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The Benta Migmatite Complex: Petrology of Two Important Localities

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Abstract: The general geology, petrography, and petrogenesis of the Benta Migmatite rocks are described and discussed in the light of two well-exposed sections near Benta, Pahang.

The rock which has previously been referred to as "flow-banded syenite" is shown to be a gneiss in which large rapakiwi ellipsoidal microcline porphyroblasts have grown metasomatically.

The origin of the Benta rocks is considered to be deep seated. An anatectic origin is proposed for the monzonite and migmatite in place of the currently favoured hybrid origin, and no genetic relationship to the Benom granite is necessarily implied.

INTRODUCTION

The purpose of this paper is to describe the detailed petrology of an excellent river section in the Sungei Lipis and of the nearby Benta quarry, where gneiss, monzonite and migmatite are exposed. These rocks have been the subject of long debate and the excellent outcrops, which are described herein, have enabled the detailed relationships between the various rock types to be resolved. However the geological evolution of these rocks still remains somewhat enigmatic.

GEOGRAPHIC LOCATION

The key map in figure 1 shows the location of the river section and of the quarry in relation to the main road between Raub and Kuala Lipis in Pahang. On the assumption that the area is approached from Raub, the following notes may be of some help in identifying the stopping places.

At the 20th milestone (32.2 km) from Kuala Lipis, 4 miles (6.4 km) from Benta, a secondary road leads off, to cross the river on the left. At this road junction there is a prominent red post box set in a white stone pillar. The river section is a further 1.5 miles (2.4 km) along the main road from this landmark. The next landmarks in order are: the next milestone, 19 miles (30.6 km) to Kuala Lipis, 3 miles (4.8 km) to Benta; a signboard marked "Hock Lee Saw Mill Co." on the roadside at 2.7 miles (4.3 km) from Benta; a small wooden mosque and wooden coffee shop on the left side of the road at 2.6 miles (4.2 km) from Benta. This is the stopping place to gain access on foot to the north bank of the Sungei Lipis. A path leads from the mosque across a wooden footbridge, and thence along the river bank eastwards to the northern bank area of figure 1. The locality is identified by the rapids in the river.

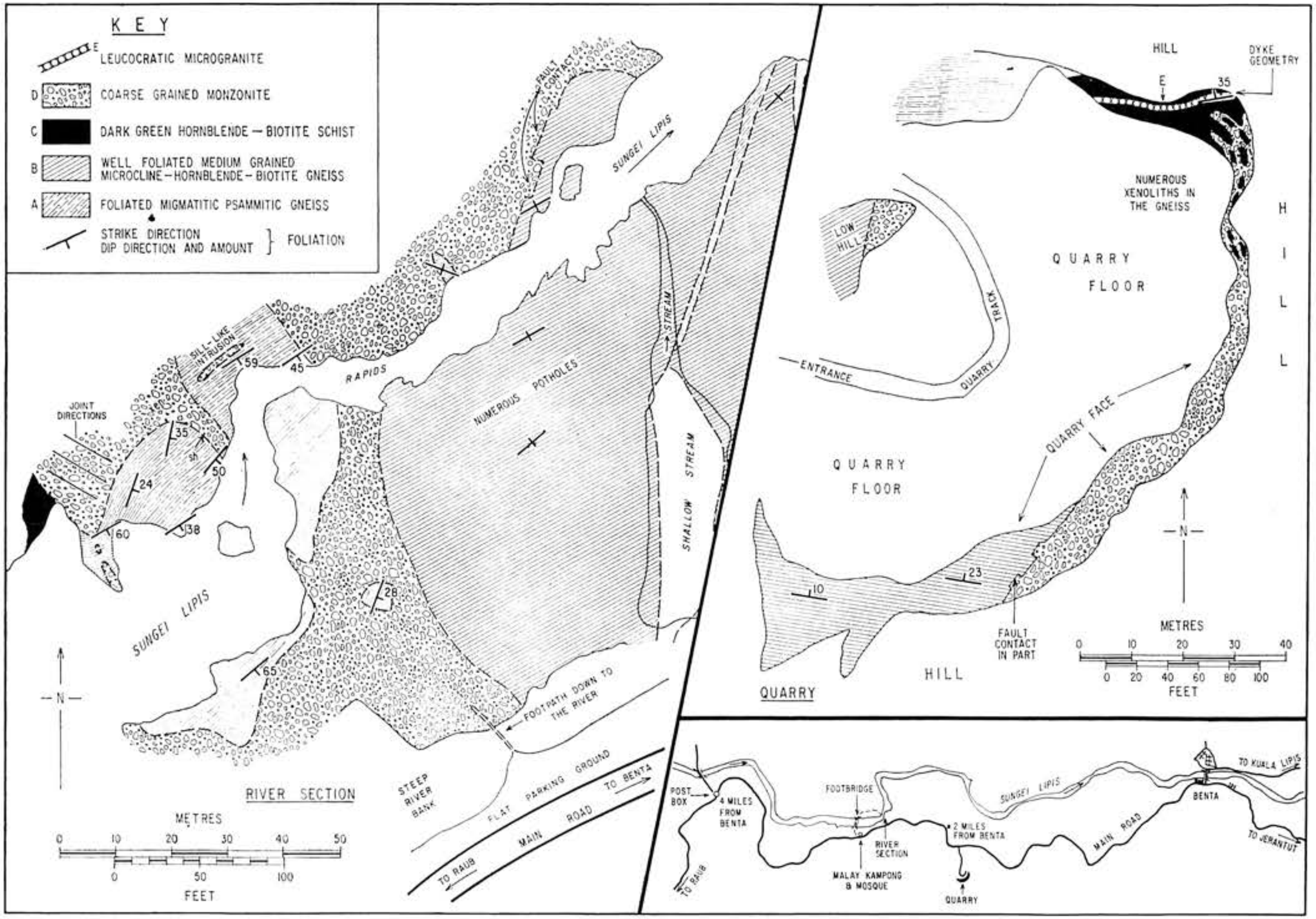

Fig. 1. Plane-table map of the river section in the Sungei Lipis and of the Benta quarry face as exposed in August 1968. The geographical features were surveyed by Messrs. Ahmad bin Jantan, Chen Shick Pei, Chin Lik Suan, Choy Kam Wai, Gan Ah Sai, Goh Choo Huat, Hasbi Mahbar, Ismail bin Md. Noor, Khoo Han Ping, Saw Kim Hee, Tan Chek Hong, Tan Teong Hing, Teh Guan Hoe, Yeap Ee Beng, Yeow Booi Chow, Wong Lee Cheong, and Wong Yoke Fah. The geological information is by the author.

At a distance of 2.5 miles (4.0 km) from Benta, there is a flat shoulder to the road on the left side at an S-bend. A footpath leads from the steep bank immediately onto the main river section of figure 1.

The river section is largely flooded when the river is high. Low water is assured during the period from May to August, during which time the exposures as shown in figure 1 can be seen in full.

A visit to the river section should be combined with a visit to the public works department road-metal quarry. It is located a little farther along the road towards Benta, and the following directions may be helpful: at 2.0 miles (3.2 km) from Benta there is a Hindu temple on the left side of the road close to the milestone 18 miles (29 km) to Kuala Lipis). At 1.8 miles (2.9 km) to Benta, a minor road leads off to the right into the quarry. It is signposted "Galian Batu, J.K.R. Raub". The quarry is about 0.2 miles (0.3 km) along this road.

PREVIOUS WORK

Scrivenor (1907) described the river outcrops briefly, and identified four different rock types which he regarded as magmatic differentiates of the Benom granite. He described them further four years later (Scrivenor, 1911) and gave them the general description of hornblende granite. In his general account of the geology of Malaya, he again described these rocks as hornblende granite, but also mentioned exposures of syenite (Scrivenor, 1931).

Willbourn (1931) recorded that the western foothills of the Gunong Benom granite batholith form a north-south trending belt of hornblende granite, syenite, and augite syenite. He noted that the Benom intrusion is of biotite granite and is generally devoid of hornblende. Four years later, he referred to the rocks of this area as syenite (Willbourn, 1935).

Richardson (in Willbourn, 1938) referred to these rocks as syenite. Later (in Ingham, 1939) Richardson described the rocks of the western margin of the Benom granite as a series of hornblendic rocks ranging from biotite-hornblende granite, through biotite syenite and pyroxene bearing varieties, to pyroxenite, and he expressed the opinion that many of them are hybrids with a granite magma.

The first detailed account of these rocks was published by Richardson (1939) in which he identified four major rock types: perknites (pyroxenites and hornblendites), hybrid rocks, flow-banded rocks, and minor acid intrusive rocks. He still maintained the name syenite for many of these rocks.

Khoo (1968) deduced that all the rocks of the western foothills of the Gunong Benom granite have been metamorphosed in the low pressure intermediate facies series of regional metamorphism. The ultimate origin of these rocks, he deduced, appears to be an igneous complex of pyroxenite, basic igneous rocks, syenite, and diabase dykes.

Ja'afar bin Ahmad (1965) described these rocks as hybrids and postulated that they have been produced as a result of assimilation of an earlier ultrabasic rock by the Benom granite. However he noted that the genesis of these so-called hybrid rocks was still uncertain. He is presently studying their petrology and geochemistry and eventually his results will be published as a Geological Survey memoir on the area.

RIVER SECTION

In August 1968 the river outcrops were mapped during a field course for Third Year geology students of the University of Malaya. Plane table maps were produced by Messrs. Goh Choo Huat, Saw Kim Hee, Tan Check Hong, Tan Teong Hing, Teh Guan Hoe, Wong Lee Cheong, Wong Yoke Fah, Yeap Ee Beng, and Yeow Booi Chau. Figure 1 is based on their maps, but the geology is as interpreted by the author.

There are four rock types exposed in this area. These may be named and briefly described macroscopically as follows:

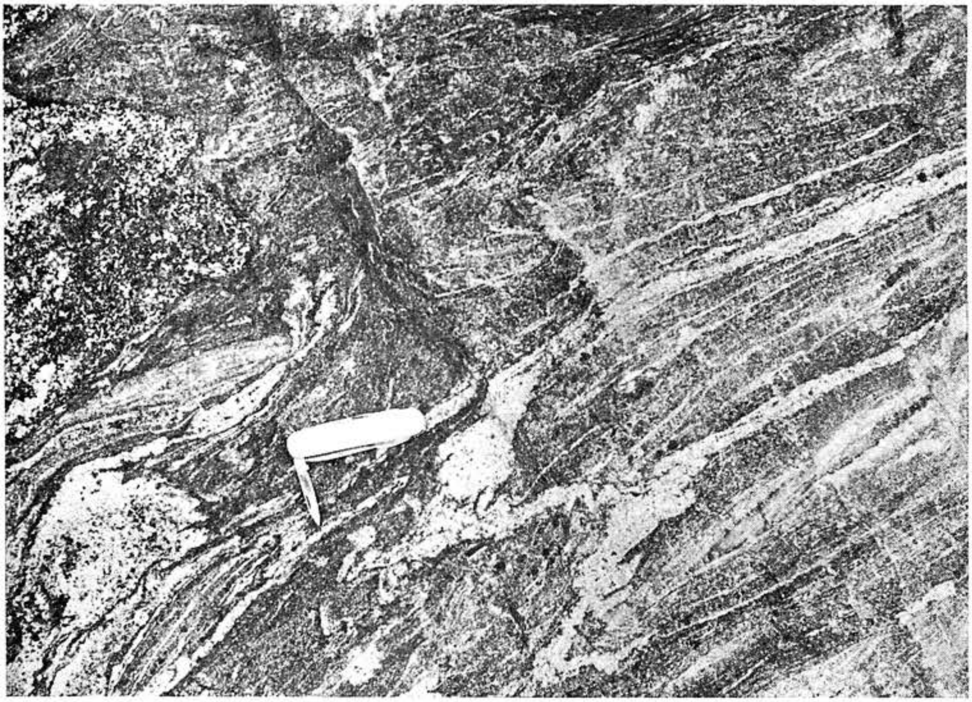

Fig. 2. Photograph of foliated venite psammitic gneiss (rock type A). The paleosome is of biotite-plagioclase-quartz psammite with rare calc-silicate bands. The neosome is of granitoid alkali feldspar-quartz veins and segregations with associated hornblende porphyroblasts. The psammite is intruded sub-concordantly by monzonite in the upper left corner. Locality: Benta quarry (6330). The handle of the knife is 8 cm long. This specimen now decorates the entrance to the geology department of the University of Malaya.

Rock A: Light grey migmatitic psammitic gneiss.

This rock is very fine grained and has a fairly well developed foliation, defined by small biotite crystals and by bands rich in pyrite crystals. Coarse grained white feldspathic segregations occur throughout the rock as irregular regions or in continuous but irregular bands parallel and sub-parallel to the foliation (Fig. 2). The rock shows complicated isoclinal folding which may be the result of flowage. Some areas of restricted extent in the folds are of green and pale brown calc-silicate. The whole rock is a migmatite of venite type, but in some outcrops the relationships between the coarser feldspathic segregations and the psammite become confused and diffuse so that nebulite would be a more appropriate term. The foliation is rather regular throughout the whole river section, with a general strike direction of from 10° to 50° east of north, and a dip varying between 24° and 65° towards the south-east.

Rock B: Well foliated light pinkish-grey and black gneiss

This rock is characterised by tabular to ellipsoidal light grey feldspar crystals of size varying from 1 to 2 cm maximum dimension, and width 2 to 6 mm. These crystals are very abundant, and their tabular nature defines the foliation of the rock (Fig. 3). They form approximately one half of the rock. The matrix is a finer grained mosaic of less well foliated black to dark green hornblende and biotite. In some areas the rock loses its foliation through development of larger equidimensional feldspar crystals. On slightly weathered surfaces the tabular crystals have a pale pinkish hue. The rock is cut by infrequent fairly regular feldspathic dykes and veins, commonly 2 to 3 cm wide An impressive feature of the gneiss is its very constant lithology, grain size, and foliation over the whole outcrop area. The foliation is parallel to that of the psammitic gneiss; the dip is difficult to measure but appears to be nearly vertical.

A characteristic feature of the gneiss is the numerous small xenoliths of psammitic gneiss. These are, without exception, perfectly aligned and very much flattened in the plane of foliation of the gneiss (fig. 3).

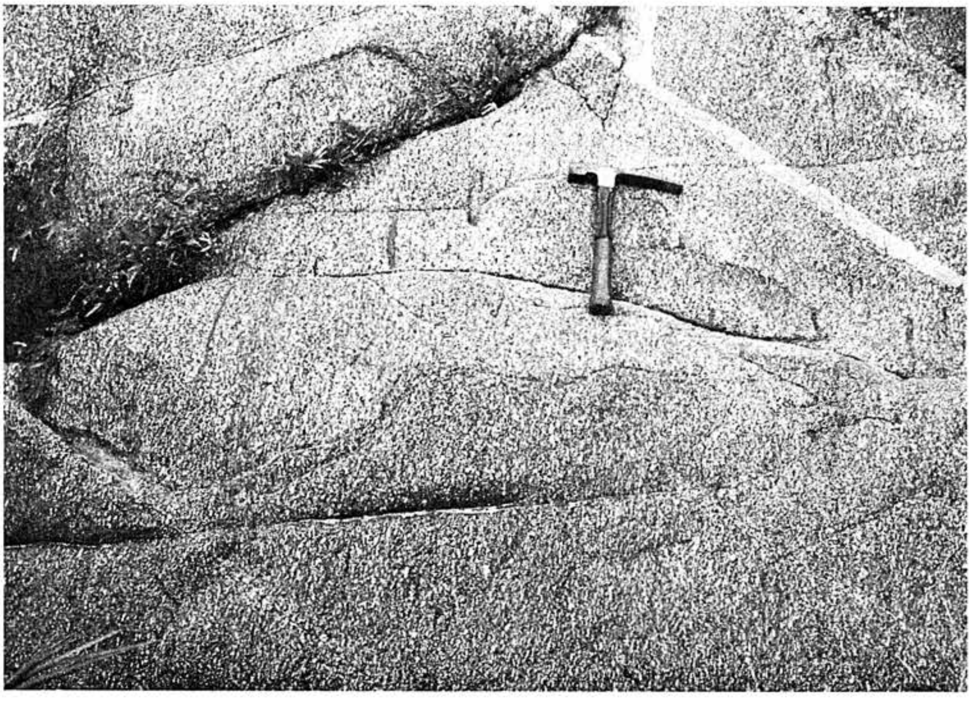

Fig. 3. Photograph of the foliated microcline-hornblende-biotite-plagioclase gneiss (rock type B). Note the common xenoliths of psammitic gneiss which are in perfect conformity with the rock foliation. The foliation is defined by the perfect alignment of tabular ellipsoidal microcline-microperthite crystals. Locality: River section in the Sungei Lipis, south bank. The hammer head is 19 cm long.

Rock C: Dark green hornblende-biotite schist with white feldspar porphyroblasts

This rock is coarse grained and individual biotite flakes of up to 6 mm can be seen. The foliation is crudely developed because of the abundance of feldspar and subhedral hornblende. The mica shows good preferred orientation. The rock is spotted white by numerous feldspar porphyroblasts of dimension up to 1.5 cm. These can be seen to be crowded with inclusions of mafic minerals.

Rock D: Porphyritic monzonite

This is a coarse grained, generally unfoliated, porphyritic rock. The phenocrysts are of tabular to subhedral light grey feldspar, often with a pinkish hue. They show excellent carlsbad twinning and are of a maximum length up to 3 cm and width up to 1.5 cm. They occur randomly in a medium grained granular matrix of dark green hornblende and biotite, and anhedral feldspar. The phenocrysts are evenly distributed in the matrix and form about half the rock. Although distinctly igneous in character, this rock occasionally shows a crude foliation. It is characterised by xenoliths, but these are large and equidimensional in contrast to those in rock B (Fig. 4).

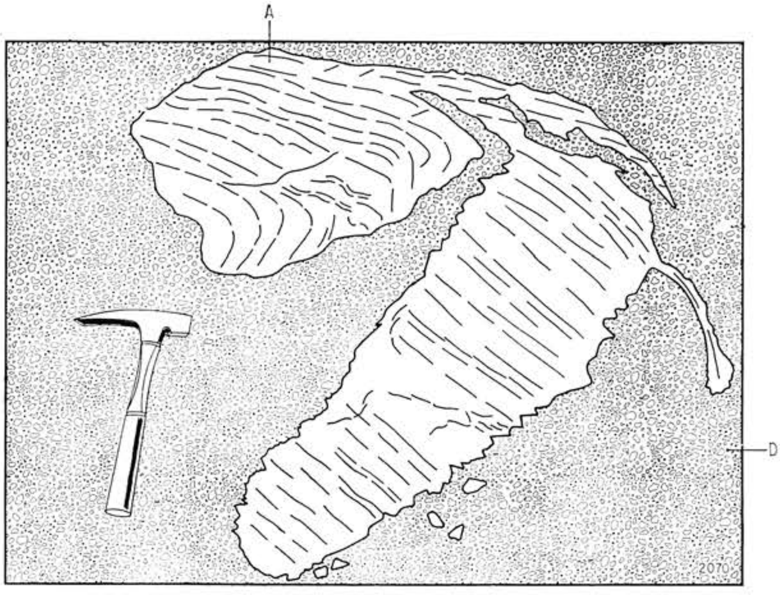

Fig. 4. Drawing from a colour transparency showing the typical irregular shape of the foliated psammitic gneiss xenoliths in the monzonite. Locality: south bank of the river section.

Relationships Between The Rock Types

The psammitic gneiss (rock A) is the oldest rock of the area. It occurs as boudinaged concordant inclusions within the foliated gneiss (rock B) (Fig. 3) and as larger irregularly shaped xenoliths within the monzonite (rock D) (Fig. 4). It is very much invaded by the monzonite as irregular intrusions and as a sill-like body on the north bank. The contacts between rocks A and D are distinctly discordant. On the other hand, although the psammitic gneiss occurs as inclusions within the foliated gneiss, both these rocks (A and B) share a common foliation.

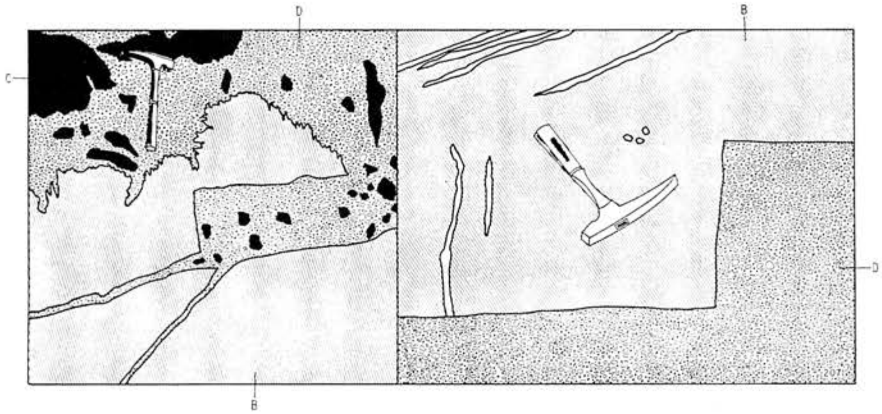

Fig. 5. Drawings from actual photographs showing the nature of the contact between the monzonite and the foliated gneiss. Left: Quarry face exposure showing both sharp, apparently joint-controlled, as well as diffuse, apparently metasomatically controlled, contacts. Right: River section exposure, north bank, showing what must be joint control of the contact. Note the pre-monzonite veining of the foliated gneiss.

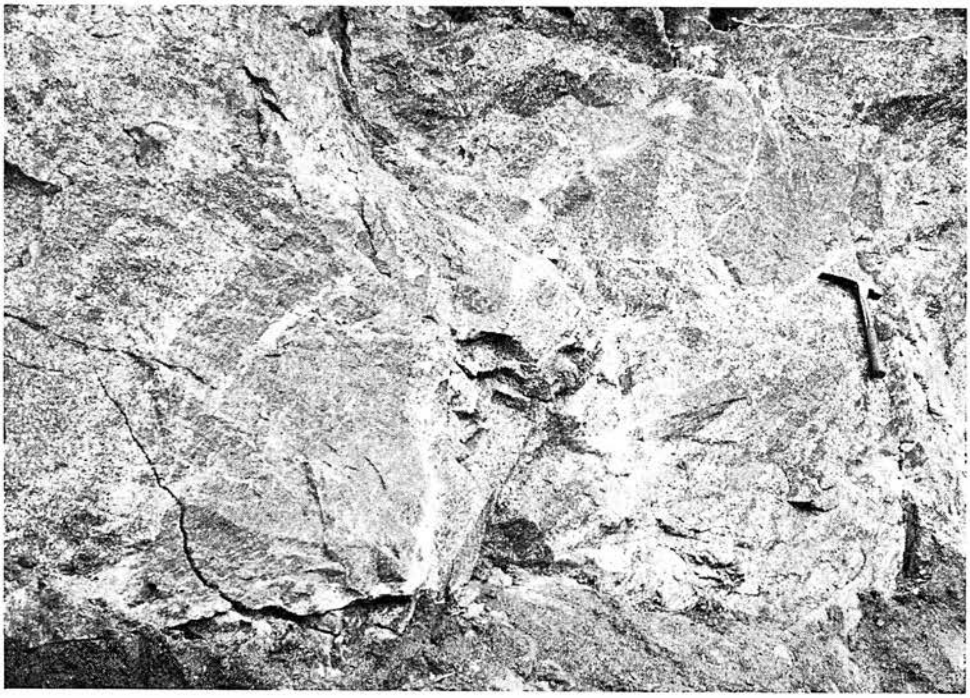

Fig. 6. Agmatite in which the light grey monzonite (rock type D) has engulfed blocks of the dark green hornblende-biotite schist (rock type C). This rock grades imperceptibly into nebulite. Locality: Benta quarry.

The relationships between the foliated gneiss (rock B) and the monzonite (rock D), which are of similar mineralogical composition, are perplexing. The contact is planar and discordant across most of the river section. Wherever it is seen, the contact is always planar and oriented at a high angle to the foliation of the gneiss (Fig. 5). On the north bank of the river the contact is planar, but characterised by small-scale block displacements. However the contact is not a simple one, and does not represent a present day zone of weakness. The displacement planes are not continuous into the monzonite and only partly continuous into the gneiss. The similarity of the mineralogy of the rocks on either side of the planar disconformity is of great significance; the only differences across the contact are the well foliated nature of the gneiss and the unfoliated nature of the coarser grained monzonite.

The dark green schist (rock C) always occurs as irregular inclusions and large blocks within the monzonite (Fig. 6). The relationship of the schist (rock C) to rocks A and B is not known since they are nowhere seen in contact.

THE QUARRY EXPOSURE

In August 1968 the quarry face was mapped by another group of Third Year University students. The plane table map was produced by Messrs. Ahmad bin Jantan, Chen Shick Pei, Chin Lik Suan, Choy Kam Wai, Gan Ah Sai, Hasbi Mahbar, Khoo Han Ping, and Ismail bin Mohammad Noor. Figure 1 is based on their maps, but the geology has been interpreted by the author.

The same four rock types as occur in the river section are to be found here.

In addition, in the northern end of the quarry, the dark green schist (rock C) and the monzonite (rock D) are cut by a tabular sill-like body of light grey microgranite (rock E). The sill is about 50 cm wide, and weathers to a pale buff colour. It is cut by micro-veins of epidote which appear pistachio green in the field. Secondary prehnite and zeolite veins commonly cut all rocks in the quarry. An excellent crystal aggregate of stilbite (5473)* was collected here.

Relationships Between The Rock Types

Because of their fresh unweathered nature on the quarry face, the differences between the foliated gneiss and the monzonite are not so readily obvious since contact features are not accentuated, as in the river section, by differential erosion. However the quarry offers fresher specimens which are more suitable for petrographic study.

The psammitic gneiss (A) occurs only at the far corner of the quarry, and it appears conformable with the dark green schist (C), but the schist is poorly foliated in comparison with the psammite and the exact nature of the contact remains in doubt.

The quarry shows the relationship between the monzonite (D) and the foliated gneiss (B) to be the same as in the river section. Planar contacts are the rule, and block faulted contacts on a small scale are quite common (Fig. 5). However the nature of the contact becomes rather enigmatic in places and gradations from well foliated, through poorly foliated gneiss, to unfoliated monzonite are frequent. At other places the monzonite appears to be distinctly intrusive into the gneiss.

* Number of specimen in the collection of the Department of Geology, University of Malaya.

The relationship between the monzonite (D) and the dark green schist (C) is well displayed in the quarry. The relationship is migmatitic, in which the monzonite permeates the schist as irregular veins, giving rise to an agmatite-type migmatite (Fig. 6). In other parts, the contacts between the schist and the monzonite are diffuse and the whole rock is more homogeneous, taking on the character of a nebulite.

The microgranite dyke is clearly intrusive and the youngest of the rocks in the quarry. Prehnite, epidote, and zeolite commonly occur along the joint planes of all rocks in the quarry. The occasional fine zeolite aggregate may be collected here.

PETROGRAPHY

Rock A

Fine grained equigranular-textured rock. Average grain size is 0.1 to 0.6 mm; porphyroblasts may attain 2 mm or larger size. The foliation is shown by the good preferred orientation of biotite and by bands rich in pyrite.

Biotite: Subhedral. Pleochroic from light brown to dark green, but the intensity of the green is not so pronounced as in the gneiss or the monzonite. Generally uniaxial. Forms about 10% volume of the rock.

Quartz: Rounded to anhedral. Closely associated with feldspar, with which it makes a mosaic. Content varies from about 20% (6287) to 50% (6330) and 60% (6281).

Plagioclase: Rounded to anhedral. Composition is around An_{30}. Generally untwinned (6287) but in some specimens the twinning is quite prominent (6330). It forms about 20% of the rock.

Alkali feldspar: Large anhedral poikiloblastic microcline microperthite to cryptoperthite porphyroblasts of 3 to 4 mm diameter are abundant in the quarry (6278), and occur also in the river section, though less prominently. They are full of rounded quartz and plagioclase crystals, and contain some biotite.

Hornblende: The exposures of psammite in the quarry contain large poikiloblastic euhedral to subhedral hornblende crystals of 2 mm length. They enclose rounded feldspar, quartz and biotite crystals. They are pleochroic from olive green to yellow green, and are prominent but not abundant (Fig. 7).

Accessory minerals are *pyrite* as cubes and pyritohedra (6287), anhedral *sphene*, and *apatite*. *Epidote* occurs in veins and as a few crystals in the river section xenoliths (6282).

The rock may be called a microcline-oligoclase-biotite-quartz-(hornblende psammitic gneiss.

Rock B

Coarse grained well foliated gneiss. The rock texture is dominated by numerous large tabular euhedral to ellipsoidal crystals of alkali feldspar of maximum dimension 1 to 3 cm and width 3 mm. These tabular crystals define the foliation. The mafic minerals, quartz and plagioclase, form a matrix to these porphyroblasts, and have a common grain size of around 2 mm.

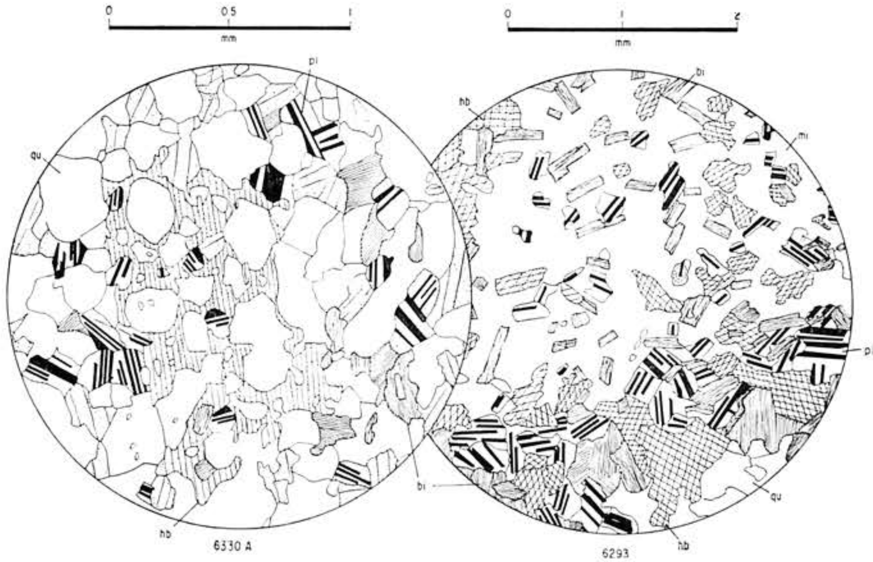

Fig. 7. Photomicrograph drawing of rocks from the Benta quarry to illustrate some interesting petrographic features. Left: Poikiloblastic subhedral hornblende in psammitic gneiss (specimen 6330). Right: Large alkali feldspar anhedral porphyroblast in the hornblende-biotite schist. The alkali feldspar is poikiloblastic and contains numerous included plagioclase, hornblende, and quartz crystals. (specimen 6293). qu = quartz; mi = microcline; hb = hornblende; bi = biotite; pl = plagioclase;. The scale is given in millimeters.

Alkali feldspar: Tabular to ellipsoidal prophyroblasts. All the crystals are characterised by a simple contact carlsbad twin; the twin plane is usually centrally located and parallel to the length of the crystals, but sometimes is slightly stepped. A most characteristic feature is a series of parallel ellipsoidal trains of inclusions of resorbed plagioclase, biotite and quartz (Fig. 8). The ellipsoidal ghost ornamentation is characteristic of the larger crystals only. This may be described as rapakiwi texture. Poorly developed margins of myrmekite occasionally outline the porphyroblasts. The alkali feldspar is of crytoperthitic to microperthitic microcline.

Plagioclase: Oligoclase An_{29} to An_{30}, subhedral and often replaced by microcline.

Hornblende: Anhedral to subhedral, pleochroic from yellow green to olive green.

Quartz: Anhedral and interstitial.

Biotite: Subhedral to euhedral, yellow to dark brownish green; only very crudely foliated.

Sphene, *apatite*, and *epidote* are common accessory minerals.

The modal composition varies from place to place, but the texture and mineralogy remain constant. The following analyses indicate the extent of the variation. Point counting was carried out using a Swift point counter with a 0.1 mm translation and a 0.33 mm row-spacing. Slides were stained by the two colour method of Bailey and Stevens (1960).

	River section (6283)	Quarry (6291)
Microcline microperthite	63% by volume	38%
Plagioclase	13	15
Quartz	5	11
Hornblende	12	25
Biotite	6	9
Sphene	1	2
Apatite	trace	0.5
Epidote	0.5	trace
Number of points counted	3343	3300

The rock may be called a microcline-plagioclase-hornblende-biotite gneiss.

Rock C

Crudely foliated equigranular rock with average grain size 1 to 2 mm.

Hornblende: Euhedral to subhedral, pleochroic from pale brown to olive green to brown green. Somewhat glomeroblastic. Forms about 30 to 40% of the rock.

Biotite: Shows moderate to good preferred orientation, interrupted only by the alkali feldspar porphyroblasts. Pleochroic from pale yellow to greenish brown. Closely associated with the hornblende. Forms about 20% of the rock.

Plagioclase: Subhedral to euhedral laths of around An_{30} composition. Some crystals are zoned, others twinned on the albite law. Rarely are the two features combined in the same crystal, but a carlsbad twin plane may subdivide a crystal into a zoned half and an albite twinned half. Forms about 20% of the rock. Where the rock occurs as inclusions within the monzonite, the plagioclase is more calcic, even to andesine An_{42} (6293), whereas in areas where there is a lesser density of monzonite permeation, the composition is oligoclase An_{30} (6288).

Alkali feldspar: Occurs as large anhedral sieve-crystals engulfing all the other constituents. They are untwinned and form a few but very large porphyroblasts, often about 12 mm diameter (Fig. 7). The feldspar is full of actinolite or hornblende acicular needles. Forms about 20% of the rock.

Epidote: Pleochroic from colourless to yellow green in thin section. It may vary from a trace to as much as 8% (6288).

Sphene: Generally anhedral and may form up to 4%.

Apatite: A minor accessory.

Quartz: Completely absent.

The rock may be called a hornblende-biotite-(epidote)-plagioclase-orthoclase schist (or gneiss).

Rock D

Generally unfoliated but occasionally has a crude foliation. It is very coarse-grained and the texture is strongly porphyritic. The phenocrysts are 3 cm long and the matrix minerals usually of 5 mm grain size.

Biotite: Subhedral, pleochroic from pale yellow to deep olive green. 2V about 2° negative. Crystals are 2 to 3 mm long and of random orientation. Generally closely associated with hornblende. Inclusions of zircon, sphene, and quartz are common.

Hornblende: Occurs intergrown with the biotite. Commonly twinned on (100). Often euhedral. Shows no preferred orientation. Pleochroic from pale brown to green, to dark green. In fact the pleochroic scheme is identical to that of the associated biotite.

Sphene: May be subhedral or euhedral.

Plagioclase: Andesine, An_{44}, but the outer zones of the crystals are of oligoclase. The ends of the crystals are frequently rounded. The crystals are somewhat clouded. High mgnification of 800 shows this feature to be due to parallel lines of minute indeterminate crystals which lie parallel to the c axis. Their orientation is obviously structurally controlled.

Quartz: Anhedral and interstitial.

Alkali feldspar: Forms large anhedral interstitial poikilitic masses of micro- to cryptoperthite (Fig. 8). No twinning is apparent. Some myrmekite

Fig. 8. Photomicrograph drawings of rocks from the Benta quarry to illustrate some interesting petrographic features. Left: Large alkali feldspar porphyroblast in the monzonite. It is anhedral and contains poikiloblastic inclusions of plagioclase, quartz, biotite, and hornblende (specimen 6292). Right: The termination of a large ellipsoidal alkali feldspar porphroblast in the foliated gneiss, characterised by ellipsoidal ornamentation and oriented inclusions (specimen 6291). qu = quartz; mi = microcline microperthite; hb = hornblende; bi = biotite; pl = plagioclase; sp = sphene. The scale is given in millimeters.

has developed along irregular contacts with the plagioclase. It is optically negative with a moderate 2V.

Apatite: Euhedral and a common accessory, occurring as needles in the feldspar.

There is some minor *epidote* in the feldspar.

The following modal analyses indicate the composition of the monzonite:

	Quarry (6292)	Quarry (6289)
quartz	13% by volume	8%
plagioclase	40	44
hornblende	14	4
alkali feldspar	20	16
biotite	12	28
sphene	< 1	< 1
epidote	< 1	< 1
pyrite	trace	nil
points counted	4160	3929

Rock E

Equigranular texture, average grain size 1 to 2 mm.

Quartz: Anhedral, forming about 15% of the rock.

Plagioclase: Occurs as two forms: 1) subhedral discrete crystals, showing good twinning. Some crystals are well zoned. Composition is oligoclase, about An_{12}. Many of the crystals are saussuritized. 2) as rims mantling cores of alkali feldspar. These rims are also of oligoclase and well twinned giving rise to a typical rapakiwi texture. Forms about 35% of the rock.

Alkali feldspar: Occurs in two forms: 1) as large anhedral crystals, often including quartz and plagioclase. 2) as cores to oligoclase rims (rapakawi). Forms about 40% of the rock.

Epidote: Anhedral, pleochroic from colourless to greenish-yellow. Distributed evenly throughout the rock, especially abundant within the plagioclase crystals, but also concentrated into veins of thickness up to 1 mm width.

CHEMISTRY

The chemical analyses of 6 rock specimens which are typical of the area are presented in Table 1. Richardson (1939) presented chemical analyses of the dark green schist (Rock C) which he called "melanocratic biotite-hornblende-orthoclase gabbro" (12457E; 2 in table 1); monzonite (rock type D) which he called "quartz-biotite-hornblende syenite" (12456B; 6 in table 1); and three specimens from the migmatite between these two rocks—13104 (no. 3 in table 1) and 13105 (no. 4 in table 1) of "feldspathised melanocratic xenoliths" of rock C in the monzonite (rock D), and 13106 of the feldspar-rich monzonite (rock D) (no. 5 in table 1), where it is rich in basic xenoliths. All of these analyses are of rocks from the Benta quarry. In addition I have been fortunate to obtain from Dr. Ja'afar bin Ahmad of the Geological Survey of Malaysia (JA 97) an analysis of the foliated gneiss (rock B). I am unaware of the exact locality

Table 1. Chemical analyses of selected rocks from the Benta area.

	1	2	3	4	5	6
Rock type	B	C	C (agmatite)	C (agmatite)	D (nebulite)	D
SiO_2	51.04	48.52	48.06	49.66	50.18	52.11
Al_2O_3	16.89	16.24	19.22	13.75	18.76	15.79
TiO_2	1.11	1.15	1.38	1.36	1.46	0.84
Fe_2O_3	1.92	2.47	1.45	2.00	1.22	2.23
FeO	5.17	6.36	6.30	7.10	5.92	5.71
Mno	0.16	0.13	n.d.	n.d.	n.d.	0.11
MgO	5.65	7.40	6.78	9.90	6.23	5.70
CaO	8.19	9.22	8.54	7.60	6.56	7.62
Na_2O	2.18	1.42	1.19	0.29	2.06	1.89
K_2O	5.26	2.90	4.46	5.06	4.76	4.23
H_2O+	0.59	2.08	n.d.	n.d.	n.d.	2.38
H_2O-	0.32	0.12	n.d.	n.d.	n.d.	0.13
P_2O_5	0.69	0.64	0.45	0.77	0.58	0.64
CO_2	0.10	0.10	n.d.	n.d.	n.d.	0.10
TOTAL	99.27	99.65	97.83	97.49	97.73	100.07

1 = Foliated gneiss (flow-banded syenite) by courtesy of Ja'afar bin Ahmad (JA 97) geol. Surv. Malaysia Loc: Benta area. Contains also Sn 2 p.p.m. 2 = Dark green schist (12457E, Richardson, 1939) (02.3.001, Alexander *et al.*, 1964). Loc. Benta quarry. Contains also ZrO_2 nil; Cl 0.07; F 0.94; S nil; BaO 0.30; Au nil; MoS_2 nil; C trace; less 0 for F,S,Cl 0.41. 3 = Feldspathised xenolith of dark green schist in the monzonite. (13104, Richardson, 1939) (02.3.002, Alexander, *et al.*, 1964) Loc. Benta quarry. Density 2.92. 4 = Feldspathised xenolith of dark green schist in the monzonite. (13105, Richardson, 1939) (02.3.003, Alexander, *et al.*, 1964) Loc. Benta quarry. Density 2.92. 5 = Feldspar rich nebulite (hybrid between monzonite and dark green schist). (13106, Richardson, 1939) (02.3.004 Alexander *et al.*, 1964) Loc. Benta quarry. Density 2.85. 6 = Monzonite (quartz-biotite-hornblende syenite). (12456B, Richardson, 1939) (02.2.002, Alexander *et al.*, 1964) Loc. Benta quarry. Contains also ZrO_2 nil; Cl 0.07; F 0.08; S 0.01; BaO 0.39; Au nil; MoS_2 nil; C 0.10; less 0 for F, S, Cl 0.06. n.d. = not determined.

of this specimen, but it is certainly from this general area and Dr. Ja'afar's description of the rock (1 in table 1) as a "flow-banded syenite" clearly indicates that it is of rock type B—the foliated gneiss.

A noticeable feature of all these 6 analyses is their high concentration in alkalis, especially potassium, and as seen above all these rocks contain alkali feldspar porphyroblasts.

The analyses were recalculated as cation percentages and Niggli molecular norms by the computer method of Hutchison and Jeacocke (1971). The Niggli norms are listed in Table 2. Only the dark green schist (rock C) and the monzonite (rock D) are saturated, and contain normative quartz. All the other rocks are undersaturated and contain normative olivine, and in one case normative nepheline in addition.

Table 2. Calculated Niggli molecular norms of the rocks listed in table 1.

	1	2	3	4	5	6
Quartz	nil	0.83	nil	nil	nil	1.27
Orthoclase	31.49	17.28	26.90	30.77	28.61	25.73
Plagioclase	38.14 $Ab_{45}An_{55}$	42.21 $Ab_{29}An_{71}$	45.56 $Ab_{24}An_{76}$	24.58 $Ab_{11}An_{89}$	47.19 $Ab_{40}An_{60}$	39.96 $Ab_{42}An_{58}$
Nepheline	1.64	nil	nil	nil	nil	nil
Halite	n.d.	0.22	n.d.	n.d.	n.d.	0.23
Total salic	71.28	60.54	72.46	55.34	75.79	67.19
Magnetite	2.03	2.60	1.55	2.15	1.30	2.40
Ilmenite	1.57	1.62	1.96	1.95	2.07	1.20
Apatite	1.46	1.52	0.96	1.66	1.23	1.55
Fluorite	n.d.	3.91	n.d.	n.d.	n.d.	0.10
Pyrite	n.d.	nil	n.d.	n.d.	n.d.	0.03
Calcite	0.26	0.26	n.d.	n.d.	n.d.	0.26
Diopside	11.94	4.32	4.49	9.39	0.71	9.18
$Wo_{50}En_xFs_{50-x}$	$En_{37}Fs_{13}$	$En_{38}Fs_{12}$	$En_{37}Fs_{13}$	$En_{39}Fs_{11}$	$En_{37}Fs_{13}$	$En_{36}Fs_{14}$
Hypersthene	nil	25.23 $En_{75}Fs_{25}$	2.80 $En_{73}Fs_{27}$	23.91 $En_{78}Fs_{22}$	4.97 $En_{73}Fs_{27}$	18.08 $En_{71}Fs_{29}$
Olivine	11.47 $Fo_{74}Fa_{26}$	nil	15.77 $Fo_{73}Fa_{27}$	5.60 $Fo_{78}Fa_{22}$	13.93 $Fo_{73}Fa_{27}$	nil
Total femic	28.72	39.46	27.54	44.66	24.21	32.81

The difference between the monzonite (6 in table 2) and the foliated gneiss (1in table 2) is very slight. The plagioclase composition is similar, around Ab_{42} to Ab_{45} and the diopside around En_{37} to En_{36}. The only difference is that the monzonite has free normative quartz whereas the foliated gneiss is undersaturated. The dark green schist and the xenoliths of the schist in the migmatite have very calcic normative plagioclase-An_{71} to An_{89} and magnesium rich hypersthene En_{75} to En_{78}.

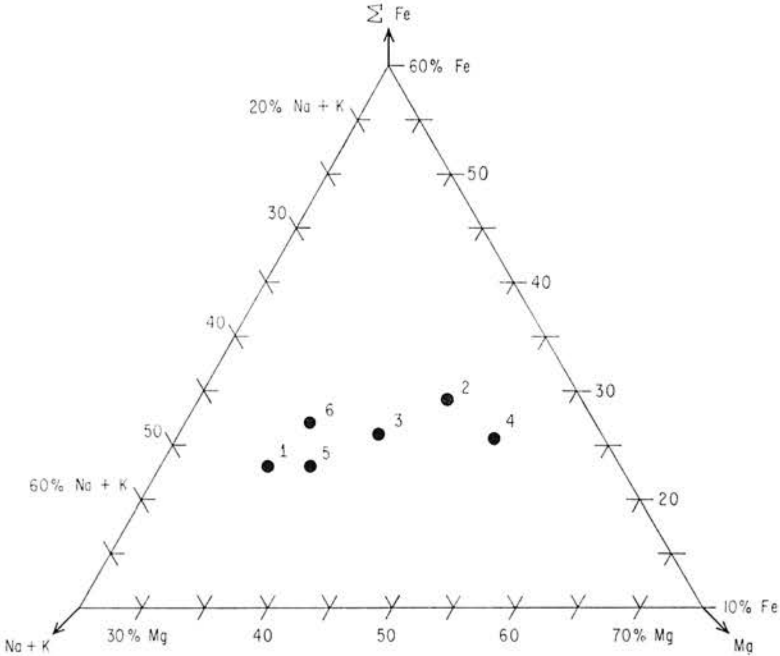

Fig. 9. Triangular variation diagram of the 6 rocks whose chemical analyses are given in table 1. The co-ordinates are of cationic total iron versus total alkalis versus magnesium.

A triangular plot of cationic percentages of total iron—total alkali—magnesium (Fig. 9) shows the similarity of the monzonite (analyses 5 and 6) and the foliated gneiss (1). Points 2, 3 and 4 are of dark green schist which occurs as xenoliths in the monzonite. This rock is clearly more basic than either the foliated gneiss of the monzonite and is of gabbroic composition.

DISCUSSION

Richardson (1939) described the foliated gneiss (B) as a "flow-banded syenite". However he was uncertain of the genesis of this rock and he stressed that "the present grouping of certain rocks as flow-banded is merely a field classification". He did, however, incline to the opinion that the so-called flow-banded rocks are hybrids. He further says that a considerable portion of the Gunong Benom foothills is composed of "flow-banded rocks" which range in composition from "biotite-hornblende-pyroxene-orthoclase gabbro" to "biotite-hornblende syenite". Ja'afar bin Ahmad (1965) continued the terminology of "flow-banded syenite".

The hypothesis that the perfect alignment of the K-feldspar crystals in rock B results from the flow of a syenite magma has many weaknesses. In particular it does not satisfactorily explain the following features:

i) The perfect concordance of the foliation of the psammite (rock A) and the planar alignment of the K-feldspar crystals of rock B in the river section (Fig. 1).

ii) The perfect alignment and concordance of the shape and foliation of the psammite xenoliths with the direction of the feldspar crystals of the containing rock B.

iii) The absence of any local irregularities of the planar structures of rock B as might be expected in a flow.

iv) The ellipsoidal rapakiwi nature of the large feldspars of rock B.

These features can be accommodated only within a theory which concludes that both the psammite (A) and the so-called flow-banded rock (B), which is herein renamed a foliated gneiss, were deformed and metamorphosed simultaneously. The parallelism of the K-feldspar rapakiwi crystals results therefore from preferred orientation during metamorphic crystallization.

There can be no doubt that the psammitic gneiss (A) and the foliated gneiss (B) are the oldest rocks of the area because they are both well foliated in comparison to the other rocks. The psammite occurs as oriented inclusions within the gneiss.

The relationship between these two rocks can have three possible interpretations:

1. The foliated gneiss (B) was mobile and brecciated the supracrustal formation (A) during emplacement. The emplacement took place slowly during simultaneous folding, causing the foliation of the intrusive rock. This interpretation might warrant the term "flow-banded" in describing rock B.

2. The foliated gneiss B was formed metasomatically *in situ* and the fine-grained supracrustal fragments of rock A are remnants of sedimentary rocks which for some reason were more resistant to the metasomatic processes. The metasomatism took place during regional folding and metamorphism, so that the unmetasomatised remnants have been metamorphosed with a concordant foliation.

3. The foliated gneiss (B) and the psammite (A) are syngenetic. But slight metasomatism has subsequently affected both rocks.

Khoo (1968) would favour interpretation 1 because he proposed that rock B was an orthogneiss. Of the three possible interpretations, I favour the third, and the following is the proposed sequence of events which would lead to the association of these two rocks:

Both rocks A and B are thought to be originally sedimentary in origin. A could have been a lithic sandstone, B an andesite tuff. The chemical analysis of B given in Table 1 is consistent with this assumption. Both these rock types are known to be common in the eugeosynclinal sequence of central Malaya. The two rock types are assumed to have been interbedded. Under deep-seated tectonic conditions of high temperature and fairly high pressure, both rocks were metamorphosed, the lithic sandstone to a psammitic gneiss, the tuff to a well foliated plagioclase-rich gneiss. Orgenic movement in connection with the metamorphism caused the brittle psammite to break, while the tuff (now foliated gneiss) acted in a plastic and pasty manner. The psammitic gneiss bands therefore became discontinuous and boudinaged. This proposed genesis explains the structural and mineralogical conformity of the two rock types A and B. The conditions of pressure and temperature must have been sufficient to cause partial anatexis of the more favourable rock A, so that it is in part a migmatite.

The mineralogy of these rocks unfortunately is devoid of definite index minerals which would give a precise definition of the metamorphic facies. However the formation of migmatite veins in the psammite gneiss would indicate a prevailing temperature of at least 650°C. The abundance of alkali feldspar and absence of muscovite in all the rocks of this region would indicate that if a minimum temperature of 650° was attained, then the prevailing pressure could not have exceeded about 3000 bars, (Winkler, 1967). From elsewhere in Malaya, the orogen is known to have been a region with a high thermal gradient, perhaps as high as 70° per km (Hutchison, 1969), so that the region can be assumed to be characterised by the Abukuma facies series of regional metamorphism. The absence of muscovite substantiates this deduction. Khoo (1968) furthermore disproved that the metamorphism could be Barrovian by the presence of andalusite in the lower grades.

It is suggested that the microcline microperthite rapakiwi porphyroblasts in the foliated gneiss are secondary, and result from potassium metasomatism. The source of the potassium is presumed to be from higher-grade deeper levels which underlay the rocks now exposed. The metasomatism was syn-metamorphic, otherwise one would expect the formation of muscovite to result from K-metasomatism. But muscovite is absent. Hence the metasomatism was under conditions of high temperature which prevented the formation of muscovite. The rapakiwi ellipsoidal ornamentation in the alkali feldspar porphyroblasts are features so common in the gneisses of Sweden (e.g. Bergström, 1963) that one can do no better than propose the same mechanism for their genesis.

Ramberg (1952) coined the expression "chemical squeezing" for the pushing out of K, Na, Si, O and H_2O from deep-seated rocks in the granulite facies. These rocks have been the source of the mobile, feldspar-forming solutions which migrate upwards into relatively low pressure overlying regions and deposit their cations.

Winkler (1967) has shown that at high temperatures, and under suitable pressure (under granulite and higher almandine amphibolite facies metamorphism) partial anatexis of the metamorphic rocks causes a separation of the rocks into a melt rich in SiO_2, K and Na (the neosome), and the unmelted remainder is accordingly enriched in Al_2O_3, Mg and Fe (the paleosome). The melt forms granitic segregations as veins in migmatite and migrates to form plutons, but it is not the melt itself which forms the porphyroblasts of K-feldspar in the overlying rocks, but solutions derived from these anatectic melts (Bergström, 1963).

The K- and SiO_2-rich solution rising up into the lower grade metamorphic pile primarily attacks the plagioclase crystals which were in equilibrium with the prevailing conditions of pressure and temperature. Some plagioclase relics are left within the large K-feldspar porphyroblasts. However the growing porphyroblasts have sufficient growth strength to expel biotite and hornblende to the matrix. Khoo (1968) also noted that the microcline porphyroblasts seem to be metasomatic replacements of plagioclase.

The K-feldspar porphyroblasts in the foliated gneiss are clearly the youngest of the crystals in this rock and their strongly penetrative character is beyond doubt. Their tendency to replace plagioclase is also beyond doubt. (Fig. 8). The plagioclase molecules of the feldspar are still maintained within the large microcline porphyroblasts as a microperthite intergrowth with the introduced K component.

There has been some formation of K-feldspar porphyroblasts within the psammite gneiss (A) but not to such an extent as in the foliated gneiss (B). This may be explained by the more suitable initial minerology of the gneiss, rich in plagioclase compared with the psammite—the potassium rich solution being readily soaked up by the pre-existing feldspar crystal aggregates.

The dark green schist (C) is more of a problem. It has lost its initial identity and there are no indications as to whether it was originally igneous or sedimentary. Its present chemical composition supports Richardson's (1939) view that it may have been a basic igneous rock (he referred to it as a gabbro). Khoo (1968) named it metabasite.

The association of gabbroic rock with gneisses showing rapakiwi texture is common in the metamorphic terrain of Sweden, and the problem as to whether the gabbro is truly igneous or metasomatically derived is a long debated question (Bergström, 1963). However there is no evidence in the Benta area whatsoever to indicate how this dark green schist (gabbro?) was formed. There are certainly no relict igneous textures, and the rock has been completely recrystallized.

The monzonite (rock D), as has been shown above, often grades imperceptibly into the foliated gneiss (B) and also has planar contacts. The similarity of the mineralogy of the monzonite and the foliated gneiss shows that these contacts, whether gradational, or planar, are metamorphically harmoneous. The only difference across these contacts is a textural one.

It is proposed that the monzonite represents mobilized foliated gneiss. The mobilization must have occurred after the region had been folded, and the foliated gneiss has assumed its present character complete with vein and joint system. During static orogenic conditions, the anatexis or partial anatexis of the foliated gneiss occurred at depths somewhat greater than that now represented by the present outcrop; the monzonitic magma being facilitated in its upward ascent by the joint system of the foliated gneiss. Although the pre-existing joints would have been obliterated during the early phase of mobilization at the level of evolution of the monzonitic magma, they would have persisted at the higher levels to which the magma eventually migrated. Hence we see the monzonite often in contact with the foliated gneiss along planar contacts, often also as gradational contacts, where the monzonite was metasomatically advancing into the foliated gneiss at the time when the region was uplifted (Fig. 5).

Whatever the original rock of the dark green schist (C) was, it must also be considered to have suffered rheomorphism together with the foliated gneiss. Partial anatexis of the dark green schist gave rise to a quartzo-feldspathic monzonitic magma. The anatexis was facilitated by jointing in the dark green schist resulting in an agmatite-type migmatite, or rheomorphic breccia (Goodspeed, 1953) (Fig. 6). One of the strong arguments for this origin is that the plagioclase in the "xenoliths" (paleosome) of the dark green schist (C) is more calcic than where there is less migmatite veining (neosome). This indicates that more albitic plagioclase has melted, as would be expected (Winkler, 1967), leaving behind more calcic plagioclase. Furthermore the neosome is feldspathic, whereas the paleosome has become enriched in mafic minerals. In some areas, the neosome and paleosome are so intimately distributed, that the rock must be called a nebulite.

The rheomorphism of the foliated gneiss and of the dark green schist must have taken place at conditions of temperature and pressure comparable to those prevailing during the earlier metamorphism of the psammite and foliated gneiss. This is a necessary requirement to explain the similar mineralogy of all the rock types in this region.

It is proposed that the introduction of epidote was a later-stage mineralogical event while the region was being uplifted and cooled. During the uplift, the microgranite sill (E) may have been intruded, and retrogressive metamorphism caused the localised formation of epidote.

The dark green schist, the monzonite, and the microgranite sill, have also experienced slight potassium metasomatism, as witnessed by the anhedral alkali feldspar porphyroblasts and the rapakiwi texture in the sill. Hence it must be assumed that K- and SiO_2-rich solutions still continued to rise from the underlying granulite facies infracrustal rocks.

It is interesting to compare the sequence of events proposed by Richardson (1939) for this region: He assumed that the agmatite was composed of xenoliths of altered gabbro (he called it orthoclase gabbro) in a matrix of feldspar-rich granitic rock. The latter he proposed was intrusive into the basic rock, and he probably had the Benom granite in mind. This present paper proposes that the feldspar-rich matrix (the neosome) was produced *in situ* by anatexis, and that the 'xenoliths' (the paleosome) have accordingly become more basic than the original rock from which they were derived because of the extraction of the more felsic and sodic neosome. Richardson (1939) proposed that the basic rock was originally a pyroxenite. Since the agmatite is assumed here to have been evolved *in situ*, the original rock would have been less basic than the dark green schist paleosome which is now present. Hence, far from being originally an ultrabasic rock, it would have been a rock of much less basic composition, and since we can see nothing of its original texture, it may even have been a pelitic sedimentary rock, and part of the original sedimentary sequence which included the proto psammitic gneiss (A) and the proto foliated gneiss (B).

CONCLUSIONS

The geological history of the region described herein may be summarised as follows:

1. Deposition of a sedimentary sequence of lithic sandstone, andesite tuff, and shale.
2. Burial to a depth of about 9 km, in an orogenic region with a geothermal gradient of about 70°C/km.
3. Folding and metamorphism in the sillimanite-cordierite-orthoclase-almandine subfacies of the amphibolite facies of Abukuma type, in which a tectonic temperature of around 650°C and pressure of about 3 kb was maintained. Partial anatexis of the psammite (A) gave rise to a venite migmatite.
4. During the metamorphism, potassium and silica-rich solutions permeated the rock sequence, being squeezed out from the deeper crustal regions undergoing granulite facies metamorphism. The rocks of that region are nowhere

exposed. The potassium was preferentially taken up by the metamorphosed andesite tuff to give the foliated microcline gneiss (B) in which alkali feldspar porphyroblasts show excellent rapakiwi texture. Alkali metasomatism also introduced K-feldspar into the dark green schist and the psammite to a lesser extent.

5. Following the orogenic folding phase, a period of more static conditions, still under high temperature, witnessed the rheomorphism of the pre-existing metamorphic rocks. The rheomorphism of the foliated gneiss (B) was facilitated by a joint system. The dark green schist (C) was completely brecciated. Being of a more feldspathic nature, the foliated gneiss was more susceptible to anatexis and large volumes of newly produced melt gave rise to the monzonite (D). The fraction of the schist which did not melt was accordingly enriched in calcic plagioclase and mafic minerals, leaving the dark green schist (paleosome) (rock D). The monzonite formed the matrix (neosome) of agmatite migmatite in which are included irregularly shaped inclusions of dark green schists (C) and psammite (A).

6. A microgranite sill, probably anatectic in origin was intruded. Alkali metasomatism continued, giving rise to rapakiwi textures. But muscovite was prevented from forming by continuing high temperature.

7. Uplift and cooling caused retrogressive metamorphism and the formation of epidote, and later zeolite.

The petrogenesis proposed above is regarded as a more realistic approach to the Benta migmatite complex. Many problems remain to be solved, but is it felt that the deep seated nature of these rocks must be recognised and the continuing use of terms such as "flow-banded syenite" and "hybrid rocks" (implying hybridization by the Benom granite) will only hinder an eventual understanding of this most interesting suite of rocks.

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