Geol. Soc. Malaysia, Bulletin 14, December 1981; pp. 75–100

Gabbroic rocks from the southern Malay Peninsula and their relation to similar rocks of other orogenic zones

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Abstract: The Linden and Gombak gabbroic stocks outcrop as two discrete bodies in the southern tip of the Malay Peninsula. They may be referred to as batholithic gabbros, which occur as relatively minor components within orogenic belts in association with large, intermediate to acidic batholiths.

The Linden stock is mainly of cumulate-textured olivine eucrite and allivalite. They are characterised by an entirely unzoned anorthite (An 92). The Gombak stock is predominantly of medium grained hypidiomorphic granular norite, which is invariably olivine-free and contains both augite and Ca-poor pyroxene (either primary orthopyroxene or inverted pigeonite). This is only the second reported occurrence of inverted pigeonite in batholithic gabbros. Systematic mineralogical, textural and petrochemical variations demonstrate that the gabbroic rocks of the Linden and Gombak stocks constitute a differentiated series derived from a single parental magma. Allivalite and olivine eucrite of the Linden stock represent crystal cumulates resulting from high level fractionation of a high-alumina, low-potash, basalt parental magma which subsequently crystallised apparently non-cumulate Gombak norite. Ca-poor pyroxene of the Linden-Gombak suite demonstrates a change in texture from ophitic in olivine-bearing Linden cumulates to granular in olivine-free Gombak norite. A similar textural change involving Ca-rich or Ca-poor pyroxene, on the cessation of olivine crystallisation, is apparently common amongst gabbroic associations and more important than previously considered.

The Linden-Gombak gabbroic association and similar batholithic gabbro suites of other orogenic belts are interpreted as unroofed magma chambers representing the root zones of palaeo calc-alkaline volcanoes by virtue of the similarity between these gabbroic rocks and the cognate plutonic xenoliths of calc-alkaline volcanics.

INTRODUCTION

Basic plutons are common in orogenic belts where they constitute the familiar gabbro-granitoid batholithic associations. In the past much emphasis was placed on the more dominant granitic components of the batholiths while neglecting the basic bodies. More recently, especially since the advent of plate tectonics, considerable work has been done on the magmatic evolution of orogenic zones. This has resulted in a renewed interest in the gabbroic bodies particularly those associated with the batholiths of the circum-Pacific region (e.g. Pitcher, 1978). This paper provides a petrological account of two basic bodies from the Malay Peninsula as a basis for comparison with similar rocks of other areas. It is directed at revealing the significant role of basic plutons in the evolution of magmatic arcs.

GEOLOGIC SETTING OF THE LINDEN AND GOMBAK GABBROIC STOCKS

The Malay Peninsula forms part of an orogenic belt which extends from the Indonesian islands of Bangka and Billiton in the south into Thailand towards the north. Granitic rocks outcrop over approximately 40 percent of the land surface. Associated with the granitoids are rare bodies of gabbroic rocks. Two such bodies, the Linden and Gombak stocks, occur in the southern tip of the Malay Peninsula within the eastern geological province which is termed the Eastern Belt (Fig. 1). The boundary between this Eastern Belt and the adjacent graben-like Central Belt is not well defined along much of its extent. However, it is clear that the Linden and Gombak stocks, together with gabbroic rocks in Billiton Island, represent elements of the Eastern Belt in view of its evolution as a volcano-plutonic arc from the Carboniferous to Late Triassic (Hutchison, 1977; 1978). Gabbroic bodies are not known within the conspicuous Main Range batholith.

The Linden Hill gabbro as named by Burton (1973), comprises 8 bodies of gabbroic rocks outcropping over a total of approximately 31 sq. km. The largest body which will be referred to as the Linden stock, is situated some 19 km northwest of Johore Baharu town (Fig. 1). The Linden stock lies within but close to the margin of a granitic batholith named the Blumut-Muntahak Granite (Rajah, *et al.*, 1977). Radiometric dating (Bignell and Snelling, 1977) yield concordant Rb : Sr and mica K:Ar ages giving this batholith a Lower Triassic age (220 Ma). In the vicinity of the Linden stock, adamellite is the typical granitic rock. Intermediate rocks within the Blumut-Muntahak batholith are mainly diorite and monzonite. Acid to intermediate pyroclastics and flows are widespread throughout the area. They are intruded and thermally metamorphosed by the Lower Triassic adamellite. The sedimentary rocks which flank the granitic batholith to the west and southwest, constitute a portion of a regional belt of similar rocks which extends into Singapore (Fig. 1). These sediments, known as the Jurong Formation, are essentially of Upper Triassic age and consist of frequent alternations of shale and sandstone with minor beds of volcanic tuff.

The body of gabbroic rocks referred to as the Gombak stock is located in central Singapore Island about 14 km northwest of Singapore City. It supports 8 quarries which provide good exposure of the gabbroic and associated rocks (Fig. 2). The Gombak stock occurs along the western margin of the Bukit Timah Granite and is flanked on the west by the Jurong Formation. The Bukit Timah Granite consists predominantly of granite *sensu stricto* with lesser amounts of granite porphyry, adamellite and granodiorite. The Bukit Timah Granite is assigned to the Lower Triassic by Bignell and Snelling (1977) and is probably a southern extension of the Blumut-Muntahak batholith.

The exact age of the Linden and Gombak stocks is uncertain since no radiometric dates are available for these rocks. Nevertheless, field observations show the Gombak stock to have been emplaced earlier than the Lower Triassic Bukit Timah Granite (Hutchison, 1964; Low, 1979; Kung, 1979). No direct information is available in the field regarding the age of the Linden stock. But, as will be shown later, the Linden stock is petrogenetically linked to the Gombak stock and so it also must pre-date the Lower Triassic Blumut-Muntahak Granite. The deduced temporal sequence of basic magmatism preceding granite emplacement in the Malay Peninsula is in common with observations in other orogenic belts.

PETROGRAPHY AND MINERALOGY

The Linden Stock

The Linden stock is made up mainly of olivine eucrite with subordinate amounts

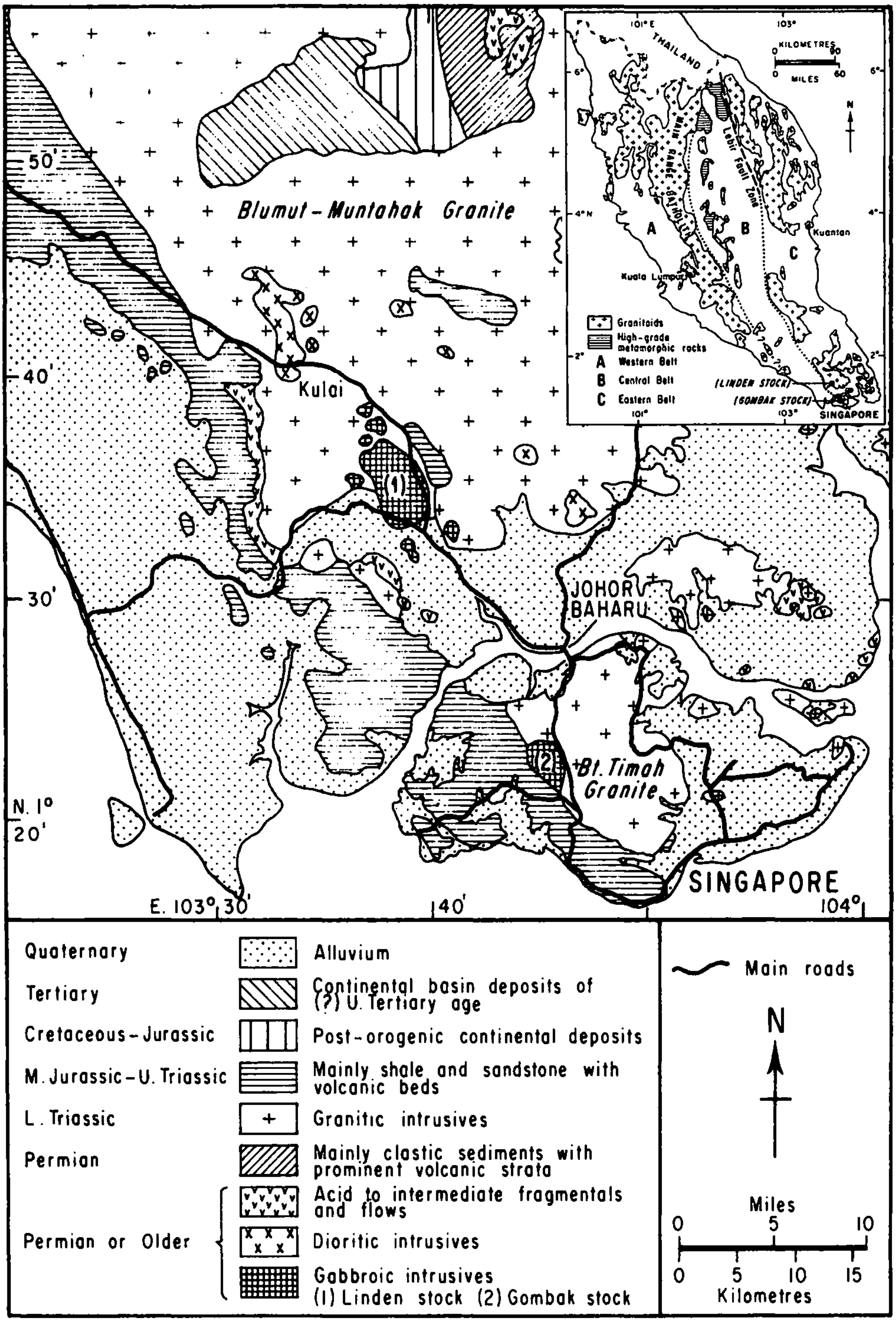


Fig. 1. Geologic map of part of the southern Malay Peninsula after Geological Survey Malaysia (1973), Burton (1973) and P.W.D. Singapore (1976). The inset shows the three geological provinces of the Malay Peninsula with the granite distribution and locations of the Linden and Gombak gabbroic stocks.

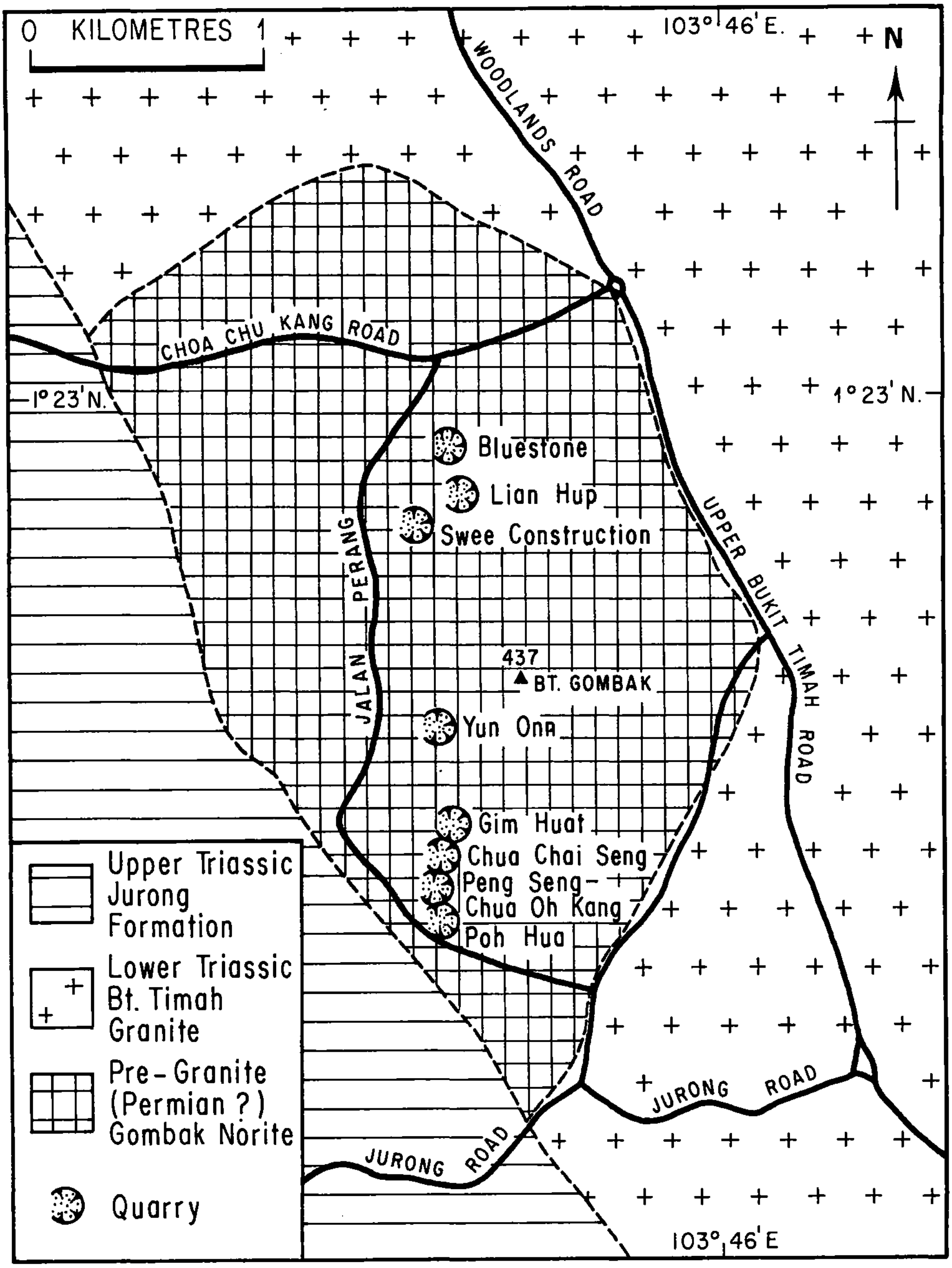


Fig. 2. The Bukit Gombak area of central Singapore showing the outline of the Gombak gabbroic stock and location of the 8 quarries which it supports.

TABLE 1

Modal compositions and mineralogical data for some representative rocks from the Linden and Gombak gabbroic stocks

Specimen	J2A1*	J2C2*	S-69*	S-58*	S-62*	S-92*	S-84*	S-16*	S-96*	8A4	S-100*	S-15*
Olivine	18.8	6.2	18.9	—	—	—	—	—	—	—	—	—
Plagioclase	75.8	49.8	51.4	68.2	58.2	50.8	60.7	67.1	54.5	67.1	44.4	28.1
Clinopyroxene	5.4	30.5	3.4	14.1	6.6	1.0	16.9	4.3	2.1	4.1	—	—
Orthopyroxene	—	13.5	26.3	17.5	34.8	15.8	20.5	18.6	24.5	23.8	—	34.6
Amphibole	—	—	—	—	—	30.8	0.9	3.0	10.1	1.8	44.6	29.4
Biotite	—	—	—	—	—	—	—	1.9	1.5	< 0.5	< 0.5	4.7
Quartz	—	—	—	—	—	—	< 0.5	4.3	6.1	2.1	10.0	3.1
Opaque minerals	—	—	—	< 0.5	< 0.5	1.3	0.9	0.8	1.2	0.5	< 0.5	< 0.5
Apatite	—	—	—	—	—	—	< 0.5	< 0.5	—	< 0.5	—	
% Fo in olivine	73	71	76				–	—	–	—	—	
% An in plagioclase	92	92	92	92–80	82					93–70	—	82–43
Clinopyroxene N_β	1.684	1.685	—	—	—	—	1.688			1.696	—	—
$2V_z$	56	49	51	—	48	—	46	—	—	44	—	—
Orthopyroxene N_α	—	1.691	1.690	—	—	—	1.702	—	—	1.721	—	1.697
$2V_x$	—	72	70	49	50	—	52	—	45	45	—	56

*Chemical analysis and brief description appear in Tables 3 and 4.
8A4 —Inverted pigeonite bearing medium grained Gombak norite. Loc. Gim Huat Quarry.

of allivalite (Table 1). Uralitised eucrite is also present though relatively insignificant in amount.

Allivalite

Allivalites are made up of olivine, plagioclase and clinopyroxene. These rocks display typical cumulate, mosaic equigranular textures. The overall texture may be described as that of an olivine-plagioclase mesocumulate (Wager and Brown, 1967). Cumulus plagioclase and olivine coexist with minor intercumulus clinopyroxene (Fig. 3). Orthopyroxene is conspicuously absent. Fresh cumulates of the Linden stock are virtually devoid of accessory minerals though altered samples may contain minor amounts of hornblende, anhedral spinel and opaques. Clinopyroxene, which is of diopside-salite composition, forms ophitic plates that include both plagioclase and olivine. The clinopyroxene is characterised by abundant schiller plates, a feature which persists in all gabbroic rocks of this suite. Textures indicative of crystal settling and subsequent adcumulus growth are best displayed by plagioclase. The mineral is entirely unzoned with grain boundary functions near 120°. The chemical composition of plagioclase extracted from an allivalite, which is given in Table 2, is determined to be An 92. K_2O content is low while Fe_2O_3 and MgO values are high.

TABLE 2

Chemical composition of plagioclase extracted from allivalite cumulate (J2A1)

Oxide	Wt %	Number of ions on the basis of 32 (O)	
SiO_2	43.95	Si	8.241
TiO_2	0.00	Al	7.632
Al_2O_3	34.53	Fe^{3+}	0.122
Fe_2O_3*	0.86	Mg	0.034
FeO	—	Ca	3.697
MgO	0.12	Na	0.316
CaO	18.40	K	0.002
Na_2O	0.87		
K_2O	0.01	Z	16.00
L.O.I.	1.02	X	4.05
Total	99.76	Molecular % Ab 7.8 An 92.1 Or 0.0	

$2V_x = 77$ X∧⊥010 = 57.0 Y∧⊥010 = 63.0
*Total Fe as Fe_2O_3

All elements were analysed by XRF except Na and Mg by AAS.

Olivine Eucrite

Olivine eucrites consisting of olivine, plagioclase, clinopyroxene and orthopyroxene also display well developed cumulate textures (Fig. 4). Plagioclase and olivine are always cumulus phases, while clinopyroxene may be cumulus, as in most samples, or rarely intercumulus. Orthopyroxene is invariably intercumulus or ophitic

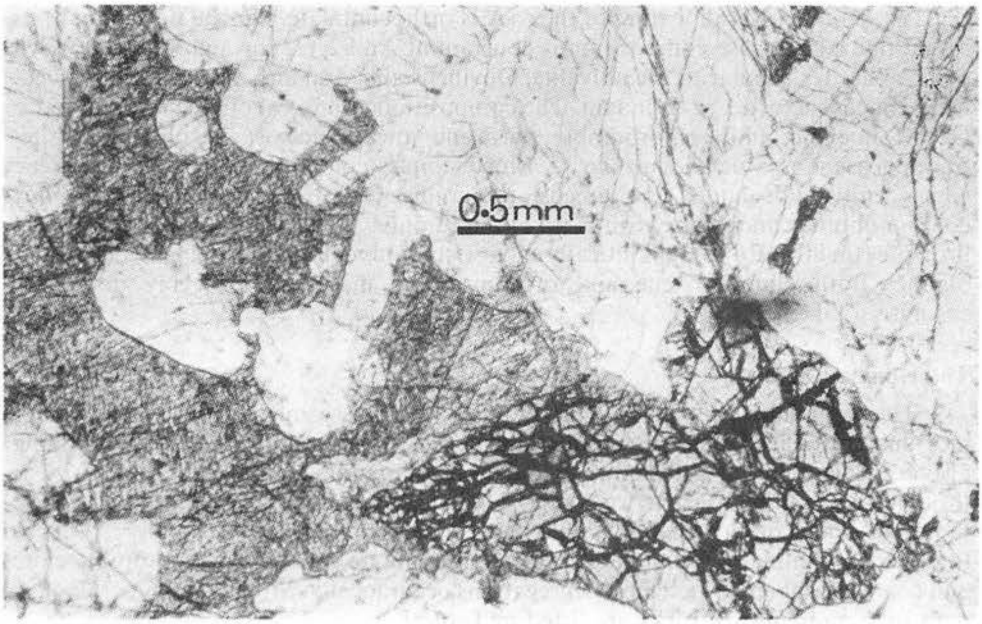


Fig. 3. Intercumulus clinopyroxene with cumulus olivine and plagioclase in allivalite cumulate. Photomicrograph under linearly polarised light.

Fig. 4. Typical texture of olivine eucrite cumulate with cumulus olivine, clinopyroxene and plagioclase. Photomicrograph under linearly polarised light.

(Pl. 1-A, B). The overall texture of the rock is orthocumulate. Optical determinations reveal that plagioclase composition is constant at An 92 ± 2 throughout the Linden olivine eucrites. similar to the allivalite. Olivine is anhedral and apparently unzoned. Oxide filled fractures are abundant. The compositional range of olivine is Fo 76 to Fo 64. Monoclinic and orthorhombic pyroxene always coexist in olivine eucrite. Clinopyroxene is a magnesian augite. Most samples contain cumulus clinopyroxene which forms subrounded equidimensional grains. On rare occasion the rock may contain ophitic clinopyroxene in place of the cumulus variety. Large ophitic plates of bronzite (En 80 to En 75) poikilitically enclose cumulus clinopyroxene, plagioclase and olivine. Both clinopyroxene and orthopyroxene may exhibit feebly developed exsolution lamellae.

The Gombak Stock

The dominant rock type of the Gombak stock is a medium grained hypidiomorphic granular norite. Fine grained norite showing textures indicative of chilling also occur. Its relation to the more abundant medium grained rock is not always clear though it is sometimes seen to form sub-rounded patches. Definite xenoliths within the Gombak stock comprise cumulate olivine eucrite, which are similar in all respects to the Linden cumulates. Cumulate textured cummingtonite bearing orthopyroxenite and coarse hornblende-rich felsic segregations occur locally. Modal and mineralogical data for representative rocks are listed in Table 1.

Medium grained Gombak norite

Normal gabbroic textures are well developed and are characteristic of the medium grained Gombak norites. Textures indicative of a cumulus origin are lacking. These rocks are invariably olivine-free. The typical mineral assemblage comprises plagioclase, augite and calcium-poor pyroxene (either primary orthopyroxene or inverted pigeonite) together with hornblende, quartz, biotite and opaques. Zone laths of plagioclase always exceed 50 % in mode. Anorthite content is highly variable and may range from An 92 to An 70 even within a single sample. Most grains, however, have a composition in the region of An 80.

One striking feature of the Gombak norite is the tendency of subhedral pyroxenes to form clusters. Pyroxene clusters in medium grained norite impart a patchy appearance to the rocks as they result in essentially plagioclase rich and pyroxene rich areas. It appears that pyroxene clustering becomes prominent only when the mineral is a modally significant constituent of the rock and, as such, is best developed amongst orthopyroxene. Individual grains within a cluster are often arranged in a radiating fashion and commonly display a definite crystallographic relation to each other. Often, rows of inclusions are continuous across the boundaries of individual grains within a cluster (Pl. 1–C, D). Orthopyroxene in some samples is clearly zoned with birefringence increasing from core to margin. The iron enriched margins of these grains display abundant exsolved blebs and lamellae of clinopyroxene while the more magnesian cores show weak exsolution. Clusters of such zoned orthopyroxene display a continuous chain of exsolved blebs across individual grain boundaries (Pl. 1–E, F). These textures imply that the individual grains have grown, at least in their later stages, as a single unit having developed a continuous iron enriched mantle which encloses the aggregate as a whole. The pyroxene clusters may be explained either by synneusis (cf. Vance, 1969) of small relatively magnesian orthopyroxene or perhaps by the process of self-nucleation (cf. Campbell, 1978).

Calcium poor pyroxene crystallised over a compositional range from En 70 to approximately En 50. Primary orthorhombic pyroxene is the Ca-poor variety up to about En 55. At compositions more ferriferous than En 55 the Ca-poor pyroxene initially crystallised as monoclinic pigeonite which subsequently inverted to orthorhombic pyroxene at subsolidus temperatures. Orthopyroxenes more magnesian than En 55 show only one set of exsolved clinopyroxene lamellae parallel to (100). These lamellae tend to be better developed with increasing ferrosilite content in keeping with the trend observed in most mafic intrusions. Inverted pigeonite is characterised by two or three sets of clinopyroxene exsolution lamellae. One broad set is believed to be parallel to (001) of the original monoclinic pyroxene. Exsolved clinopyroxene lamellae arranged in 'herring-bone' fashion within the host orthopyroxene (Pl. 1–G) is positive textural evidence of inversion from pigeonite (Cox, *et al.*, 1979, p. 304). The lamellae were initially exsolved parallel to (001) of a pigeonite twinned on (100). On inversion, the twinned structure was eliminated without affecting the orientation of the exsolution lamellae. Two interesting textures exhibited by inverted pigeonite of the Gombak norite are worth mentioning. Discrete grains not visibly connected in thin-section, often occur in groups and have a similar orientation. This feature is apparently not uncommon in inverted pigeonite and has been recorded by Von Gruenewaldt and Weber-Diefenbach (1977), Campbell (1978) and Himmelberg and Ford (1976). In addition, composite grains of inverted pigeonite comprising differently orientated core and margin are observed. Significantly, McDougall (1961) notes that a single pigeonite crystal may invert to two or more 'areas' of orthopyroxene which have different orientations.

The occurrence of inverted pigeonite amongst the norites of the Gombak stock is significant since it appears to represent only the second known occurrence of inverted pigeonite amongst basic rocks associated with granitic batholiths. The other reported occurrence is from the gabbros in the Moro region of the Peruvian Coastal Batholith (Mullan and Bussell, 1977). Furthermore, the crystallisation of pigeonite as the Ca-poor pyroxene at an Mg:Fe ratio of 55:45 is unknown amongst the tholeiitic fractionated complexes from which inverted pigeonite is commonly reported. In these complexes, pigeonite first crystallises as the Ca-poor pyroxene when the Mg:Fe ratio is approximately 70:30 (Hess, 1960; Wager and Brown, 1967), though examples with ratios 85:15 and 60:40 have also been recorded (Poldervaart and Hess, 1951; Philpotts, 1966).

Hornblende, quartz, and biotite may occur in significant amounts in the medium grained norites. Both green and brown varieties of hornblende are present and usually rim the pyroxene grains. Hornblende may occasionally form discrete grains showing well formed crystal faces when in contact with quartz but interstitial to all other minerals. Most of the hornblende in these rocks are believed to be magmatic, though the possibility that some may be metamorphic in origin cannot be discounted. Quartz and opaque minerals are always interstitial.

Description of Plate 1

Photomicrographs of samples from the Linden and Gombak gabbroic stocks. All photomicrographs under crossed polars except H under linearly polarised light. Scale: A, B, C, D, E, F and H: length of photomicrograph equals 4 mm; G, length of photomicrograph equals 1 mm.

A, B — Intercumulus (ophitic) orthopyroxene enclosing plagioclase, clinopyroxene and olivine. Olivine eucrite cumulate.

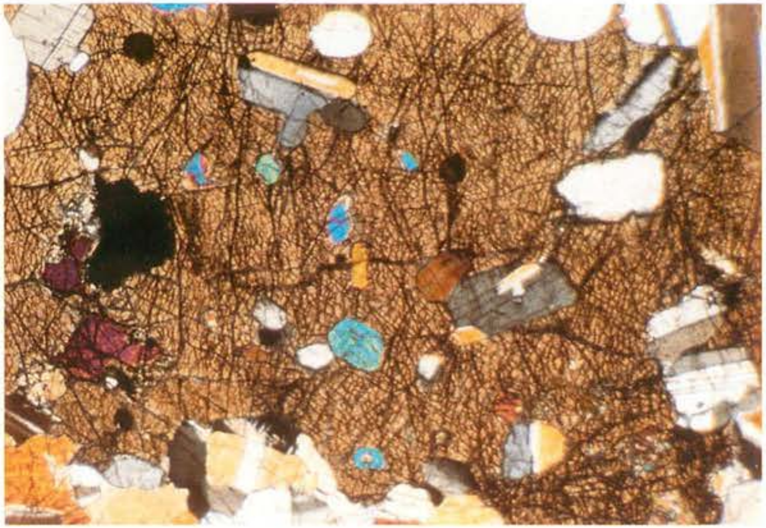
C — Orthopyroxene cluster in Gombak norite. Note the continuous chain of inclusions and the equal illumination of grain pairs within the cluster.

D — Orthopyroxene cluster in Gombak norite.

E, F — Zoned orthopyroxene clusters in Gombak norite showing increasing birefringence from core to margin within the clusters as a whole. The iron enriched margins of the clusters display exsolved blebs and lamellae of clinopyroxene which are continuous across individual grain boundaries.

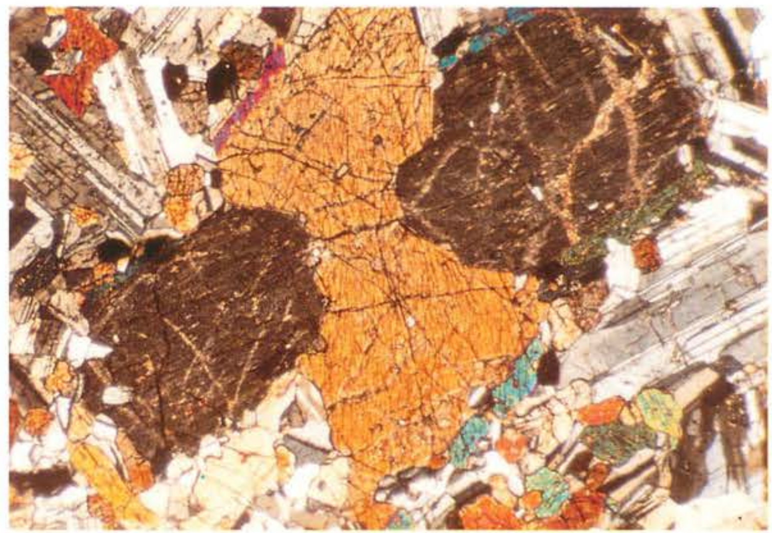
G — Inverted pigeonite showing exsolved clinopyroxene lamellae arranged in 'herring-bone' fashion within the host orthopyroxene.

H — Cumulus orthopyroxene poikilitically enclosed in plagioclase and cummingtonite. Cummingtonite is partially replaced by biotite and hornblende. Cummingtonite orthopyroxenite.


A


B


C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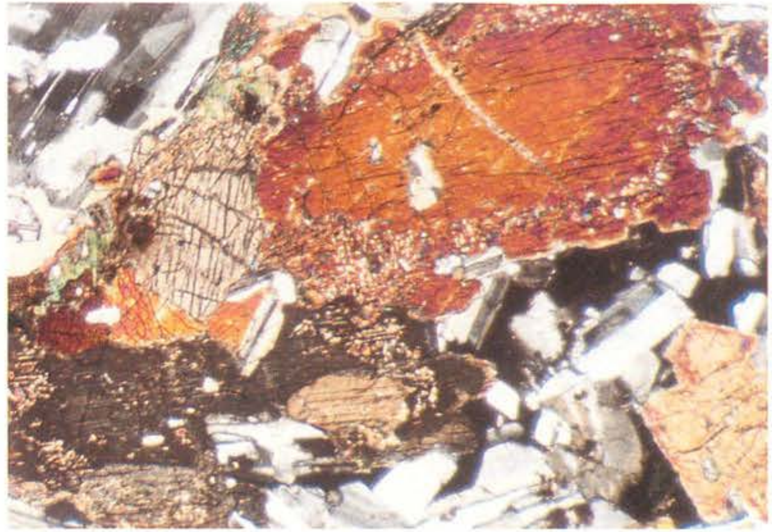
E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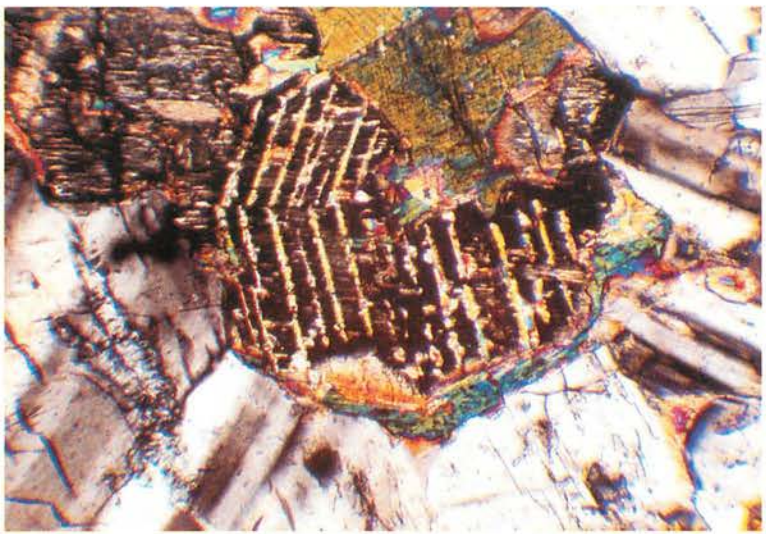
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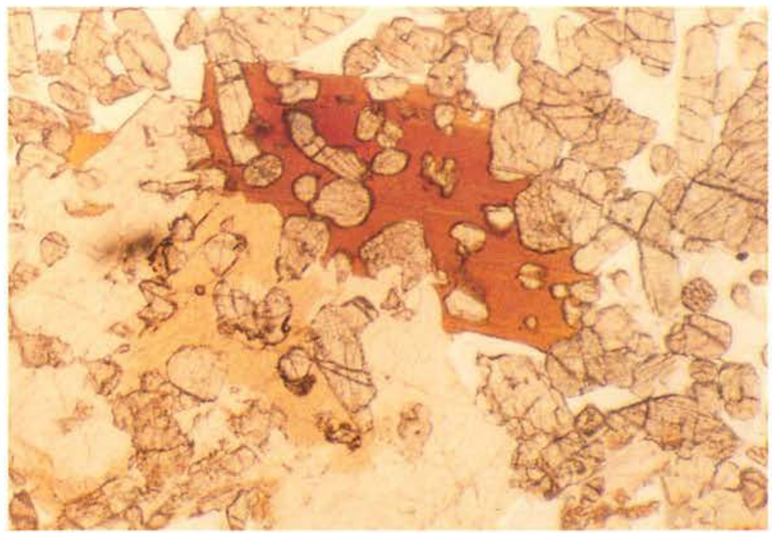
H

Cummingtonite orthopyroxenite

Bronzite (En 73–En 75) is the most abundant mineral and the only cumulus phase (Pl. 1–H). The prismatic grains vary in length from less than 0.2 mm to approximately 4 mm. Clinopyroxene was not detected in any of the examined samples. Cummingtonite ($2V_z = 77$, $Z \Lambda c = 21$) in these rocks usually occurs as interstitial, poikilitic plates enclosing numerous euhedral orthopyroxene crystals. The distinctly different habits and sharp boundaries of the two minerals are strong evidence against a secondary origin for the cummingtonite, after orthopyroxene. This cumulate textured rock is therefore of special interest because of its primary cummingtonite. Strongly pleochroic brick red biotite may replace cummingtonite. More commonly, however, the colourless cummingtonite is found to be replaced, in patches, by brown pleochroic hornblende (Pl. 1–H). Exceptionally clear plagioclase usually form poikilitic plates. It may also occur as interstitial aggregates of fine sized subhedral laths together with anhedral quartz. Zoning may be extreme from An 82 to An 43 or less.

TEXTURAL AND MINERALOGICAL COMPARISON OF THE LINDEN AND GOMBAK STOCKS AND ITS IMPLICATION

The spatial proximity of the Linden and Gombak stocks coupled with the systematic mineralogical and textural variations between their rock types strongly suggest a petrogenetic link between the two stocks. Petrochemical considerations further demonstrate that the Linden-Gombak suite of gabbroic rocks represent a differentiated series derived from a single parental magma. Allivalite and olivine eucrite of the Linden stock clearly represent crystal cumulates fractionated from a basalt magma which has subsequently crystallised apparently non-cumulate norite and minor felsic segregations comprising the Gombak stock.

A consideration of diagnostic textural and mineralogical criteria, such as the cumulus or intercumulus habit and cryptic variation of the minerals, suggest the following primary crystallisation sequence for the Linden-Gombak suite: (i) early crystallisation and accumulation of plagioclase and olivine with minor intercumulus clinopyroxene (allivalite cumulate); (ii) continued crystallisation of cumulus olivine and plagioclase joined by cumulus clinopyroxene and crystallisation of significant intercumulus orthopyroxene (olivine eucrite cumulate); (iii) cessation of olivine, crystallisation of granular orthopyroxene and interstitial Fe-Ti oxides (fine and medium grained Gombak norite); (iv) incoming of hornblende, quartz and minor biotite (medium grained Gombak norite) and (v) precipitation of pigeonite as the Ca-poor pyroxene (inverted pigeonite bearing medium grained norite).

The position of cummingtonite orthopyroxenite within the Linden-Gombak crystallisation sequence is problematic because of uncertainty as to whether the rock has crystallised from a primary or modified magma. Besides the exit of olivine and the entry of late magmatic phases, the most prominent modal variation is the reversal of the clinopyroxene-orthopyroxene ratio from earliest to latest differentiates. Clinopyroxene is dominant in early cumulates whereas orthopyroxene is clearly more abundant in medium grained norite.

Orthopyroxene demonstrates an important change in habit with the termination of olivine crystallisation. The mineral first appears as large ophitic plates in the Linden cumulates (Pl. 1–A, B), and later changes to a granular or prismatic habit in the olivine-free rocks (Pl. 1–C to F). Olmsted (1979) describes a similar change in habit, though involving clinopyroxene instead of orthopyroxene, from the Rearing Pond gabbro, north-west Wisconsin. He interprets this change in texture as due to a change in the ratio of growth to nucleation rates of the pyroxene corresponding to the cessation of olivine crystallisation as the magma composition leaves the olivine field. Olmsted (1979) points out that a similar textural change of pyroxene has also occurred in other intrusions (e.g. Skaergaard intrusion) where fractionation of olivine has caused the liquids to move from olivine-normative to olivine-free compositions. However, in none of these cases has it been possible to definitely demonstrate that Ca-poor pyroxene may be involved. The change in orthopyroxene habit from ophitic in olivine-bearing Linden cumulates to granular in olivine-free Gombak norite, confirms the prediction of Olmsted (1979) that this pyroxene textural change might also involve Ca-poor pyroxene in addition to Ca-rich pyroxene. Walawender and Smith (1980) describe yet another occurrence from the gabbros of the Peninsular Ranges Batholith, southern California. Apparently, this relationship between pyroxene habit and the termination of olivine crystallisation is more widespread and, thus, more important than previously thought. The involvement of clinopyroxene in some intrusions and orthopyroxene in others, may have important petrogenetic significance, in that it may reflect variations in initial magma composition or perhaps differences in mineralogy of

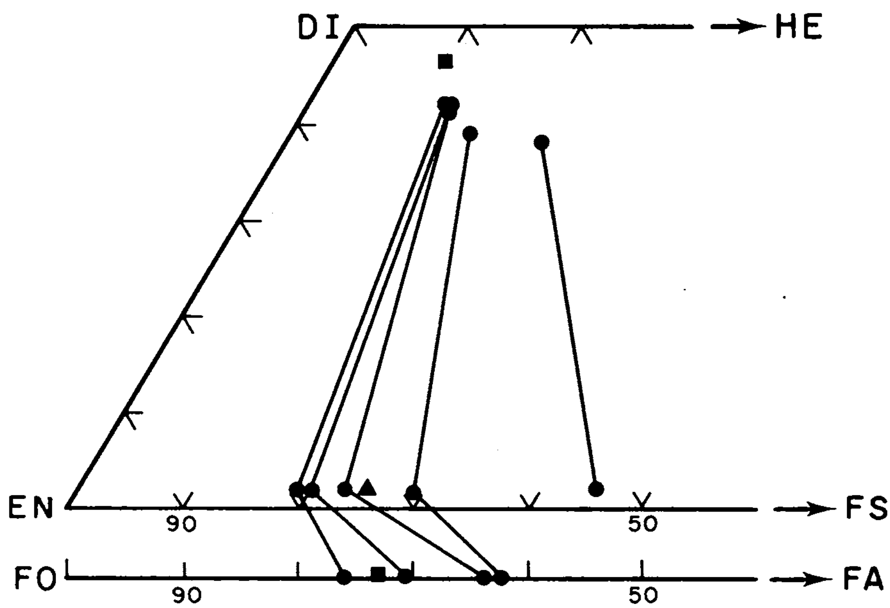

Fig. 5. Variation in composition of coexisting clinopyroxene, calcium-poor pyroxene (assumming 2% Ca) and olivine. Pyroxene compositions were determined by optical methods while olivine composition was determined by X-ray diffraction. The tie-lines represent the following samples from left to right: S-69, J2C1, 26H, S-84 and 8A4. Coexisting clinopyroxene and olivine in allivalite cumulate (J2A1)—squares; Orthopyroxene in cummingtonite orthopyroxenite—triangle.

the early crystallising phases. One important consequence of this pyroxene-olivine relationship would be its control over the variety of cumulate peridotite associated with differentiated mafic-ultramafic associations. In the case of the Linden-Gombak suite and the gabbros of the Peninsular Ranges Batholith, harzburgite comprising cumulus orthopyroxene and cumulus olivine is not to be expected. Similarly, wehrlite with cumulus clinopyroxene and cumulus olivine should not occur as a crystal-fractionated differentiate of intrusions, such as the Rearing Pond gabbro, in which clinopyroxene is always ophitic when crystallising together with olivine.

Compositional variation of co-existing clinopyroxene, orthopyroxene and olivine from the Linden-Gombak suite is illustrated in Figure 5. Olivine shows limited iron enrichment up to Fo 64, beyond which it does not crystallise. The apparent crystallisation trend of clinopyroxene from the Linden-Gombak suite demonstrates an initial decrease in calcium at constant Fe/Mg ratio with subsequent Fe enrichment at constant calcium content. Delayed crystallisation of pigeonite within the Ca-poor pyroxene trend probably reflects moderate water content in the magma which could be responsible for depressing the pyroxene crystallisation temperatures in relation to subsolidus inversion temperatures and thus extending the field of hypersthene crystallisation (Wager and Brown, 1967, p. 436). High water contents would result in non-crystallisation of pigeonite. The significant development of anorthite in the Linden-Gombak suite is similarly attributable to the effect of water pressure since addition of water to the An–Ab system lowers the liquidus of plagioclase and results in increasingly calcic compositions.

GEOCHEMISTRY

Thirty-seven representative samples were chemically analysed. Chemical data and corresponding CIPW norms are presented in Tables 3 and 4. Analysis for Si, Ti, Al, Fe, Mn, Ca and P were by X-ray fluorescence using the technique of Norrish and Hutton (1969) as outlined by Hutchison (1975). K was determined by flame emission while Na and Mg were analysed by atomic absorption. All FeO determinations were by titration.

Chemical Characteristics

The Linden-Gombak suite as a whole is characterised by high alumina and extremely low alkali contents. K_2O in particular in very low with a maximum of only 0.53 percent. The suite is clearly subalkaline in character as is evident from the total alkali-silica diagram (Fig. 6). Significantly, TiO_2 contents are also relatively low and, almost always, less than 1.0 percent. The Linden cumulates are highly calcic (13.37 to 16.34 %) and aluminous (17.69 to 25.27 %) but low in SiO_2 contents (between 42 and 46 percent). Silica content of the Gombak norites range from 46 to 52 percent. In the absence of a definite chilled margin, the composition of the magma parental to the Linden-Gombak suite is estimated by taking the average of all 19 unaltered, apparently non-cumulate gabbroic analyses (Table 5, no. 1). The calculated average composition is closely similar to that of Kuno's (1968) parental high-alumina basalt and the average Cascades high-alumina basalt given by Waters (1962), (Table 5). Thus it would appear that the parental magma of the Linden-Gombak suite was most likely a high-alumina basalt.

TABLE 3

Chemical analyses and CIPW norms of representative cumulate rocks from the Linden stock

Sample no.		J2A1	J2E	J2C1	J2C2	J2D2	3825	3895	3829	J2D3
SiO_2		42.72	44.86	45.47	45.94	43.44	45.23	45.08	45.98	45.69
TiO_2		0.06	0.19	0.19	0.20	0.18	0.25	0.25	0.47	0.26
Al_2O_3		25.27	19.31	17.87	17.84	21.19	20.18	17.69	24.60	24.65
Fe_2O_3		0.45	0.88	0.58	1.73	0.56	1.15	0.82	0.14	0.11
FeO		5.36	7.72	6.17	5.42	6.14	5.60	6.70	5.10	3.76
MnO		0.10	0.16	0.14	0.14	0.12	0.13	0.15	0.12	0.08
MgO		9.95	12.48	11.78	11.86	11.75	10.70	10.33	5.62	5.22
CaO		14.54	13.37	16.34	15.91	14.12	15.49	15.92	14.95	15.94
Na_2O		0.57	0.51	0.48	0.47	0.54	0.67	0.59	0.96	1.21
K_2O		0.05	0.06	0.03	0.03	0.08	0.06	0.06	0.18	0.51
P_2O_5		0.04	0.03	0.06	0.04	0.03	0.07	0.05	0.07	0.07
SO_3		0.03	0.06	0.10	0.12	0.04	0.02	0.14	0.10	0.00
L.O.I.		1.74	1.50	1.28	0.91	1.59	1.42	2.82	1.52	2.17
Total		100.88	101.13	100.49	100.61	99.78	100.97	100.60	99.81	99.67
CIPW NORM										
Or		0.30	0.36	0.18	0.18	0.48	0.36	0.36	1.08	3.09
Ab		3.08	4.33	4.10	3.99	4.66	5.70	5.11	8.27	9.03
An		66.84	50.44	46.93	46.67	56.20	52.12	46.54	63.43	61.86
Ne		0.97	—	—	—	—	—	—	—	0.80
Mt		0.66	1.28	0.85	2.52	0.83	1.68	1.22	0.21	0.16
Il		0.12	0.36	0.36	0.38	0.35	0.48	0.49	0.91	0.51
Ap		0.10	0.07	0.14	0.10	0.07	0.17	0.12	0.17	0.17
Di	Mg	3.42	9.36	20.95	20.66	9.11	15.19	19.76	6.15	10.57
	Fe	1.15	3.53	6.72	5.15	2.91	4.55	7.69	3.33	4.63
Hy	En	—	6.21	0.45	5.03	0.56	1.86	1.84	6.79	—
	Fs	—	2.69	0.17	1.44	0.20	0.64	0.82	4.22	—
Ol	Fo	16.41	14.48	13.62	10.55	17.54	12.52	10.76	3.23	5.91
	Fa	6.98	6.90	5.52	3.33	7.09	4.75	5.30	2.21	3.27
D.I.		4.35	4.69	4.28	4.17	5.14	6.05	5.48	9.36	12.92
Normative Plag.		An 95	An 92	An 92	An 92	An 92	An 90	An 90	An 88	An 87

J2A1[a]—Allivalite mesocumulate.
Loc: Linden Hill, Johore.

J2E—Olivine eucrite orthocumulate.
Loc: Linden Hill, Johore.

J2C1—Olivine eucrite orthocumulate.
Loc: Linden Hill, Johore.

J2C2[a]—Olivine eucrite orthocumulate.
Loc: Linden Hill, Johore.

J2D2—Olivine eucrite orthocumulate.
Loc: Linden Hill, Johore.

3825—Olivine eucrite orthocumulate.
Loc: Linden Hill, Johore.

3895—Olivine eucrite orthocumulate.
Loc: Linden Hill, Johore.

3829 - Uralitized eucrite cumulate.
Loc: Senai Estate, Johore.

J2D3 - Uralitized eucrite cumulate.
Loc: Linden Hill, Johore.

a—modal data in Table I.
L.O.I.—Loss On Ignition.

D.I. - Differentiation Index of Thornton and Tuttle (1960)

TABLE 4

Chemical analyses and CIPW norms of representative rocks from the Gombak stock

Sample no	S-58	S-62	S-98	S-88	S-92	S-91	S-16	S-97	S-59	S-96	S-7	S-84	S-82	S-86
SiO_2	48.83	49.04	47.42	48.51	48.62	46.77	50.53	51.32	47.73	48.88	48.24	48.40	50.34	47.90
TiO_2	0.56	0.25	0.35	0.91	1.00	1.14	0.84	1.32	1.19	0.57	1.06	0.57	0.69	0.73
Al_2O_3	19.80	18.33	16.59	18.98	18.86	18.76	18.27	17.69	18.44	17.85	18.76	17.11	17.44	21.58
Fe_2O_3	0.33	0.69	0.98	0.17	0.38	0.19	0.53	0.34	0.21	0.33	0.22	0.42	0.15	0.25
FeO	7.90	8.95	8.50	8.94	9.65	9.34	8.27	8.00	9.34	8.97	9.52	8.12	8.80	6.98
MnO	0.17	0.19	0.20	0.19	0.18	0.18	0.16	0.15	0.18	0.18	0.18	0.17	0.17	0.15
MgO	6.97	8.70	9.41	6.92	6.72	8.14	6.44	5.91	7.68	8.99	6.62	9.42	7.36	6.72
CaO	12.47	11.54	13.75	12.48	11.19	12.22	10.28	10.74	11.33	11.16	11.40	12.11	11.12	12.36
Na_2O	1.65	1.23	0.72	1.60	1.93	1.05	1.69	1.93	1.58	1.21	1.58	1.25	1.70	1.56
K_2O	0.17	0.10	0.08	0.11	0.17	0.09	0.41	0.42	0.09	0.17	0.19	0.21	0.33	0.14
P_2O_5	0.09	0.02	0.05	0.13	0.20	0.00	0.15	0.23	0.07	0.01	0.15	0.06	0.12	0.05
SO_3	0.00	0.00	0.19	0.00	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.00
L.O.I.	1.52	1.08	1.15	0.97	1.23	1.34	1.30	1.39	1.52	1.46	1.39	1.76	1.54	1.18
Total	100.46	100.12	99.39	99.91	100.17	99.23	98.87	99.44	99.36	99.78	99.31	99.63	99.79	99.60
CIPW NORM														
Q							3.74	4.62					1.15	
Or	1.02	0.06	0.48	0.66	1.02	0.54	2.48	2.53	0.54	1.02	1.15	1.27	1.99	0.84
Ab	14.11	10.51	6.21	13.68	16.51	9.08	14.65	16.66	13.66	10.41	13.65	10.81	14.64	13.41
An	46.61	44.62	42.63	44.75	42.76	47.21	42.07	39.07	43.90	43.50	44.45	41.35	39.68	52.29
Mt	0.48	1.01	1.45	0.25	0.56	0.28	0.79	0.50	0.31	0.49	0.33	0.62	0.22	0.37
Il	1.08	0.48	0.68	1.75	1.92	2.21	1.64	2.56	2.31	1.10	2.06	1.11	1.33	1.41
Ap	0.22	0.05	0.12	0.31	0.48	—	0.36	0.56	0.17	0.02	0.36	0.15	0.29	0.12
Di Mg	7.47	6.53	14.05	7.92	5.41	7.26	4.34	6.49	6.32	6.48	5.52	10.54	7.48	4.92
Di Fe	5.11	4.15	7.63	6.06	4.54	4.82	3.22	4.81	4.42	3.94	4.64	5.46	5.41	2.99
Hy En	11.54	17.68	14.08	11.38	11.60	13.20	14.43	12.00	13.32	18.69	13.92	15.13	15.19	11.77
Hy Fs	9.06	12.89	8.77	9.99	11.16	10.06	12.28	10.20	10.69	13.01	13.41	8.99	12.61	8.22
Ol Fo	1.78	0.82	2.32	1.66	1.97	2.91	—	—	2.31	0.76	0.25	2.78	—	2.07
Ol Fa	1.54	0.66	1.59	1.60	2.08	2.44	—	—	2.04	0.58	0.26	1.82	—	1.59
D.I.	15.13	11.10	6.70	14.34	17.53	9.62	20.87	23.81	14.21	11.43	14.80	12.08	17.78	14.25
Normative Plag.	An 76	An 80	An 87	An 76	An 71	An 83	An 73	An 69	An 75	An 80	An 75	An 78	An 72	An 79

S-58[a] — Fine grained plagioclase-orthopyroxene phenocrystic norite. Loc. Peng Seng Quarry, Singapore.
S-62[a] — Fine grained plagioclase-orthopyroxene phenocrystic norite. Loc. Peng Seng Quarry, Singapore.
S-98 — Fine grained subporphyritic norite. Pyroxene rich. Loc. Lian Hup Quarry, Singapore.
S-88 — Fine grained plagioclase phenocrystic norite. Loc. Poh Hua Quarry, Singapore.
S-92[a] — Fine grained plagioclase phenocrystic hornblende rich norite. Loc. Teck Whye Flats, Singapore.
S-91 — Fine to medium grained norite. Loc. South-west edge of Gombak stock, Singapore.
S-16[a] — Medium grained quartz-hornblende bearing norite. Loc. Swee Quarry, Singapore.
S-97 — Medium grained quartz-hornblende bearing norite. Loc. Lian Hup Quarry, Singapore.
S-59 — Medium grained norite. Loc. Peng Seng Quarry, Singapore.
S-96[a] — Medium grained quartz-hornblende bearing norite. Loc. Bluestone Quarry, Singapore.
S-7 — Medium grained quartz-hornblende bearing norite. Loc. Bluestone Quarry, Singapore.
S-84[a] — Medium grained gabbro-norite. Loc. Chua Chai Seng Quarry, Singapore.
S-82 — Medium grained quartz-hornblende bearing norite. Loc. Gim Huat Quarry, Singapore.
S-86 — Medium grained norite. Loc. Peng Seng—Chia Oh Kang Quarry, Singapore.

TABLE 4 (continued)

Chemical analyses and CIPW norms of representative rocks from the Gombak stock

Sample no.		S-18	S-63	S-95	S-85	S-99	S-70	S-25	S-100	S-65	A-3	S-69	S-15	S-13	S-67
SiO_2		49.99	49.74	48.81	51.34	49.38	49.67	51.70	55.53	59.84	66.05	44.85	53.94	52.95	53.26
TiO_2		0.51	0.31	0.40	0.33	0.57	0.11	0.55	0.30	0.51	0.38	0.20	0.31	0.33	0.41
Al_2O_3		19.99	16.55	19.45	18.01	17.28	19.03	15.48	15.24	17.72	18.29	17.94	4.56	4.57	4.52
Fe_2O_3		0.28	0.65	0.41	0.22	0.38	0.38	0.12	0.09	0.09	0.16	0.55	0.49	1.17	0.54
FeO		6.81	8.45	7.97	7.78	8.22	6.83	7.22	5.45	4.57	2.08	7.10	13.97	14.03	15.36
MnO		0.15	0.18	0.18	0.16	0.19	0.14	0.15	0.15	0.08	0.02	0.13	0.32	0.35	0.35
MgO		6.34	9.79	6.68	6.87	8.27	8.78	8.81	6.85	3.18	1.29	14.29	20.38	20.31	19.40
CaO		11.82	10.30	12.11	10.67	11.75	10.01	9.67	11.14	6.79	5.17	11.97	2.72	3.18	3.02
Na_2O		1.33	0.71	1.83	1.86	1.02	0.89	1.48	1.25	2.56	4.15	0.46	0.42	0.32	0.40
K_2O		0.53	0.30	0.17	0.35	0.38	0.89	1.07	1.10	1.55	1.15	0.12	0.57	0.31	0.32
P_2O_5		0.08	0.06	0.10	0.07	0.11	0.07	0.09	0.03	0.20	0.10	0.05	0.02	0.02	0.04
SO_3		0.06	0.04	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
L.O.I.		1.67	2.53	1.65	1.45	1.74	2.93	3.28	2.67	2.68	1.79	2.14	2.24	1.98	2.44
Total		99.56	99.61	99.76	99.11	99.41	99.73	99.62	99.80	99.77	100.66	99.80	99.94	99.52	100.06
CIPW NORM															
Q		2.80	3.41	—	2.78	1.87	2.06	3.04	10.77	17.35	23.66	—	2.67	2.80	2.99
Or		3.20	1.83	1.02	2.12	2.30	5.43	6.56	6.69	9.43	6.88	0.73	3.45	1.88	1.94
Ab		11.50	6.19	15.78	16.11	8.85	7.78	13.00	10.89	22.31	35.52	3.99	3.64	2.78	3.47
An		48.05	42.34	45.21	40.71	42.49	46.80	33.66	33.69	33.25	25.29	47.64	9.08	10.37	9.83
Mt		0.42	0.97	0.61	0.33	0.57	0.57	0.18	0.13	0.13	0.24	0.82	0.73	1.74	0.80
Il		0.99	0.61	0.77	0.64	1.11	0.22	1.08	0.59	1.00	0.73	0.39	0.60	0.64	0.80
Ap		0.19	0.15	0.24	0.17	0.27	0.17	0.22	0.07	0.49	0.24	0.12	0.05	0.05	0.10
Di	Mg	5.65	5.28	7.29	6.27	8.44	2.20	8.42	12.49	0.04	—	7.88	2.59	3.21	2.85
	Fe	3.65	2.79	5.34	4.43	5.07	1.08	4.19	6.20	0.04	—	2.41	1.13	1.38	1.42
Hy	En	13'52	22.68	11.05	14.61	17.20	21.57	18.87	11.77	8.14	3.25	10.98	50.75	50.37	48.17
	Fs	10.03	13.77	9.28	11.83	11.85	12.14	10.78	6.71	7.83	3.13	3.86	25.33	24.80	27.65
Ol	Fo	—	—	1.77	—	—	—	—	—	—	—	15.28	—	—	—
	Fa	—	—	1.64	—	—	—	—	—	—	—	5.91	—	—	—
D.I.		17.51	11.43	16.81	21.01	13.01	15.27	22.60	28.35	49.09	67.13	4.71	9.75	7.45	8.39
Normative Plag.		An 80	An 87	An 73	An 70	An 82	An 85	An 71	An 74	An 58	An 40	An 92	An 70	An 78	An 73

S-18 — Medium grained quartz-hornblende bearing norite. Loc. Swee Quarry, Singapore.
S-63 — Medium grained quartz-hornblende bearing norite. Loc. Yun Onn Quarry, Singapore.
S-95 — Medium grained norite. Loc. Phoenix Estate, Singapore.
S-85 — Medium grained quartz-hornblende bearing norite. Loc. Chua Chai Seng Quarry, Singapore.
S-99 — Partially uralitized norite. Loc. Lian Hup Quarry, Singapore.
S-70 — Uralitized norite. Loc. Yun Onn Quarry, Singapore.
S-25 — Uralitized norite. Loc. Swee Quarry, Singapore.
S-100[a] — Medium to coarse grained hornblende rich segregation. Loc. Yun Onn Quarry, Singapore.
S-65 — Medium grained biotite quartz diorite. Loc. Yun Onn Quarry, Singapore.
A-3 — Quartzo-feldspathic segregation. Loc. Bluestone Quarry, Singapore.
S-69[a] — Olivine eucrite orthocumulate xenolith. Loc. Yun Onn Quarry, Singapore.
S-15[a], S-13, S-67 — Cummingtonite orthopyroxenite cumulate (xenoliths?). Loc. Yun Onn Quarry, Singapore.

[a] – modal data in Table 1.

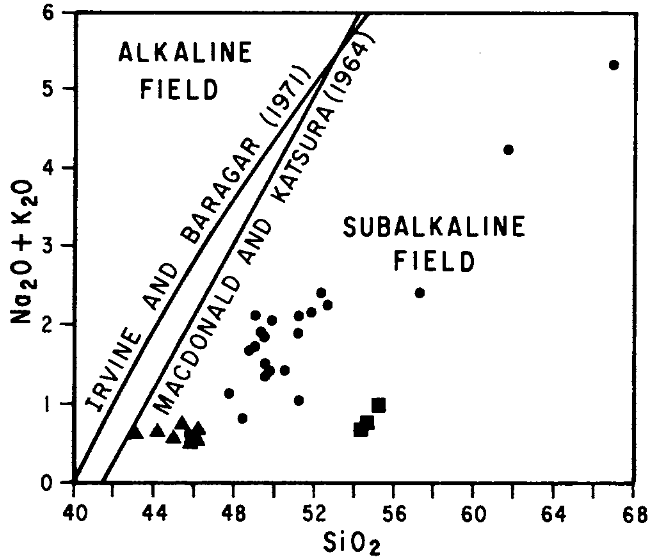

Fig. 6. Alkalies—silica plots for samples from the Linden and Gombak stocks. Symbols: Triangles—Linden cumulates; Dots—Gabbroic rocks and associated minor felsic segregations of the Gombak stock; Squares—Cummingtonite orthopyroxenite, Gombak stock. Note that in all variation diagrams analyses are recalculated to total 100% volatile-free before plotting.

Harker-type variation diagrams of oxides against SiO_2 have been used to examine the pattern of chemical variations within the gabbroic suite. It is apparent from Figure 7 that rocks from the Linden and Gombak stocks constitute a coherent group developing a single trend of variation for most elements. This feature provides strong evidence in support of an earlier conclusion, drawn on petrographic grounds, that there is a direct petrogenetic link between these two stocks. With increasing SiO_2, a continuous decrease is shown by MgO and CaO. K_2O is virtually constant through the Linden cumulates and subsequently shows a gradual increase within the Gombak norites. FeO (total iron) shows an initial increase reaching maximum at about 49% SiO_2 and then decreases with increasing SiO_2. TiO_2 is low and increases slightly amongst the Linden cumulates. An abrupt increase in TiO_2 content corresponds with approximately

TABLE 5

High-alumina basalts and the average composition of the Gombak norite

No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
1	49.04	0.70	18.41	8.78	0.17	7.58	11.62	1.42	0.23	0.09
2	48.90	0.97	17.58	10.22	0.16	7.79	10.82	2.32	0.27	0.09
3	49.15	1.52	17.73	9.69	0.14	6.91	9.91	2.88	0.72	0.26

1 Average composition of unaltered apparently non-cumulate gabbroic rocks from the Linden-Gombak suite. Average of 19 analyses.
2 Kuno's (1968) parental high-alumina basalt.
3 Cascades high-alumina basalt (Waters, 1962). Average of 21 analyses.

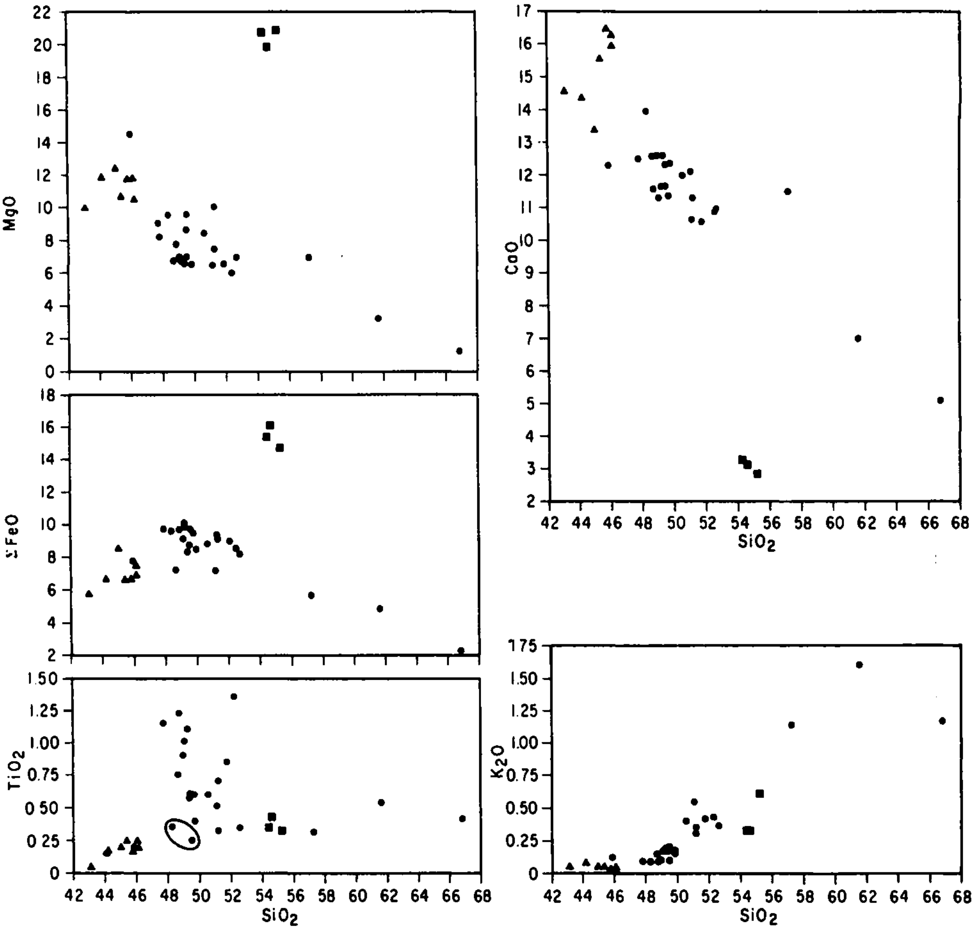

Fig. 7. Harker-type variation diagrams of oxides versus silica. Symbols as for Figure 6.

49 % SiO_2 and this is followed by a gradual decrease. The maxima for TiO_2 and FeO which coincide at approximately 49 % SiO_2, marks the incoming of Fe–Ti oxides as a crystallising phase. A gradually increasing trend for FeO as opposed to the abrupt increase in TiO_2 content, must be related to the changing composition of the ferromagnesian minerals. In the TiO_2 versus SiO_2 diagram, two analyses (circled in the diagram) from the Gombak stock lie intermediate between what would otherwise be two distinct trends distinguishing rocks from the Linden and Gombak stocks. It is not surprising that these two analyses are of fine grained Gombak norite where chilling has suppressed the crystallisation of the opaques and subsequently reduced the TiO_2 contents.

The variation of the Linden-Gombak suite in the AFM diagram demonstrates a trend towards iron enrichment (Fig. 8). The subsequent variation towards more acidic compositions is, however, uncertain because of the scarcity of samples representing the

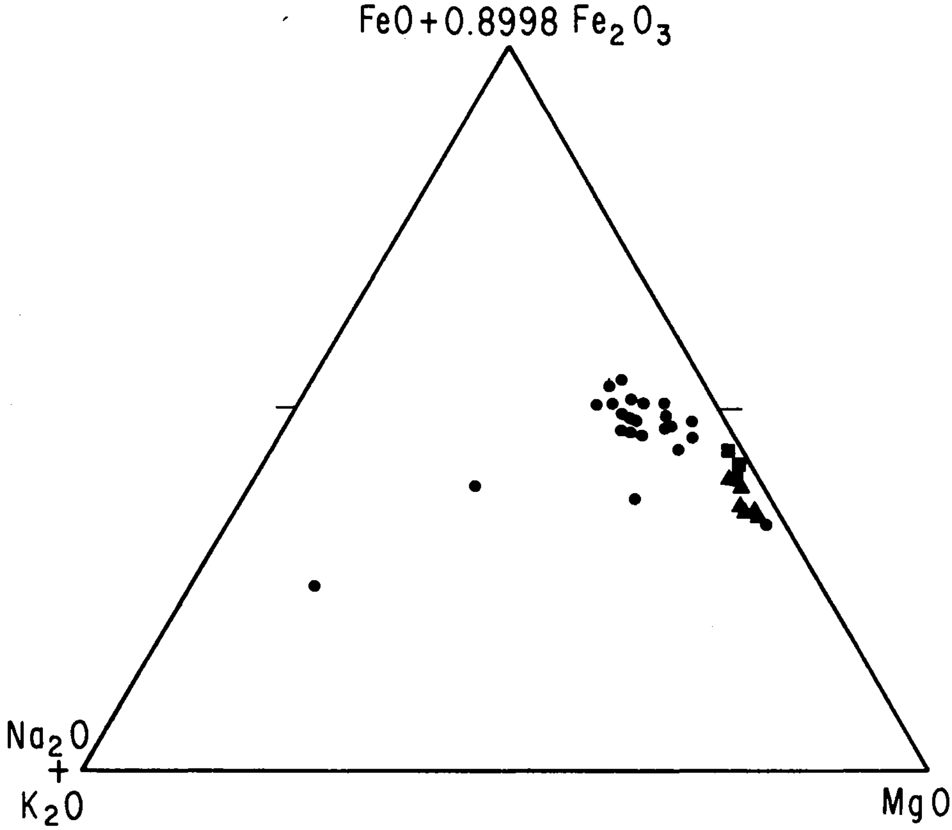

Fig. 8. AFM variation diagram for samples from the Linden and Gombak stocks. Weight percent. Symbols as for Figure 6.

middle and late stages of differentiation. The limited range of SiO_2 in the Linden-Gombak suite suggests that either (i) the suite, as now exposed, represents only a part of the whole differentiated sequence, or (ii) that the differentiation of the magma was rather limited and failed to produce any significant amount of more acidic differentiates.

DISCUSSION

Comparison with other 'batholithic gabbros'

It has long been recognised that gabbroic bodies associated with intermediate to acidic batholiths in orogenic belts represent a distinct class of basic rocks (e.g. Benson, 1926). These batholithic gabbros, or 'minor associates of batholithic complexes' (Wyllie, 1967), are distinguished from the gabbros of cratonic-stratiform, ophiolite and concentrically zoned complexes by their tectonic setting coupled with certain pertinent field characteristics (Joplin, 1959) including the absence, or relatively minor amounts, of associated peridotites and related ultramafic rocks. The term batholithic gabbro is here preferred to the often used equivalent cordilleran gabbro since the continental margin type tectonic setting implied in the latter term is not always established, as for example, in the Malay Peninsula.

In the Malay Peninsula, batholithic gabbro bodies represent only a minute fraction of the associated batholiths. Elsewhere, especially amongst the circum-Pacific batholiths of the Americas, similar gabbroic bodies may be significant in volume as for instance in the Batholith of southern California and the Coastal Batholith of Peru, where basic rocks comprise 14 and roughly 16 percent of the total areal extent of the batholiths respectively (Larsen, 1948; Cobbing and Pitcher, 1972; Pitcher, 1978). It seems necessary that any comparison of the character of batholithic gabbros must include those of the western Americas and, in particular, the gabbros of the North American Pacific margin which are the best studied.

The recent publication of Walawender and Smith (1980) provides a synthesized account of the numerous gabbroic bodies within the Peninsular Ranges Batholith of Southern California. They recognise 2 series amongst the gabbroic rocks, namely an olivine-pyroxene gabbronorite series and a much subordinate amphibole-gabbro series. A third group of quartz norite is cosidered as a contaminated phase. The olivine-pyroxene gabbronorite series, comprising an olivine-clinopyroxene subseries and an amphibole-orthopyroxene subseries, is remarkably similar to the Linden-Gombak suite. Anorthite-olivine-ophitic orthopyroxene characterised cumulates of the olivine-clinopyroxene subseries are equivalent to the Linden stock. The amphibole-orthopyroxene subseries which is defined by the absence of olivine, the presence of granular orthopyroxene and the crystallisation of significant Fe-Ti opaques, is correlatable with the Gombak stock. The revealing TiO_2 versus SiO_2 variation of the Linden-Gombak suite is exactly reproduced by the olivine-pyroxene gabbronorite series (Fig. 4 in Walawender and Smith, 1980).

The similarity between the Linden-Gombak suite and the olivine-pyroxene gabbronorite series prompts the possibility that the series scheme as outlined by Walawender and Smith (1980), for the Peninsular Ranges gabbros, may prove to be an effective classification for batholithic gabbros in general. Other published descriptions, particularly from the circum-Pacific region, indicate that many of these suites may indeed be broadly classified within either the olivine-pyroxene gabbronorite series (e.g. Erikson, 1969; 1977; Mack, *et al.*, 1979; Mullan and Bussell, 1977; Price and Sinton, 1978) or the amphibole-gabbro series (Mullan and Bussell, 1977) or as contaminated rocks. In the Malay Peninsula, the amphibole-gabbro series is not recognised though a contaminated suite, the Kemuning gabbroic suite (Kumar, 1980), is known.

The Linden-Gombak and other gabbroic suites within the olivine-pyroxene gabbronorite series exhibit overall similarities in mineral chemistry, order of crystallisation and texture. The whole rock chemistry of these rocks is, in general, also very similar being characterised by high Al_2O_3 and very low K_2O contents. However, some differences do exist. The occurrence of inverted pigeonite in the Gombak norite and the Moro gabbro in contrast to its absence in other batholithic gabbros has already been mentioned. In addition, magmatic hornblende and opaque minerals (essentially magnetite or titanomagnetite) may be present or absent in rocks of the olivine-clinopyroxene subseries though invariably present in the amphibole-orthopyroxene subseries as exemplified by their absence in the olivine-clinopyroxene subseries of the Linden-Gombak suite. The presence or absence of these phases and their point of entry within the crystallisation sequence must be controlled by the differing PH_2O of the magmas parental to these gabbroic suites (cf. Cawthorn, 1976). The Linden-Gombak suite represents an example of an olivine-pyroxene gabbronorite series which has crystallised under only moderately high PH_2O resulting in the presence but delayed crystallisation of pigeonite, amphibole and opaques. Crystallisation under conditions of high PH_2O would result in non-crystallisation of pigeonite and earlier crystallisation of amphibole and opaques as in most examples of the olivine-pyroxene gabbronorite series.

The olivine-pyroxene gabbronorite series in relation to the cognate plutonic xenoliths of calc-alkaline volcanics

Another group of rocks which are petrologically identical to the Linden-Gombak suite and, thus, the olivine-pyroxene gabbronorite series, are the cognate plutonic ejecta of calc-alkaline volcanoes. Examples of such volcanoes include those in the West Indies (Baker, 1968; Lewis, 1973; Rea, 1974), the Mariana Island Arc (Stern, 1979),

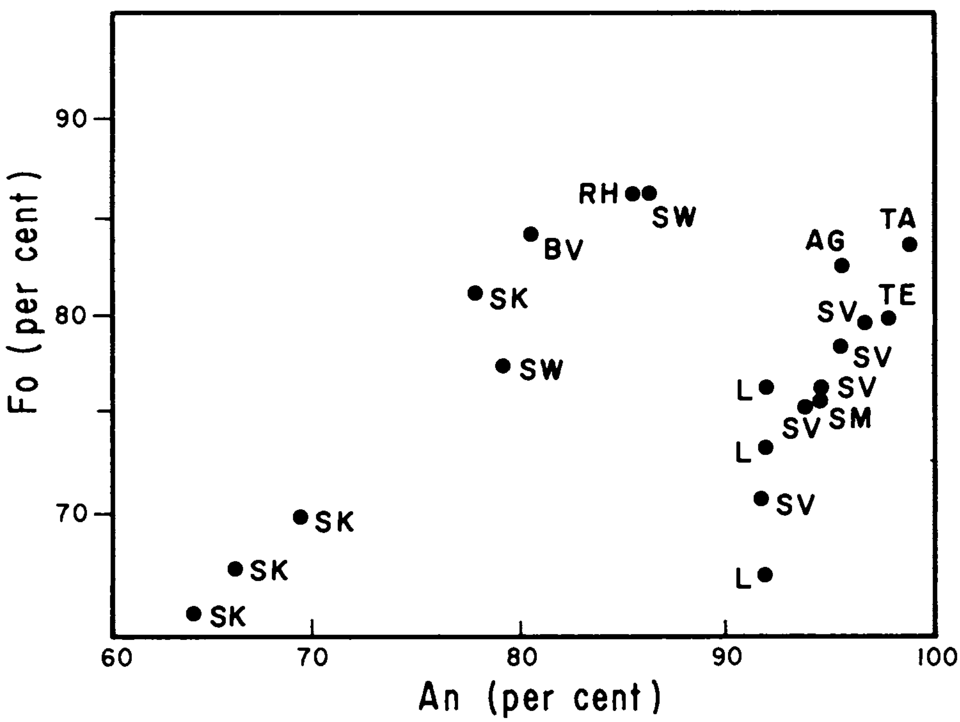

Fig. 9. Plot of composition of coexisting olivines (Fo mol. percent) and plagioclases (An mol. percent) for some subalkaline plutonic rocks, modified from Lewis (1973). RH—Rhum intrusion; SW—Stillwater intrusion; BV—Bushveld intrusion; SK—Skaergaard intrusion: well described stratiform complexes. Plutonic ejecta of calc-alkaline volcanoes: TA—Taga allivalite; TE—Taga eucrite; AG—Agrigan xenolith; SV—St. Vincent blocks. SM—San Marcos Gabbro cumulate, southern California; L—Linden cumulates.

the Izu-Hakone region of Japan (Kuno, 1950; 1968) and the Cyclades. Greece (Nicholls, 1971). The mineralogy, sequence of crystallisation, texture and chemistry of the xenoliths are very similar to those of the olivine-pyroxene gabbronorite series. For example, the coexistence of highly calcic plagioclase with relatively Fe-rich olivine in these xenoliths (Wager, 1962; Lewis, 1973; Stern, 1979) is identical to that in the olivine-clinopyroxene subseries and differs from the plagioclase-olivine assemblages typical of stratiform complexes as illustrated in Figure 9. Xenoliths of the Soufriere volcanics, St. Vincent, which are mostly olivine-clinopyroxene subseries types containing both amphibole and opaques (magnetite), have previously been indicated to be similar to gabbroic rocks of the Virgin Islands plutons and the San Marcos Gabbro of the Peninsular Ranges Batholith (Lewis, 1973). Plutonic ejecta from other West Indian volcanoes are essentially similar to those from St. Vincent but normal, apparently non-cumulate hornblende gabbros and norites are also common in addition to anorthite-olivine bearing blocks. Plutonic ejecta described by Stern (1979) from Agrigan include both olivine-clinopyroxene subseries types and olivine-free amphibole-orthopyroxene subseries varieties. Interestingly, the xenoliths from Agrigan are devoid of amphibole, and opaques (titanomagnetite) are only present in the olivine-free, orthopyroxene bearing rocks. The analogy with the Linden-Gombak suite is evident.

All cited studies on the plutonic xenoliths of calc-alkaline volcanics have led to the conclusion that these plutonic ejecta represent crystal cumulates or basaltic magma solidified at depth, derived from differentiating magma chambers feeding the calc-alkaline volcanoes. It is only logical to assume that gabbroic rocks identical to these ejecta are preserved at depth. The similarity between batholithic gabbroic bodies of the olivine-pyroxene gabbronorite series to the cognate xenoliths implies that these bodies are the currently exposed differentiated, basaltic magma chambers or 'subtraction reservoirs' representing the root zones of paleo calc-alkaline volcanoes. The inferred parental status of high-alumina basalt for both the calc-alkaline volcanics associated with plutonic xenoliths, and the olivine-pyroxene gabbronorite series batholithic gabbros is evidence in support of the above conclusion. Furthermore, most batholithic gabbro bodies are indicated to have been emplaced and fractionated high in the crust so substantiating a direct link between these bodies and coeval volcanism. Kuno (1968) expressed a similar interpretation on relating gabbroic stocks of orogenic belts to calc-alkaline volcanism. Mack, *et al.*, (1979) interpreted gabbroic associations in the western Sierra Nevada foothills in a similar manner.

ACKNOWLEDGEMENTS

I am most grateful to Dr. K.R. Chakraborty for invaluable advice and encouragement. I am also indebted to him and Mr. Low Keng Lok for allowing me to work on samples they had collected. Thanks are due to Mr. Ching Yu Hay for drafting, Mrs. Anna Lee for typing and Mr. Jaafar Hj. Abdullah for printing photographs. The project was financed by a research grant from the University of Malaya.

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Manuscript received 27 April 1981