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Metamorphic episodes of the western foothills of Gunung Ledang (Mt. Ophir), Johore–Malacca, with a background account on the geology.

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Abstract: The western foothills area of Gunung Ledang is underlain by a predominantly pelitic group and a calc-silicate group of rocks. The former is made up of both spotted and non-spotted pelitic hornfelses with minor metavolcanics and calc-silicate hornfels. The latter is predominantly calc-silicate hornfels, metavolcanics and thin-banded calc-silicate hornfels and amphibolite. Minor rock types in the calc-silicate group are marble, amphibolite and pelitic hornfelses. These layered rocks are invaded by the Late Cretaceous Ledang granite on the east and the Belading granite on the west.

There is evidence of an early regional metamorphism registered in the rocks as relict schistosities and preferred mineral orientation . This episode is believed to be low grade. A second episode of contact metamorphism gave rise to the formation of minerals such as cordierite, sillimanite, andalusite, diopside, forsterite and wollastonite. This is followed by polymetasomatism giving rise to development of axinite, vesuvianite, lime garnet, scapolite, chondrodite and prehnite. Metamorphic zonations are shown by the contact metamorphism and polymetasomatism.

It is speculated that the regional metamorphism is a Middle-Late Triassic event if the layered rocks are extensions of the Middle-Late Triassic Gemas beds. The other metamorphic episodes are coeval with the Ledang intrusion of Late Cretaceous age.

INTRODUCTION

This paper presents evidence for the occurrence of some metamorphic episodes in the western foothills area of Gunung Ledang (Mt. Ophir), Johore-Malacca (Fig. 1) and gives a brief account of the geology. The area concerned is of about 40 sq. km from Bukit Asahan in Malacca to the Bekoh Estate area about 2 km north of Tangkak, Johore.

The area concerned is part of a larger area mapped in field mapping exercises by several staff and almost all the Third Year students of the Dept. of Geology, University of Malaya since 1976. Staff who have participated in the field mapping are Dr. B.K. Tan (1976–81), En. J.K. Raj (1977–78), En. Samsudin Hj. Taib (1979), En. K.L. Low (1980–81) and the author (1976–81). The combined efforts of all involved in the field mapping have contributed towards unravelling the geology of the area which is structurally and petrologically both complex and challenging.

GEOLOGICAL SETTING

The area lies in the Central Belt of Peninsular Malaysia near or at the western margin of the Belt (Fig. 2) The rocks of the western foothills have been invaded by the high level Ledang granite found by Yap (1981) to be emplaced in the Late Cretaceous (69 Ma). Various publications have the Lower Palaeozoic Foothills Formation bordering

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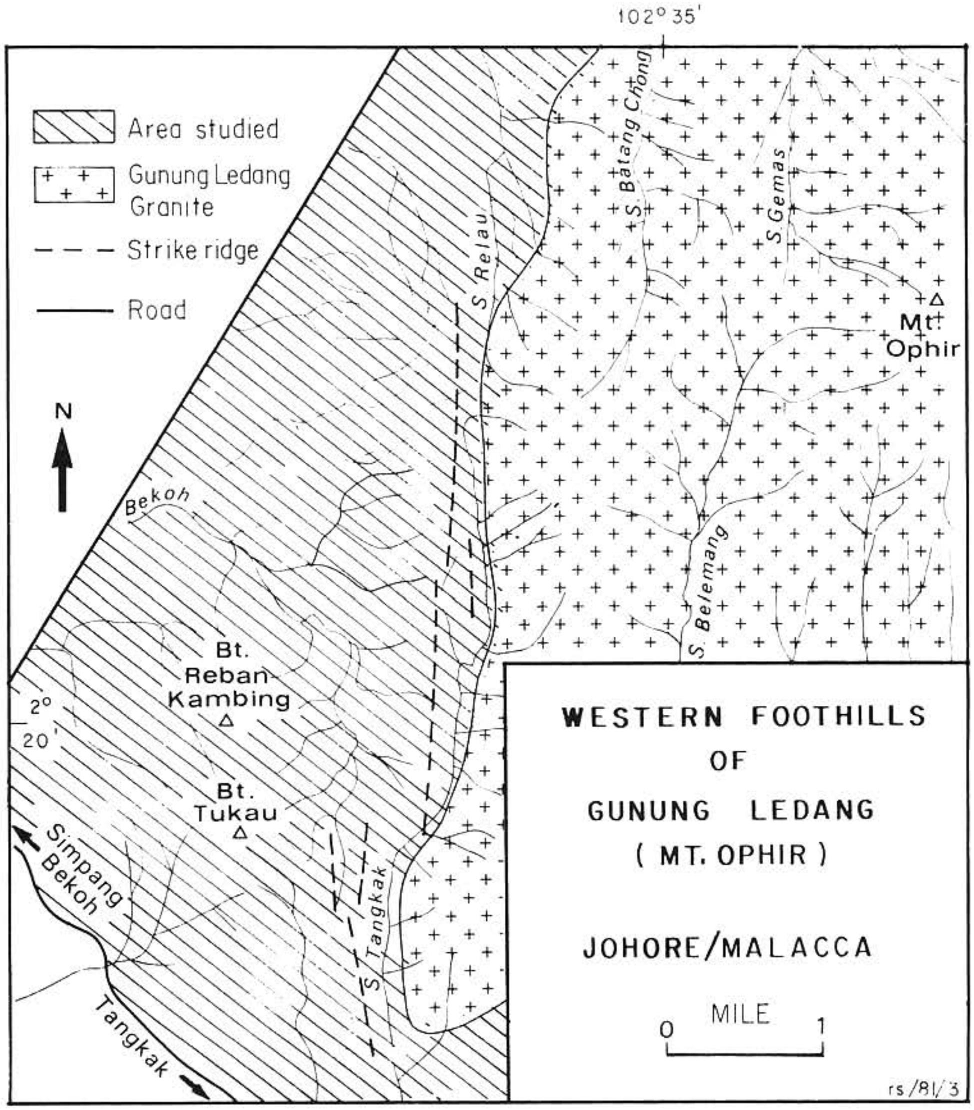

Fig. 1. Western foothills area of Gunung Ledang.

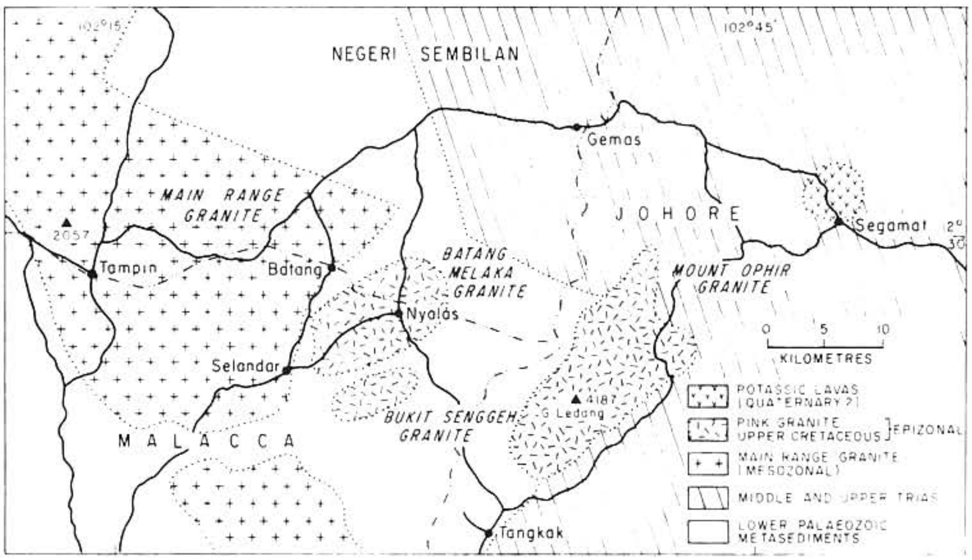

Fig. 2. Geological setting of the western foothills area of Gunung Ledang (Figure from Hutchison, 1973).

the Main Range granite (Yin and Shu, 1973; Hutchison, 1973). But Ong (1976) appears to imply that the rocks of the area are Middle to Upper Triassic. However, in this study, the author notes that the rocks of the western foothills bear similarities to rocks of the Triassic Gemas Beds described by Lum (1980) north of the area.

PREVIOUS WORK

Relatively little is known about the rocks of the western foothills. The area is part of Sheet 114 mapped by Ong (1976) who found the area to be underlain by metamorphic rocks. An area mapped by Lim (1972) includes the northern part of the western foothills area. Granites and feldspars from the Tangkak Quarry (part of the Belading granite in this study) were studied by Ng (1974).

GENERAL GEOLOGY

As relatively little has been published about the general geology of the area, it is necessary to give a brief but sufficient account to provide the necessary background information.

Layered Rocks

The western foothills area is underlain by metamorphosed layered rocks intruded by the Ledang granite on the eastern side and the Belading granite on the western parts (Fig. 3). The layered rocks can be divided into 2 lithologically distinct groups

(a) a predominantly pelitic group and
(b) a predominantly calc-silicate group.

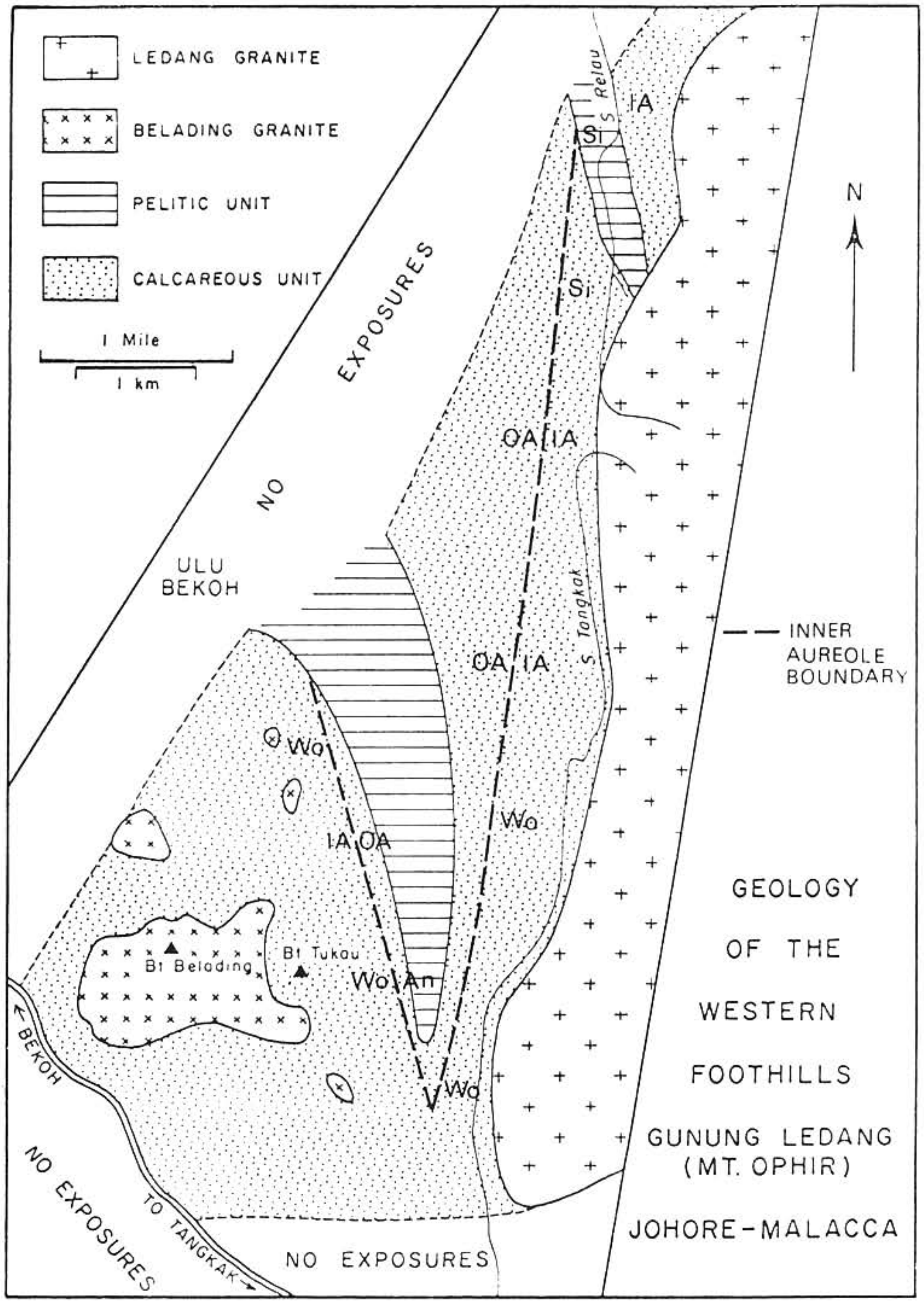

Fig. 3. Geology and demarcation of inner and outer aureoles of the Ledang and Belading granites in the western foothills area of Gunung Ledang. Note the Ledang and the Belading aureoles impinge (OA = outer aureole, IA = inner aureole, Wo = wollastonite, An = andalusite, Si = sillimanite).

TABLE 1

MAJOR AND MINOR ROCK TYPES OF THE PELITIC AND CALC-SILICATE GROUPS OF LAYERED ROCKS IN THE WESTERN FOOTHILLS AREA OF GUNUNG LEDANG

	MAJOR ROCK TYPES	MINOR ROCK TYPES
Predominantly Pelitic Group	(a) Spotted pelitic hornfels (b) Non-spotted pelitic hornfels	(a) Metavolcanics (b) Calc-silicate hornfels
Predominantly Calc-Silicate Group	(a) Calc-silicate hornfels (b) Metavolcanics (c) Thin-banded calc-silicate hornfels and amphibolite	(a) Marble (b) Amphibolite (c) Thin banded calc-silicate hornfels and marble (d) Thin banded calc-silicate hornfels and pelitic hornfels

The lithologies of the 2 groups of rocks are summarized in Table 1. Owing to the complex nature of the folding in the area, at present it is still uncertain which of the 2 groups of rocks is older. From Fig. 3, it can also be seen that the pelitic group occurs in the Bekoh Estate and Sungai Relau area separated by a terrain underlain by the calc-silicate group. At present, it is also still uncertain whether the two pelitic group occurrences belong to the same stratigraphic horizon or to two separate horizons.

The pelitic group

The major rock types in this group are pelitic hornfelses both spotted and non-spotted. They are rich in brown biotite and the spotted varieties contain porphyroblasts of cordierite or shimmer aggregates. The spotted and non-spotted pelitic hornfelses are interbedded with individual beds often about 10–15 cm thick.

The pelitic hornfelses have minor interbeds of metavolcanics and calc-silicate hornfelses. The metavolcanics include metamorphosed lava and metamorphosed tuffaceous rocks sometimes with lapilli-size clasts. Some of the calc-silicate hornfelses also appear to be originally finer-grained tuffaceous rocks. Except for the metamorphosed lava, all the other minor rock types of the pelitic group are major rock types of the calc-silicate group and some brief petrographic descriptions of these rocks will be given in the section on the calc-silicate group. The metamorphosed lava has a fine-grained quartzose groundmass with common biotite and some hornblende. Enclosed in the fine-grained matrix are some relict phenocrysts of plagioclase, sometimes rather euhedral.

The calc-silicate group

The major rock types in this group are calc-silicate hornfelses, metavolcanics and rocks consisting of thin banded calc-silicate hornfels and amphibolite. All of them are interbedded and each of them is commonly thick bedded. The minor rock types in this group are amphibolite, marble, thin-banded calc-silicate hornfels, marble, thin banded calc-silicate hornfels, and pelitic hornfels. These minor rock types occur as relatively thin layers interbedded with the major types.

CALC-SILICATE HORNFELSES

The calc-silicate hornfelses occur in many varieties. This diversity is caused not only by the original diversity of compositional types but also by different grades of metamorphism and different types of metasomatic responses. The most common type is pale greenish grey ranging from rather fine to medium-grained made up predominantly of quartz, diopside and plagioclase. Others come in shades of pale grey, greenish, brown and even rather dark grey. The colours depend largely on the mineralogical composition. Rocks which are metasomatized near the granite contacts show more colour variations and are almost invariably porphyroblastic. Rocks not metasomatized are seldom porphyroblastic especially to the naked eye. However, sometimes they develop irregular clots of dark green diopside seldom more than 1 cm across.

The calc-silicate hornfelses are the most predominant type of the group. They can be found throughout the whole outcrop area of the group.

METAVOLCANICS

The metavolcanics consist of various types of metamorphosed tuffaceous rocks with a good range in clast sizes. Rocks which are identified here as originally tuffaceous are those which still contain recognizable clasts. However, varieties which were originally only of ash could well become some of the calc-silicate hornfelses described earlier. Indeed, some of the metamorphosed tuffaceous rocks with smaller and lesser amount of clasts appear to grade petrographically into calc-silicate hornfelses.

The clasts in the metamorphosed rocks have been found to be the following: quartzite, metasiltstone, slate, biotite schist, muscovite schist, metamorphosed lava, quartz, fieldspar, pelitic hornfels, metamorphosed tuff and marble. The sizes of the clasts range from microscopic to lapilli-size grains, usually ovoid with lengths up to 2 cm and in an exceptional case a marble clast has a length of about 20 cm. The rocks with plentiful lapilli-size clasts (called metamorphosed lapilli tuff) are particularly common in the ridge west of the north-south Sungai Tangkak-Sungai Ulu Relau valley. The rocks with microscopic clasts are widespread.

The groundmass of the metamorphosed tuffaceous rocks ranges from quartz-plagioclase-diopside predominant to amphibolitic with quartz-plagioclase-hornblende. Biotite may or may not be present in the groundmass. From the groundmass mineral assemblages it appears that the groundmass ranges from basaltic-andesitic to more acidic and less Fe-rich, dacitic perhaps.

THIN-BANDED CALC-SILICATE HORNFELS AND AMPHIBOLITE

This type is very distinctive and easily recognizable as it typically consists of one to 30 cm thick alternating bands of green or pale grey calc-silicate hornfels and dark brown or black amphibolite. Occurrence of this type is also widespread, commonly occurring on both sides of the Bekoh Valley at the Sungai Relau area and also as a thin veneer covering the Belading granite at the new Tangkak Quarry.

The calc-silicate hornfels consists predominantly of quartz, diopside and plagioclase like those described above and metasomatized varieties show other minerals which will be described later.

The amphibolite very distinctively contains conspicuous to rather major amounts of brown biotite which gives the rock its brown tone. Other major minerals in this rock are quartz, plagioclase and hornblende. Some sphene may also be present.

MINOR ROCK TYPES

The calc-silicate hornfels in the minor category are similar to these already mentioned above. The amphibolite here generally does not show so much biotite as in the amphibolite in the thin-banded calc-silicate hornfels and amphibolite. Indeed biotite may also be absent in this amphibolite. The pelitic hornfels may sometimes be spotted as well and when it is not spotted it may appear to be rather similar to the biotite-rich amphibolite mentioned above. The marble in the thin-banded calc-silicate hornfels and marble is always rather fine grained but the marble occurring as metre-thick beds or pods or as large loose blocks are generally pale grey or white and coarse-grained.

Each of these minor rock types are of rather rare occurrence. However, the more massive marble has been found only on the hills flanking the Sungai Tangkak and the thin-banded calc-silicate hornfels and marble has been found only on the eastern side of Bukit Tukau-Bukit Reban Kambing area.

GRANITIC ROCKS

The Ledang Granite

The Ledang granite is, compared to other granitic bodies in Peninsular Malaysia, much studied and described (Paramanathan, 1966; Hutchison, 1973; Yap, 1981 and others). It is a biotite granite and popularly believed to be pink. However, in the western foothills area, the granite is seldom pink and those localities which are pink are only very pale pink. The western margin of the Ledang granite occurs in the western foothills area (Fig. 3) and the contact appears to be rather straight and parallel to the Sungai Tangkak and further north it crosses the Sungai Ulu Relau.

The Belading granite

The Belading granite is at present being unroofed and underlies the Bukit Tukau-Bukit Belading-Bukit Reban Kambing range area at shallow depths, where it can be seen that the granite underlies the cover at shallow depths at various places.

The granite is biotite-bearing and sometimes pale pinkish. Petrographically it appears to be similar to the Ledang granite. The Belading granite has miarolitic cavities and is also a high level granite like the Ledang granite. However, at the present level of erosion there is no evidence to show that the Belading granite is connected to or is an offshoot of the Ledang granite. It is uncertain whether the Belading granite is emplaced earlier or later than the Ledang granite. The two granites may even be coeval. Here, the Belading granite will be regarded as a separate body.

Minor granitic bodies

Granitic sheets, sills and dykes, up to a few metres thick, and minor quartz veins invaded the layered rocks near the margins of both the Ledang and Belading granites. Such bodies are especially common at the southern part of the area. Sometimes these minor bodies are pegmatitic, and rarely tourmaline crystals are present.

STRUCTURES

The predominant bedding strike of the layered rocks is north-south. The beds are generally steeply dipping and the area appears to have suffered tight folding. In some outcrops recumbent-like fold structures have been seen and it is uncertain whether these are slumps or tectonic in origin. The lack of sedimentary structures made structural interpretations more difficult. Cross-beddings have been seen at 2 localities, both indicating right-side up and a loose block in the Sungai Relau area appears to show graded bedding.

Several major faults have been postulated in the area (Yin and Shu, 1973; Ong, 1976). However, field evidence for these faults has not been encountered. Only minor faulting has been seen.

Stratigraphic Correlation

To have more meaningful discussion of the timing of the metamorphic episodes to be given later, it is necessary to know the age of the layered rocks. As the area is polymetamorphic, direct fossil dating is rather difficult and lithological correlation will not be easy. The adjacent area have no lithologically similar rocks. It is therefore necessary to reconstruct the pre-metamorphic stratigraphy to effect a correlation assuming that the rocks of the western foothills area are not an older (and separate) unit of rocks than those in adjacent areas.

The similarities of the minor rock types of the pelitic group to the major rock types of the calc-silicate group most probably indicate conformable transition from one group to the other. The occurrence of pelitic rock fragments in the metavolcanics may indicate that rocks of the pelitic group may underlie the calc-silicate group of rocks.

From the petrography it appears that the area was once underlain by a sequence made up of argillaceous rocks, possibly also calcareous, and volcanics, mainly tuff and some lava with minor lenses of limestone. The volcanics appear to range from basaltic to andesitic and acidic. The argillaceous rocks appear to be relatively thin and considering the general steepness of the calc-silicate group of rocks and the structures the general impression is that the thickness of the calc-silicate group is of the order of 1 km.

The portraiture of the stratigraphy of the area resembles the Permo-Triassic of the Central Belt. Nearer to the area, the Middle to Upper Triassic Gemas beds of Lum (1980) have much resemblance to the rocks in the foothills area. The Gemas beds according to Lum (1980) consist of argillaceous, arenaceous and tuffaceous rocks with sedimentary structures such as slumps and graded bedding. The rocks in the area appear to have less resemblance to the Lower Palaeozoic Foothills Formation and moreover the regional strike of the Permo-Triassic rocks trend southwards into the western foothills area. In the geological map compiled by Yin and Shu (1973) the area south of the western foothills area is also shown to be underlain by Triassic rocks. All these considerations favour a Permo-Triassic age for the rocks of the western foothills and they may even be Late Triassic.

METAMORPHISM

All the layered rocks in the western foothills area have been metamorphosed. There is evidence that three metamorphic episodes have occurred in the area. Polymetamorphism in the area include

(a) regional metamorphism followed by
(b) contact metamorphism and
(c) polymetasomatism being the latest episode

REGIONAL METAMORPHISM

Regional metamorphism appears to be the earliest metamorphic episode which affected the rocks. Evidence for this early episode is, however, not readily obvious. Firstly, the later episodes of metamorphism have obliterated much of the evidence. Secondly, the calc-silicate hornfels, a major rock type, has a composition such that prismatic or platy minerals could not develop and therefore the fabric due to regional and contact metamorphisms show little obvious difference. Thirdly, the episode of regional metamorphism appears to be low grade and the lack of less 'perishable' porphyroblastic minerals has resulted in a lack of relics which could serve to unravel its earlier history. However, in both exposures and thin-sections evidence for an early regional metamorphic episode can still be seen.

Evidence from the pelitic group

In the pelitic group occurring in the Bekoh valley, the non-spotted pelitic hornfels shows a schistose fabric defined by preferred alignment of brown biotite plates. The adjacent interbeds of spotted pelitic hornfels, however, do not show any schistose fabric. Here, it is interpreted that the schistosity may be a mimetic one in which the biotite developing during later contact metamorphism has grown mimetically after aligned layered silicates such as muscovite and chlorite. The spotted pelitic hornfels fails to preserve the original schistose fabric, if present, because plentiful development of porphyroblasts of cordierite have destroyed the layered silicates and therefore the fabric as well.

In rocks of the pelitic group in the northern part of the area, there is also evidence of an early schistose fabric. Specimens also show schistose fabric defined by preferred dimensional orientation of brown biotite. Some specimens show preservation of an earlier schistose fabric by having preferentially aligned Fe-Ti oxides in a hornfelsic matrix.

The development of biotite schists from muscovite-chlorite schists is the first evidence of contact metamorphism in the aureoles of the Donegal granites and the growth of the biotite has been interpreted to be mimetic after muscovite and chlorite (Naggar and Atherton, 1970). This may have happened in the pelitic rocks of the western foothills area.

Evidence from the calc-silicate group

CALC-SILICATE HORNFELS

The calc-silicate hornfels also show signs of vague relict preferred mineral orientation in the field. Considering that the calc-silicate hornfels is widespread in the area, the small number of times this feature has been encountered probably indicate its rarity. The fabric is mostly encountered in the southern part of the area.

The minerals which show preferred orientation are usually opaque minerals, sphene and diopside aggregates. It is believed that the diopside is not formed during the regional metamorphism but has formed during the later contact metamorphism from aligned lower grade regional metamorphic minerals such as tremolite. The reactions which occurred could be as follows.

1. Dolomite + Quartz → Tremolite + Calcite + Carbon Dioxide
(regional metamorphism)

2. Tremolite + Calcite + Quartz → Diopside + Carbon Dioxide + Water
(contact metamorphism)

The suggestion here is that the alignment of diopside is mimetic after aligned tremolite.

METAVOLCANICS

Both macroscopically and microscopically the metavolcanics especially the tuffaceous types exhibit excellent fabric of the regional metamorphic episode. The rock fragments in the metamorphosed tuffaceous rocks often are ellipsoidal or elongate and show preferred orientation. This feature is interpreted as caused by rotation to preferred alignment due to regional metamorphism. This feature is not sedimentary origin as the direction of the longest axes of the clasts has been found to be at an angle to the bedding between two lithologically different beds, as at Sungai Relau.

In support of the above interpretation, the prismatic hornblende crystals in some metamorphosed tuffaceous rocks with an amphibolitic groundmass show preferred alignment parallel to the alignment of the accompanying rock fragment clasts. The schistose groundmass is also an evidence for an earlier regional metamorphic episode. From the petrography it appears that the hornblende is unlikely to be of regional metamorphic origin and is more likely of contact metamorphic origin. The earlier groundmass could be schistose of low grade minerals such as actinolite.

THIN-BANDED CALC-SILICATE HORNFELS AND AMPHIBOLITE

The amphibolite, like the amphibolitic groundmass of the metavolcanics, contains hornblende which shows preferred orientation.

MINOR ROCK TYPES

The minor rock types are most fruitful in providing evidence for an early regional metamorphic episode. Their thin-banded nature and some of their compositions are particularly suitable to show the earlier history.

The amphibolite is usually schistose with aligned prismatic hornblende. In the thin-banded calc-silicate hornfels and pelitic hornfels, the latter shows mimetic schistose fabric defined by biotite plates. In the thin-banded calc-silicate hornfels and marble, the marble may sometimes show calcite grains with dimensional preferred orientation resulting in a schistose rock.

CONTACT METAMORPHISM

The evidence of contact metamorphism is everywhere in the western foothills area and there is no doubt from the distribution of contact metamorphic and also metasomatic minerals that the contact metamorphism was caused by the intrusions of both the Ledang and Belading granites. The south and central parts of the area have been intruded by the granites on both east and west sides and the resultant contact metamorphism of the area has given rise to impinging aureoles which are geological rather rare situations. The northern part of the area has only been affected by the Ledang granite. However, the lack of exposures west of the ridge flanking the west bank of Sungai Tangkak Sungai Ulu Relau prevents the lower grades of contact metamorphism to be studied. The non-exposure of lower grades of contact metamorphism in the north and the unavailability of the lower grades in areas of the Bekoh valley and further south due to contact metamorphism by granites from both sides of the valley, are the only deficiencies in what appears to be another classic area of contact metamorphism.

Both the pelitic and calc-silicate groups have undergone contact metamorphism. Details of evidence of contact metamorphism, apart from the hornfelsic texture of most of the rocks, are given below.

Evidence from the pelitic group

Only transformations of the major pelitic rock types will be given in this section and details regarding the minor rock types of this group are similar to similar rocks in the calc-silicate group to be given later.

The exposed rocks of this group occurring furthest away from any granite contact are at the centre of Bekok valley. Pelitic rocks here are both spotted and non-spotted hornfelses. The spotted hornfels contains biotite, quartz, opaque minerals, sometimes muscovite and always cordierite porphyroblasts (Plate 1). The cordierite

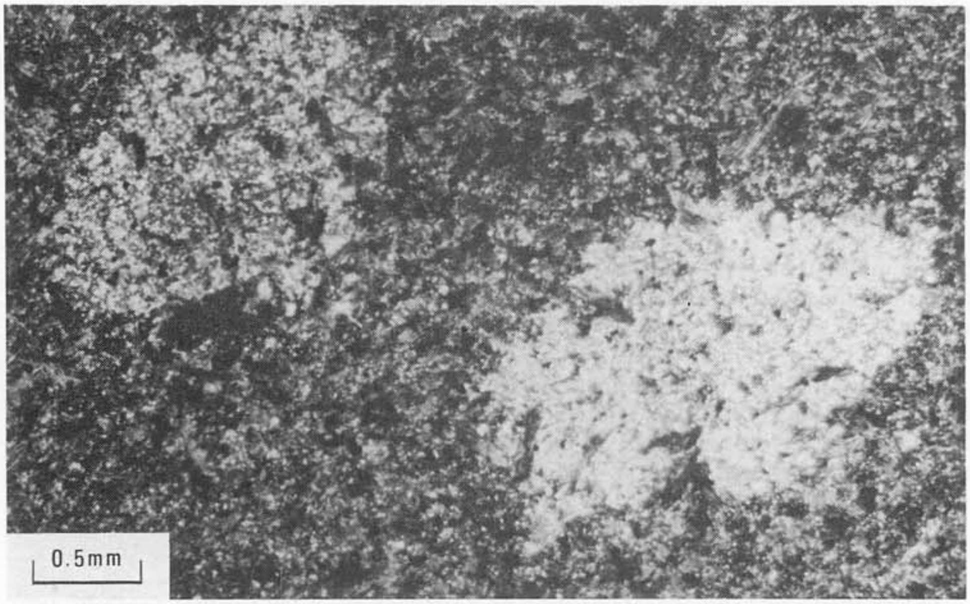

Plate 1. Cordierite porphyroblasts in spotted pelitic hornfels. Locality: Sungai Relau (X-polars).

porphyroblasts are rather spherical with poorly defined crystal boundaries and are strongly sieved with inclusions of quartz and brown biotite.

Nearer, to the granite contact, a locality further south of the previous locality, the pelitic hornfels developed irregularly shaped, and very sieved crystals of andalusite. Cordierite may or may not be present and it may be enclosed by the later andalusite. The andalusite-bearing rocks are biotite hornfelses.

The pelitic group of rocks exposed nearest to the granite contact is at the Sungai Relau. The spotted pelitic hornfels here developed sillimanite (fibrolite). The spotted hornfels are porphyroblastic cordierite hornfels containing biotite.

The development of the contact metamorphic minerals cordierite, andalusite and sillimanite and the formation of the higher temperature polymorph sillimanite rather than andalusite nearer to the granite contact are indications of contact metamorphism.

Evidence from the calc-silicate group

Members of this group show indications of contact metamorphism in various ways.

CALC-SILICATE HORNFELS

The rocks show the effect of contact metamorphism by the development of minerals such as diopside and wollastonite. Diopside is found in rocks all over the western foothills and also in association with or adjacent to rocks of the pelitic group containing cordierite, andalusite or sillimanite. This is not surprising as diopside is stable up to high grades of metamorphism.

On the other hand, wollastonite, a common contact metamorphic mineral, is found only in rocks nearer to both contacts of the Ledang and Belading granites. The mineral is found adjacent to rocks containing sillimanite but not andalusite. It therefore is evident that the rocks containing wollastonite are of metamorphic grades equivalent to the sillimanite-bearing rocks and higher grade than diopside-bearing rocks not near the granite contacts.

In some of the wollastonite-bearing rocks the wollastonite has been seen to grow calcite into a quartz-rich groundmass (Plate 2) and this feature probably indicates a wollastonite-forming reaction involving calcite such as

$$\text{Calcite} + \text{Quartz} \rightarrow \text{Wollastonite} + \text{Carbon Dioxide}$$

METAVOLCANICS

In metavolcanics with groundmass compositions similar to the calc-silicate hornfels, similar mineralogical developments occurred. Diopside-plagioclase-quartz assemblages commonly occur but in addition wollastonite may also occur in rocks nearer to the granitic contacts.

The metavolcanics with amphibolitic groundmasses consist of hornblende, plagioclase and quartz with or without diopside. The occurrence of diopside in these

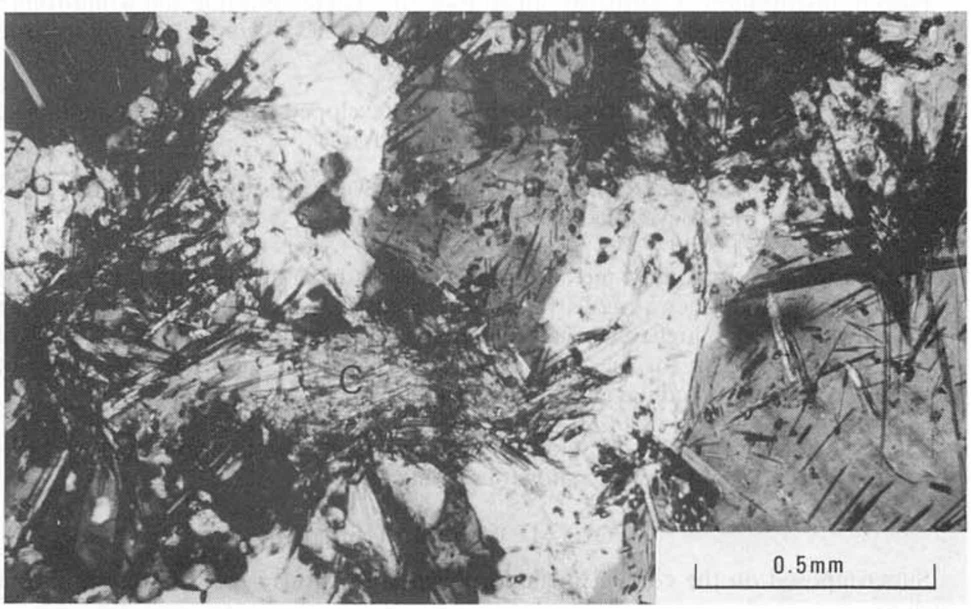

Plate 2. Wollastonite needles in quartz groundmass. Note wollastonite growing from remnant of calcite grain (c). Locality: Ledang aureole, Bekoh Estate (X-polars).

rocks is random and does not appear to be related to physical conditions but reflect the original compositions. The mineral assemblages of these amphibolitic groundmasses can be formed by both regional and contact metamorphism. However, here, it is believed that it is contact metamorphic in origin.

Clasts of rock fragments in the metavolcanics are metamorphosed and it is uncertain whether the hornfelsic clasts are the product of the contact metamorphism or they are already hornfelsic before sedimentation. However, a specimen from a locality occurring near the Ledang granite contact contains clasts of marble at the contact of which with the groundmass are developed coarse prismatic wollastonite due to contact metamorphism.

THIN-BANDED CALC-SILICATE HORNFELS AND AMPHIBOLITE

The responses to contact metamorphism are similar to the calc-silicate hornfels and amphibolitic groundmass of the metavolcanics already described.

MINOR ROCK TYPES

The mineralogical development in the calc-silicate hornfels, amphibolite and pelitic hornfels are similar to those already described. The only other rock not mentioned earlier is the marble which developed phlogopite, forsterite and diopside. The forsterite may be serpentinized. These minerals are probably formed by contact metamorphism of magnesian carbonates.

Contact metamorphic zonation

Plots of distribution of cordierite, andalusite, sillimanite, diopside and wollastonite in rocks already studied provisionally show that two zones of contact metamorphism can be recognized (Fig. 3). They are

(a) an outer aureole where the pelitic hornfels developed cordierite and andalusite and calc-silicate hornfels developed diopside and

(b) an inner aureole where the pelitic hornfels developed sillimanite and the calc-silicate hornfels developed wollastonite.

As is common in most contact metamorphic aureoles, the minerals in the outer aureole can persist into the inner aureole. It is also evident that the inner aureole has been metamorphosed at a higher temperature than the outer aureole. This is proof of contact metamorphism for the mere occurrence of low pressure minerals does not necessarily result from contact metamorphism.

The occurrence of various contact metamorphic minerals of various rock types in the outer and inner aureoles are shown in Table 2.

POLYMETASOMATISM

Superimposed on the contact metamorphism are various types of metasomatism such as

(a) boron

TABLE 2

DISTRIBUTION OF SOME CONTACT METAMORPHIC MINERALS IN THE OUTER AND INNER AUREOLES OF THE LEDANG AND BELADING GRANITES (EPIDOTE OCCURS QUITE RARELY AND SO DATA INCOMPLETE).

Rock	Mineral	Outer aureole	Inner aureole
Pelitic Hornfels	Biotite		
	Cordierite		
	Andalusite		
	Sillimanite		
Calc-silicate Hornfels	Plagioclase		
	Calcite		
	Diopside		
	Wollastonite		
	Epidote	? ?	? ?
Metavolcanics	Plagioclase		
	Calcite		
	Hornblende		
	Epidote		
	Diopside		
	Wollastonite		
Marble	Phlogopite	No Marble found in outer aureole yet	
	Diopside		
	Calcite		
	Forsterite		
Amphibolite	Biotite		
	Diopside		
	Hornblende		
	Plagioclase		
	Epidote	? ?	? ?

(b) fluorine
(c) iron
(d) possible chlorine and
(e) possible water and calcium

The evidence for each of these mentioned metasomatism is the development of characteristic metasomatic minerals in the rocks.

Boron metasomatism

Evidence of boron metasomatism is widespread in the western foothills area. Rocks in the inner aureoles are much effected especially of the aureoles in the Bekoh valley where they coalesce. The inner aureole rocks of the Belading granite to the south and west are also affected. There is also an impression that the effects of boron metasomatism in the Ledang aureole decrease northwards. However, it is possible that his may not be real but a reflection of a decrease in exposures northwards. Boron metasomatic effects are evident at the boundaries of the inner aureole with the outer aureole and from the data presently available it appears that the rocks of the outer aureole are scarcely affected.

In the calc-silicate hornfelses and metavolcanics with calc-silicate groundmasses, the effect of boron metasomatism is to cause the development of axinite. The axinite usually form nodules of spherical to ovoid shapes measuring from a few cm to as much as about 15 cm across. There nodules sometime appear to favour a particular band in the rock and it appears that here the control is compositional. In the rock enclosing the axinite modulus, it is quite rare to find any axinite. The rather equant axinite crystals in the aggregates range from reddish brown to dark brown and from a few mm to about 1 cm across.

The boro-silicate which will develop in pelitic compositions is tourmaline. But in the pelitic hornfelses, there is hardly any tourmaline, usually a few tiny grains are visible in thin section. However, pelitic hornfelses invaded by thin granitic veins in the Bekoh valley have tourmaline both in the rock and as clusters growing out from the granitic veins.

It is clear from the above that the granitic veins in the pelitic hornfelses are the carriers of boron. However, although granitic sheets are quite common in the inner aureole where axinite developed in calc-silicate rocks, it is still not clear whether the occurrence of axinite has any relation to proximity to granitic sheets. From field observations, the general impression is that the occurrence of axinite has no relation to the occurrence of granitic sheets. There are areas with plentiful axinite but with no exposed granitic sheets.

Fluorine metasomatism

Evidence of fluorine metasomatism has only been seen in calcareous rocks such as the calc-silicate hornfels, metavolcanics with calc-silicate groundmasses and marble. It is only confined to the inner aureole especially of the Belading granite. From the data available it appears that the aureole of the Ledang granite is only slightly affected by fluorine metasomatism and in the northern parts there is hardly any sign of it.

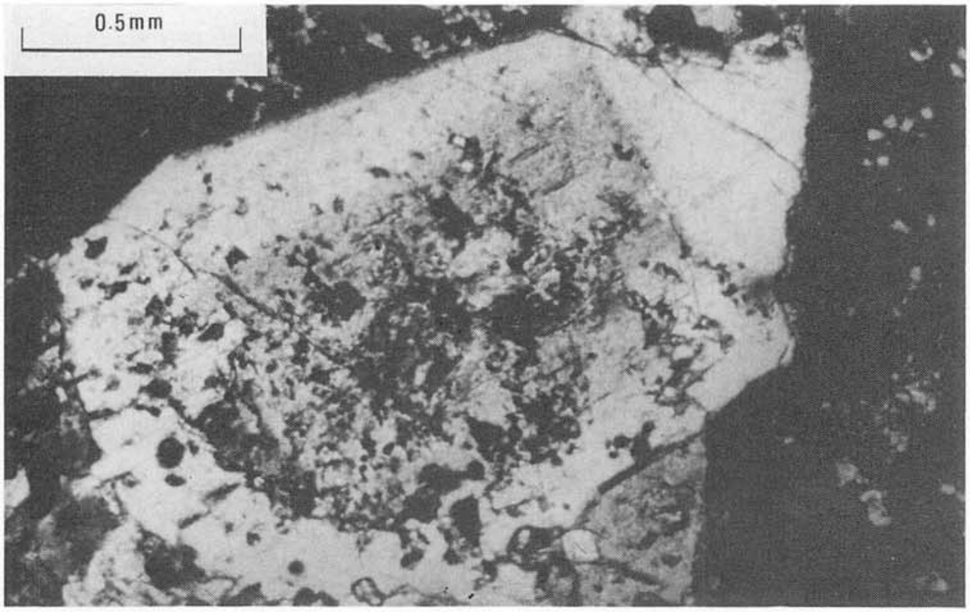

Plate 3. Zoned vesuvianite enclosed in garnet (dark background). Locality: Southern part Belading aureole (X-polars).

In rocks of calc-silicate compositions in the area, evidence of fluorine metasomatism is exemplified by the development of late vesuvianite (Plate 3) which encloses contact metamorphic wollastonite. The vesuvianite occurs as green or brown prismatic crystals up to about 4 cm up length and also as irregularly shaped grains. They are found near granitic contacts where the calc-silicate rocks are particularly rich in them. Here, again, like the development of axinite, the original rock composition appears to play a significant role in the fixation of the metasomatic fluorine. Vesuvianite occurs more commonly in the calc-silicate hornfels than in the metavolcanics.

In the marble, the magnesian fluor-silicate, chondrodite developed. It is found in some of the more massive marble in the inner aureole of the Ledang granite in association with forsterite and phlogopite indicating the magnesian nature of the marble. Thin marble bands in the rocks adjacent to the Belading granite have not been seen to develop chondrodite or other humite minerals. Maybe these thin marble bands are not magnesian in contrast to those more massive types.

Other rock types in the area have little good evidence to show that they have been affected. There is no abnormal increase in the amounts of muscovite or appearance of topaz, possible fluorine metasomatism minerals, in the pelitic hornfels. Also, although the metavolcanics with amphibolitic groundmass possess apatite, it is still uncertain that they have been formed due to introduction of fluorine.

Iron metasomatism

The possibility of iron metasomatism is exemplified by the development of pinkish

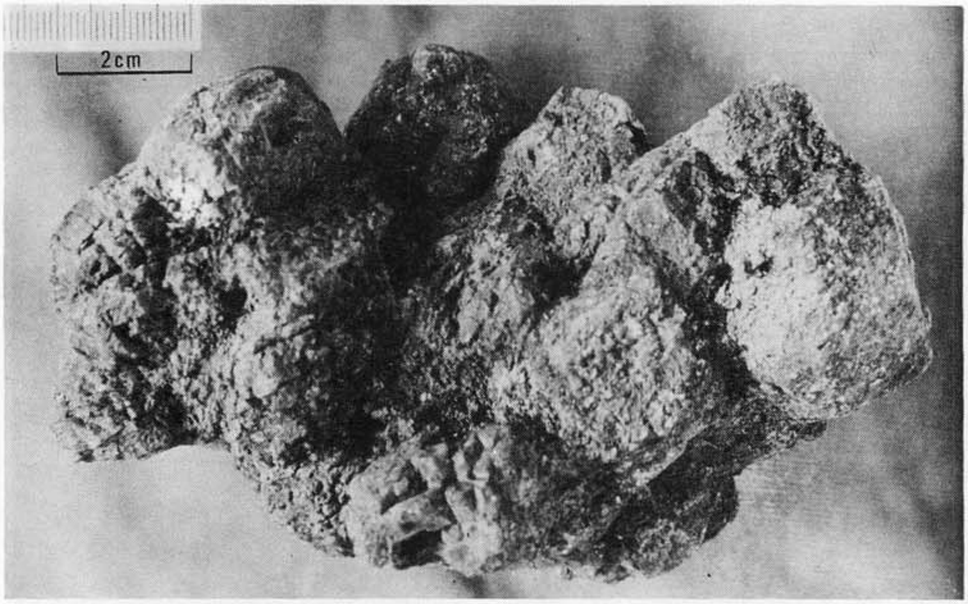

Plate 4. Dodecahedral garnet cluster. Locality: Southern part Belading aureole.

brown andraditic lime garnet within the inner aureoles of both the Ledang and Belading granites. At this stage of study, it appears that the garnet only occurs rather sporadically in the Ledang aureole but in the Belading aureole it is widespread and common especially in areas adjacent to the granite contact. It occurs only in the calc-silicate hornfels.

The garnet usually occurs as large irregularly shaped aggregates and sometimes as beautiful dodecahedra up to 5 cm across. These garnet dodecahedra sometimes occur in clusters (Plate 4). It is a late mineral enclosing all the contact metamorphic minerals mentioned and also vesuvianite. This late growth of the garnet favours the interpretation that it is metasomatic and not contact metamorphic in origin. It appears that the rocks are deficient in Fe_2O_3 in order for the garnet to develop during contact metamorphism.

Possible chlorine metasomatism

Within the inner aureoles of both the Ledang and Belading granites, scapolite usually of dipyre range of compositions is common and very widespread. It has so far not been discovered in the outer aureoles but it appears to have a wider spread than vesuvianite and garnet. It is also a late mineral enclosing earlier contact metamorphic minerals such as diopside and wollastonite and hence is probably metasomatic in origin.

Besides chloride, scapolites can also contain ions such as SO_4^{2-} and CO_3^{2-} and it is possible that the scapolite in the western foothills area may have been formed due to introduction of SO_4^{2-} or CO_2 for example. However, until the scapolites have been analysed, it cannot really be certain whether chloride or other ions have been introduced. But the dipyre composition appears to rule out the possibility of CO_2 introduction producing high meionite molecule and the high marialite molecule favours presence of chloride. In tandem with fluorine metasomatism which occurred, chlorine metasomatism is believed to be an attractive possibility.

The rocks which developed scapolites are the calc-silicate hornfels and some metavolcanics. It appears that the scapolite will only develop in the metavolcanics with diopside-bearing groundmasses including amphibolitic types. Metavolcanics with amphibolite groundmasses without diopside do not develop scapolite even though interbedded calc-silicate hornfels may develop plentiful scapolite. Compositional control appears to play an important role in the discrimination.

Possible water and calcium metasomatism

Prehnite has been found to occur in narrow veins, a mm or so thick and also as a late mineral in the calc-silicate hornfels in both aureoles of the Ledang and Belading granite. Compared to the other metasomatic mineral occurrences, the prehnite occurs very rarely. It is possible that the prehnite, a hydrous calcium aluminium silicate, is formed with the involvement of introduction of water as the calc-silicate hornfels, after contact metamorphism, is relatively dry. Possibly calcium metasomatism is also involved.

The role of calcium metasomation, if any, is difficult to deduce. In addition to playing a possible role in the development of prehnite, it may also have played significant roles in the development of lime garnet and vesuvianite for example.

Zonation

Some indications of metasomatic zonation is already apparent in so far as the effects of fluorine, iron and possibly chlorine metasomatism are confined to the inner aureoles. The effects of boron metasomatism are more widespread and not confined to the inner aureole only. However, boron metasomatic effects appear to be markedly decreased in the outer zone. Prehnitization has only been encounted on a few occasions in both inner and outer aureoles. More detailed studies of the zonations of the metasomatic minerals are still in progress. Table 3 summarizes the distribution of the various metasomatic minerals.

From the relation of the distribution of the metasomatic minerals and evidence such as granitic veins being the source of boron, it appears reasonable to conclude that the various types of metasomatism originated from the granitic bodies. Prehnitization could also be similarly. originated but the poor development prevents any strong inferences.

TIMING OF THE METAMORPHIC EPISODES

The timing of the earliest regional metamorphic episode is fraught with uncertainty as the age of the rocks has yet to be directly determined. If the rocks belong to the Foothills Formation, which is popularly believed at present to be Lower Palaeozoic,

TABLE 3

DISTRIBUTION OF VARIOUS METASOMATIC MINERALS IN THE INNER AND OUTER AUREOLES OF THE LEDANG AND BELADING GRANITES

Metasomatic Mineral	Outer aureole	Inner aureole
Axinite	?	————————
Tourmaline	————	?
Vesuvianite		————
Chondrodite		? ————
Garnet		————
Scapolite		————————
Prehnite		————————

then we can put a vague lower limit to the time of regional metamorphism—early Palaeozoic. The Foothills Formation consist of a lower series pelitic schists with some amphibole schists and serpentinite and an upper series of markedly less or not metamorphosed rocks such as conglomerate and arenaceous rocks. At the 'top' of this formation early Devonian graptolites have been found in argillaceous rocks and so it is believed that the formation is Lower Palaeozoic. This deduction however, will be satisfactory if the formation is a simple tilted sequence. Unfortunately it is not, and its structure is certainly relatively more complex. The time represented by the change from schists to the less metamorphosed parts of the formation has much to offer as a subject for titillating speculation. The possibility of an unconformity (or more?) in the formation is a moot point (also see Haile and Stauffer, 1973).

As mentioned earlier, the rocks of the western foothills area have strong resemblance to the Gemas beds further north which are believed to be Middle to Upper Triassic from fossil evidence. If the western foothills area is indeed underlain by Middle to Upper Triassic rocks, then the regional metamorphism could be an event between Middle to Late Triassic and Late Cretaceous (age of Ledang granite). Hazarding a speculation, the regional metamorphism could have ended with the Late Triassic orogenic event affecting the Peninsula and started a very short time earlier.

The contact metamorphism is obviously coeval with the Late Cretaceous Ledang intrusion. The Belading granite could have been emplaced at about the same time as the Ledang granite.

The polymetasomatism is later than the development of the contact metamorphic minerals. All the metasomatic minerals except prehnite are probably formed soon after the development of wollastonite. The prehnitization is obviously a cooling event and indeed the confirmative K-Ar age of about 68 Ma for the biotite of the Ledang granite (Yap, 1981) maybe dates the age of prehnitization.

CONCLUSIONS

The western foothills area of Gunung Ledang shows evidence of an early regional metamorphism followed by contact metamorphism due to the intrusion of the Ledang and Belading granites. After the development of the contact metamorphic minerals, polymetasomatism of boron, fluorine, iron and possible chlorine, water and calcium occurred. The regional metamorphism is probably of low grade occurring in Middle-Late Triassic. The other two metamorphic episodes are coeval with the Late Cretaceous Ledang intrusive event.

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