rb and Tl abundances, but the ratios are not very different. The high modal content of phlogopite (∿15 vol. %) gives a plausible explanation why sample 23 has the lowest K/Rb and K/Tl ratios. Mineral analyses were not performed except one K and Rb determination in a sample of scapolite. Scapolite from a lens found in calc-silicate rock has 0.43 wt. % of K and 6 ppm of Rb (K/Rb = 716). More mineral analyses are desirable since partition data for Tl among coexisting minerals are virtually non-existent.

7. CONCLUSIONS

1. The mechanism of origin of a series of migmatite and granodiorite gneiss in Glamorgan township by partial melting of a paragneiss proposed by Chesworth (1967, 1970b), is confirmed in this study by the behaviour of major and trace elements.

K/Rb, K/Tl and Rb/Tl ratios are not alone sufficient to distinguish mechanisms of origin of migmatite. The principal factor governing the distribution of Rb and Tl in granodiorite gneiss and equivalent bands of migmatites is the mineralogical composition of the residuum which remains after partial melting. If mica is present in a large amount in the residuum a newly-formed melt has similar or higher K/Rb, K/Tl and Rb/Tl ratios as the parent rock and/or the residuum. If, however, K-feldspar is also present, the value of K/Rb, Tl ratios will depend on the proportion of biotite and K-feldspar in a given rock type.

2. The K, Rb and Tl and major element data support the view of Chesworth (1967) that pink granite originated by late magmatic processes from a granodioritic melt. The pink granite has higher abundances of K, Rb and Tl than the granodiorite gneiss, but there is no significant differences in the average K/Rb, K/Tl and Rb/Tl ratios between these two rocks.

3. The distribution of K_2O/Na_2O, $Fe_2O_3 + FeO/MgO$, Larsen index and K/Rb ratios in the pink granite of the Stormy Lake pluton gives grounds for interpretation of differentiation sequence of the pluton, and in which the middle of the pluton is more differentiated. The decrease of K/Tl and Rb/Tl at the margin (due to Tl enrichment in the rocks near the contact) is interpreted as a migration of volatile Tl compounds (probably halides) to the margin. Variation of K/Tl and Rb/Tl in pink granite veins (decrease towards the contact) is similar to the variation in the pink granite body.

4. K, Rb and Tl are enriched in calc-silicate contact rocks affected by metasomatic processes. The lower K/Tl and Rb/Tl ratios may indicate preferential intake of Tl relative to K and Rb into the marble. Pyrite is probably one of the main Tl-bearing phases in the altered marble.

5. It is apparent from the K, Rb and Tl data carried out in this study, that K/Rb, K/Tl and Rb/Tl ratios are useful geochemical indicators of genetic relationships in magmatic metamorphic and metasomatic rocks.

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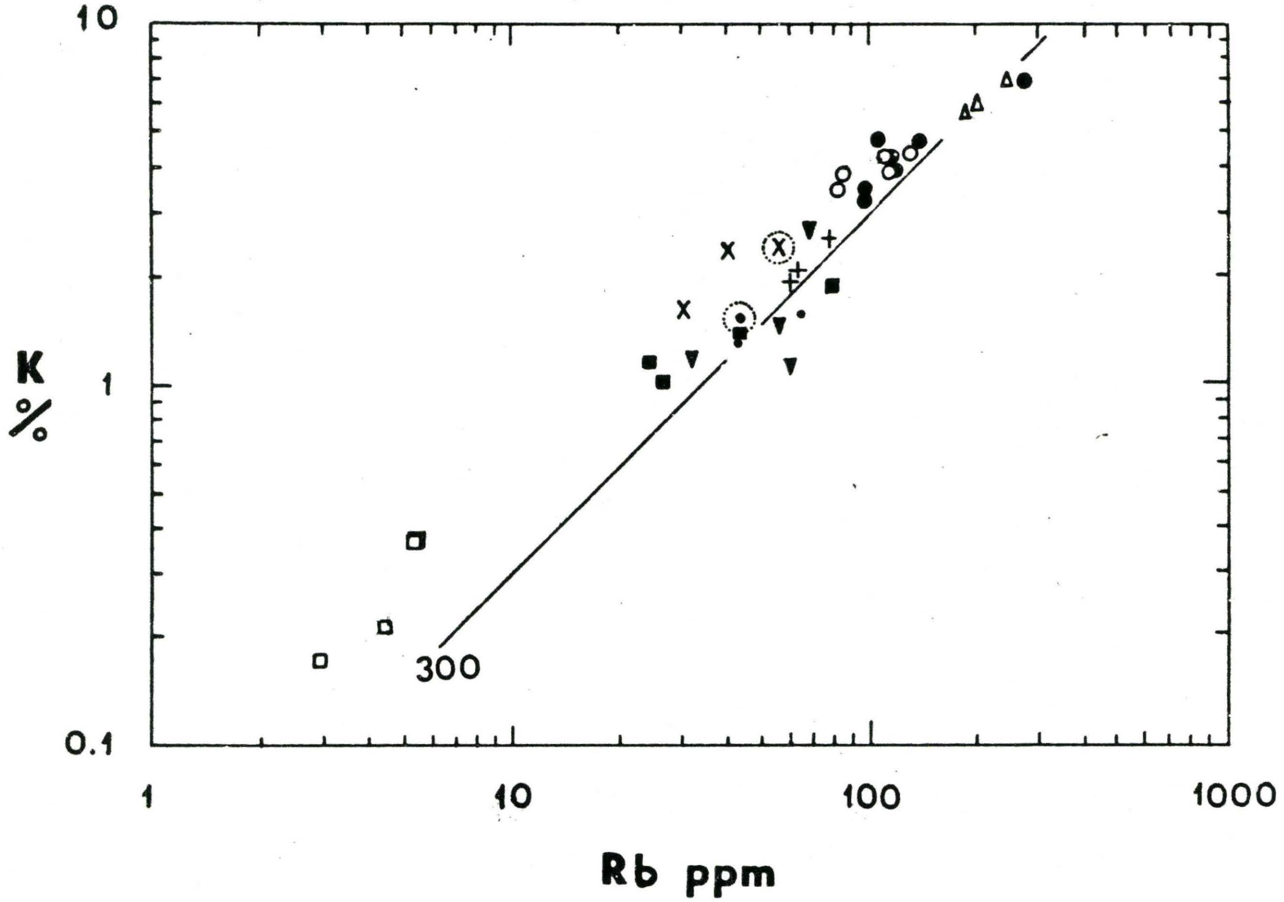
APPENDIX 1

K-Rb-Tl relations.

▼	paragneiss
□	altered marble
■	para-amphibolite
+	granodiorite gneiss
x	granodiorite bands of migmatite
•	dark bands of migmatite
○	pink granite
●	pink granite veins
Δ	pegmatite

Samples in circle are composite samples. Also shown are lines of constant ratios.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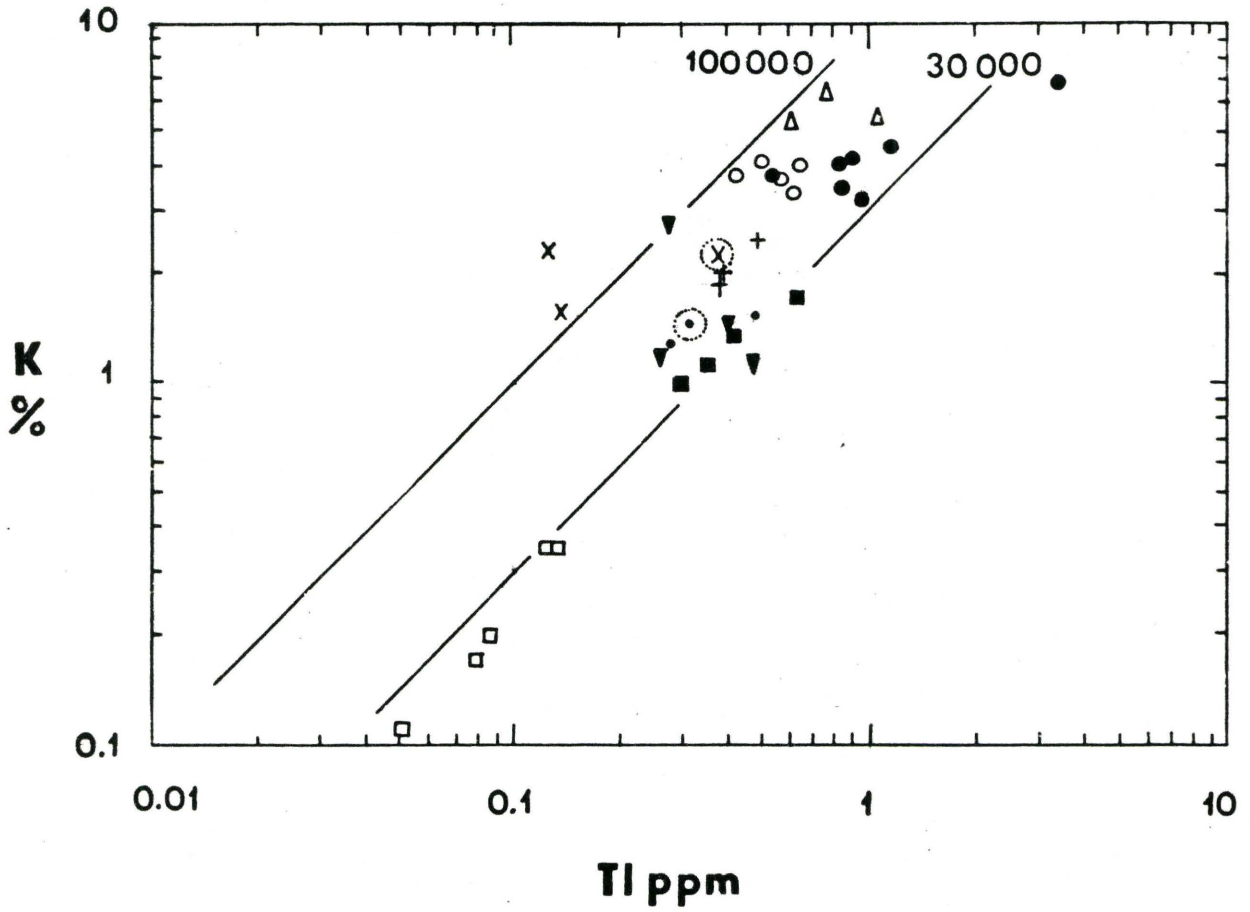
K
%
1
10
100
1000
Rb ppm
300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%
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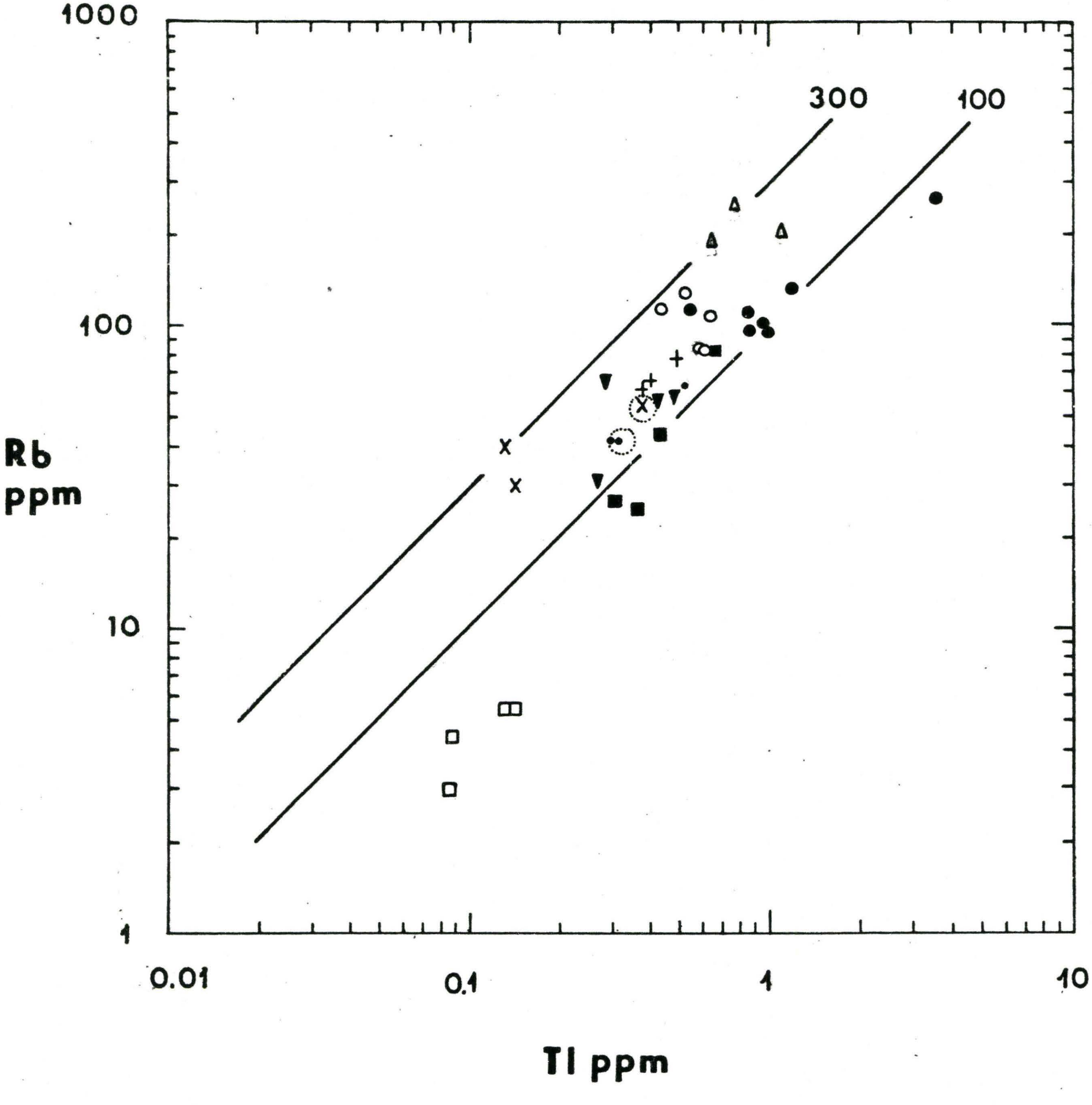
Tl ppm
100000
30000


1000
100
10
1
Rb ppm
0.01
0.1
1
10
Tl ppm
300
100

APPENDIX II

Sample Locations for Glamorgan Rocks

No.	Catalogue number*	Rock type	Locality	Notes
1	PG-1	pink granite	Roadcut on road to Glamor Lake, 0.6 mile from junction with Buckhorn Road to the east	Stormy Lake body
2	PG-2	ditto	Roadcut on road to Glamor Lake, 0.9 mile from junction with Buckhorn Road to the east	ditto
3	PG-3	ditto	Roadcut on road to Glamor Lake, 1.4 miles from junction with Buckhorn Road to the east	ditto
4	691012-21	ditto	Roadcut on Buckhorn Road, 0.2 mile to the north from turn-off to Glamor Lake	ditto
5	A 11	ditto	Chesworth (1967)	ditto
6	691012-16	pink granite vein	Roadcut on Hwy 503, 1.7 miles from junction with Irondale Road to the west	Contact of marble and granite (migmatite)
7	691012-15	ditto	ditto	ditto
8	691012-14c	ditto	ditto	ditto
9	691012-14b	ditto	ditto	ditto
10	690422-1	ditto	Roadcut on Hwy 503, 1.5 miles from turn-off Buckhorn Road to the west	ditto

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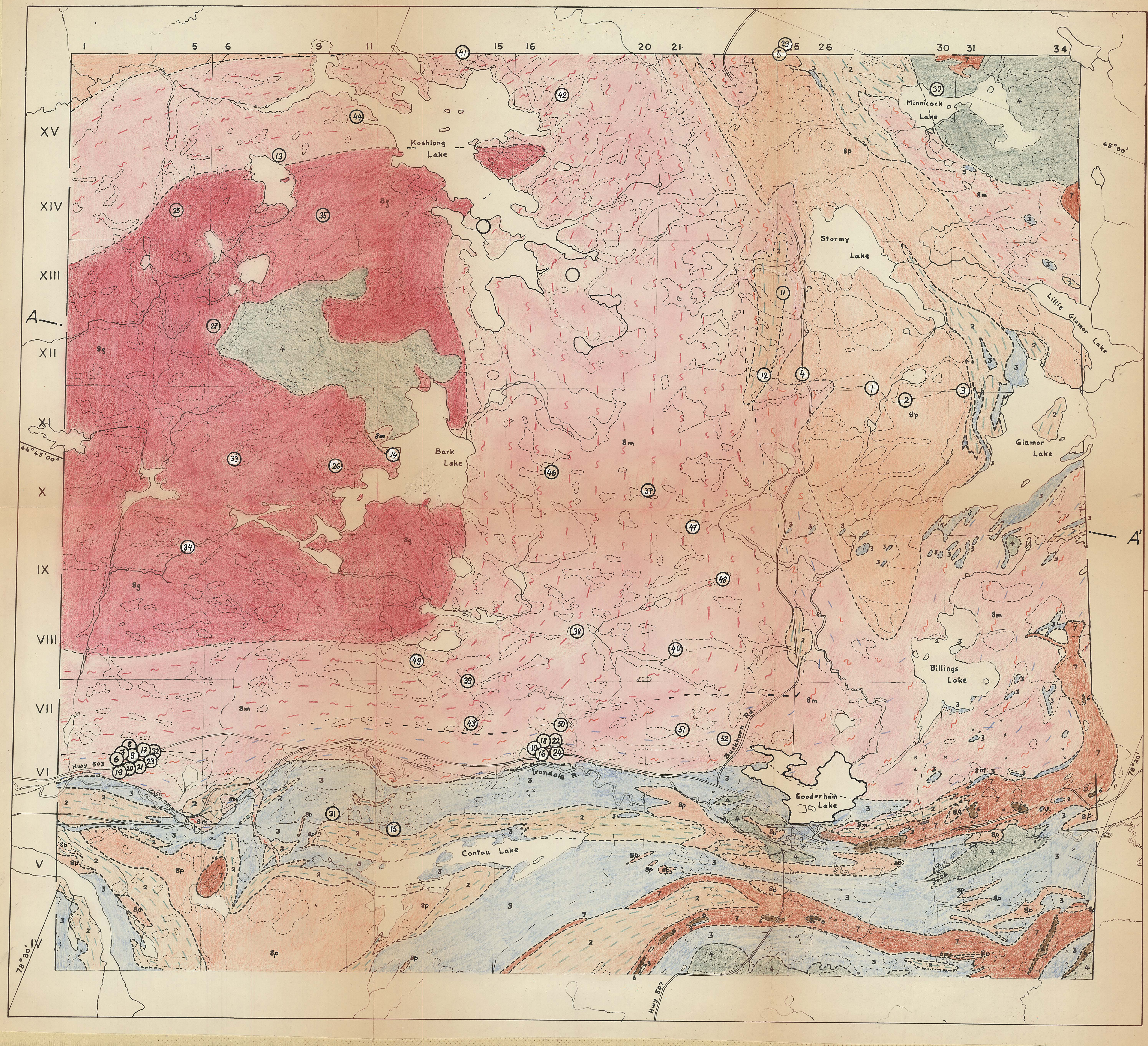
*Department of Geology
McMaster University

No.	Catalogue number	Rock type	Locality	Notes
11	E 12	least-altered paragneiss	Chesworth (1967)	
12	G 11	ditto	ditto	
13	C 3	amphibolitic paragneiss	ditto	
14	H 5	ditto	ditto	
15	691012-9	pure marble	1.8 miles from Devils Gap Dam to the east	
16	690422-2	altered marble	Roadcut on Hwy 503, 1.5 miles from turn-off Buckhorn Rd. to the west	Contact of marble and granite (migmatite)
17	691012-17	ditto	Roadcut on Hwy 503, 1.7 miles from junction with Irondale Road to the west	ditto
18	690422-466	ditto	Roadcut on Hwy 503, 1.5 miles from turn-off Buckhorn Road to the west	ditto
19	691012-14a	contact skarn	Roadcut on Hwy 503, 1.7 miles from junction with Irondale Road to the west	ditto
20	691012-13a	ditto	ditto	ditto
21	691012-19	para-amphibolite	ditto	ditto Inclusion in pink granite vein
22	691012-1	ditto	Roadcut on Hwy 503, 1.5 miles from turn-off Buckhorn Road to the west	ditto
23	691012-18	ditto	Roadcut on Hwy 503, 1.7 miles from junction with Irondale Road to the west	ditto

No.	Catalogue number	Rock type	Locality	Notes
24	690422-3	para-amphibolite	Roadcut on Hwy 503, 1.5 miles from turn-off Buckhorn Road to the west	ditto
25	D 1	granodiorite gneiss	Chesworth (1967)	
26	H 4	ditto	ditto	
27	F 2	ditto	ditto	
29	A 12	pegmatite	ditto	
30	B 14	ditto	ditto	
31	N 4	ditto	ditto	
32	691012-13b	pink granite vein	Roadcut on Hwy 503, 1.7 miles from junction with Irondale road to the west	Contact of marble and granite (migmatite)
33	H 2	dark bands of migmatite (melanosome)	Chesworth (1967)	
34	J 1	ditto	ditto	
35	D 4	ditto	ditto	
36	D 6	ditto	ditto	
37	H 9	ditto	ditto	
38	K 8	ditto	ditto	
39	L 6	ditto	ditto	
40	L 10	ditto	ditto	
41	A 6	pink granite type of migmatite leucosome	ditto	
42	B 8	granodiorite type of migmatite leucosome	ditto	
43	M 6	ditto	ditto	
44	B 4	ditto	ditto	
45	E 8	ditto	ditto	

No.	Catalogue number	Rock type	Locality	Notes
46	H 8	granodiorite type of migmatite leucosome	Chesworth (1967)	
47	I 10	ditto	ditto	
48	J 11	ditto	ditto	
49	L 5	ditto	ditto	
50	M 8	ditto	ditto	
51	M 10	ditto	ditto	
52	M 11	ditto	ditto	



GLAMORGAN TOWNSHIP

Haliburton County, Ontario

PreCambrian Rocks

🟧	8p	Pink granite, graphic granite, pegmatite
🟥	8g	Granodiorite gneiss
▨	8m	Migmatite : granodiorite gneiss leucosome; pink granite leucosome; marble melanosome
🟧	7	Syenite
🟫	6	Nepheline syenite
🟩	4	Diorite, metagabbro
🟦	3	Marble
▨	2	Paragneiss

⬚	Outcrops
⬚	Geological boundary
⬚	Minor road
(33)	Sample locality

SCALE

0 1 2 inch

0 1 mile

Sources:

Ont. Dept. Mines, Prelim. Geol. Map No. 59 (revised) 1968.

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