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# Sub-ophiolite metamorphic rocks in the Tungku area, Lahad Datu, eastern Sabah, Malaysia: origin and tectonic significance

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**Abstract:** Sub-ophiolite metamorphic rocks (garnet amphibolites) found as clasts in late Early Miocene to late Middle Miocene mélange formed at high pressures and temperatures are interpreted as derived from a metamorphic sole underlying the Darvel Bay Ophiolite Complex, formed during subduction of ocean crust and the emplacement of the ophiolite complex in Sabah. Mineral chemistry and bulk rock geochemistry of the garnet amphibolites show that they are MORB tholeiites and represent oceanic crustal materials. These rocks were metamorphosed as pyroxene granulites and garnet amphibolites at high temperatures and pressures characteristic of upper mantle and were deformed and recrystallised with mylonitic textures in the amphibolite facies. A K/Ar age of 76 ± 21 Ma obtained from garnet amphibolite during the present study coincides with the Late Cretaceous-Palaeogene age of subduction beneath the Darvel Bay Ophiolite inferred from the stratigraphic evidence.

## INTRODUCTION

Good exposures of the metamorphic rocks underlying the allochthonous ophiolite complex are very scarce in Sabah, this is due to the nature of the exposure or to the highly tectonized nature of the area, or obscured by the effects of the subsequent tectonism. However, the occurrences of the metapyroxenite and garnet amphibolite pebbles in the Sungai Pungulupi, Tungku area provide a record for the formation of the basal mylonitized peridotite and metamorphic soles in Sabah, relating to the subducted and/or obducted oceanic lithosphere.

In the Tungku region of Dent Peninsula, SE Sabah, approximately 50 miles east of Lahad Datu town (Fig. 1), garnet amphibolites abundantly occur as blocks and pebbles in chaotic deposit of late Early Middle to late Middle Miocene age along the stream of the Sungai Pungulupi. The pebbles are of various sizes and shapes. In this river, other pebbles such as ultramafic rocks, gabbros, felsic intrusives, volcanic rocks and sedimentary rocks are also abundant. A few pebbles of garnet amphibolite were collected for petrology and geochemistry studies. In this study these rocks were interpreted as related to the early stages of the Darvel Bay Ophiolite emplacement. However, Morgan (1974) has studied the garnet metapyroxenite pebbles from the same locality and considered that these rocks represented a mantle xenolith. Yong (1994) found a single pebble of garnet amphibolite which associated with the mélange in the northern part of the Danum Valley Field Centre (DVFC).

This paper gives an account of the petrography, mineral chemistry, whole rock geochemistry and age of the garnet amphibolite and also discusses their origin and significance in the tectonic evolution of Sabah. The work described where was presented as a Ph.D thesis by Omang (1993).

## ANALYTICAL METHODS

Mineral analysed were carried out on a JEOL Superprobe 733 electron microprobe at Birkbeck College and mineral compositions were recalculated using a suite of programs developed by Prof. Hall. Mineral formula proportions were calculated on the basis of: 6(O) – pyroxene; 23(O) – amphibole; 24(O) – garnet and 32(O) – feldspar. Cation ratios are abbreviated as follows: $Xmg = Mg/(Mg + Fe^{2+})$. Bulk rock geochemistry of garnet amphibolite used in this study was analysed in the geochemistry laboratories at Royal Holloway, University of London using a Philips, PW 1480 XRF Spectrometer and are presented on a volatile-free basis normalised to 100% totals for major elements. K/Ar age dating was carried out at the Natural Environment Research Council Isotope Geosciences Laboratory at Keyworth Nottingham.

## PETROGRAPHY

The rocks are fine to medium grain size and show porphyroblastic and gneissic textures (Fig. 2), but sometimes a mylonitic texture is also visible; rounded amphibole, plagioclase porphyroclasts up

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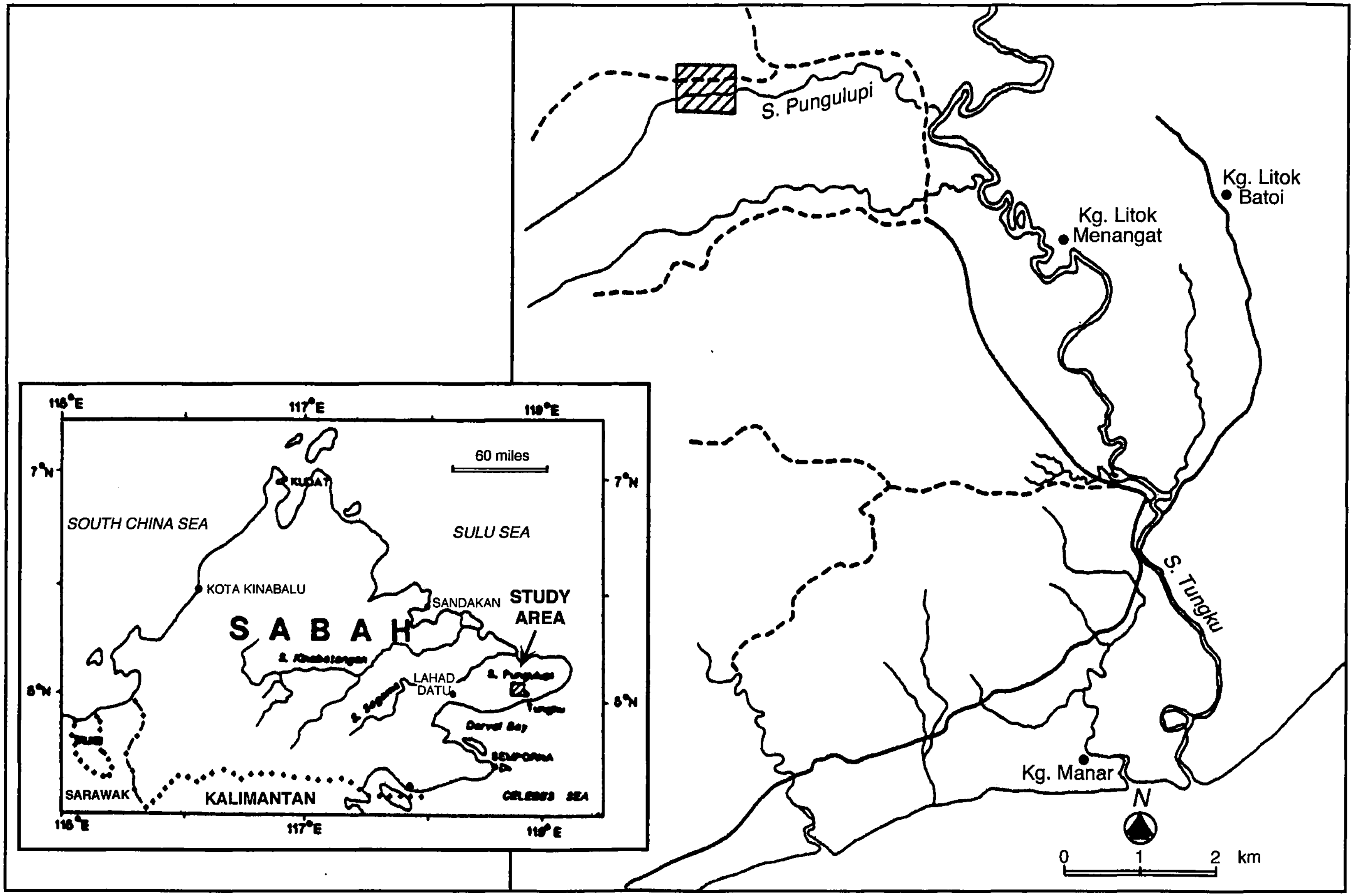


**Figure 1.** Map of Sabah showing the location of the Sungai Pungulupi in the Tungku area, Dent Peninsula, Sabah.

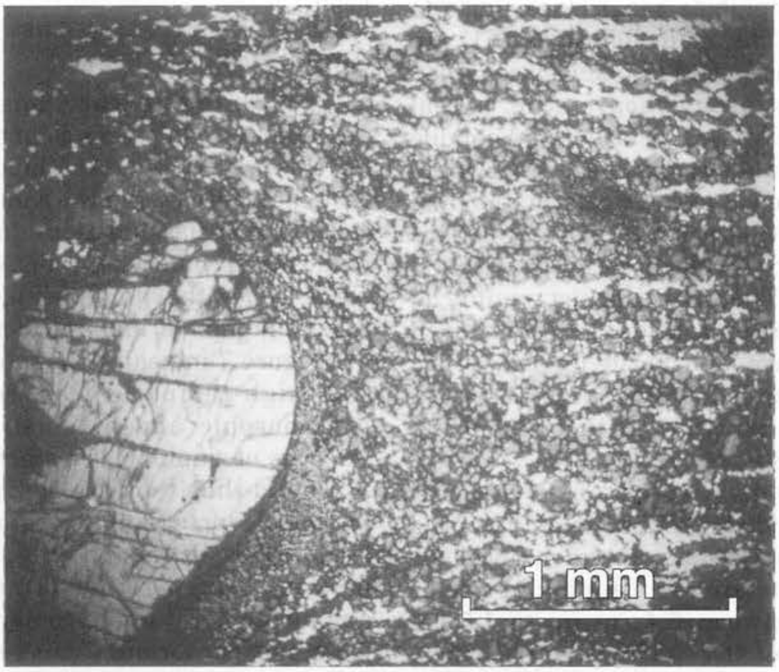


**Figure 2.** Photomicrograph of garnet amphibolite (specimen EKc) showing a fractured garnet crystal with alteration to hornblende enclosed in a fine grained mylonitic hornblende-plagioclase matrix forming an augen structure. Pebble from Tungku river, Dent Peninsula, Sabah. Scale bar 1 mm.

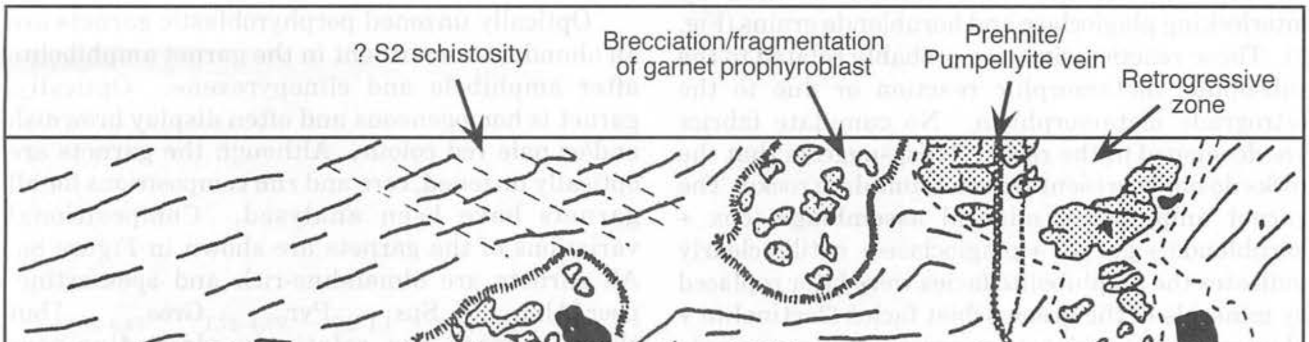


**Figure 3.** Schematic sketch of a thin section of garnet amphibolite (sample EKc) from thin-section using shadow master. Further descriptions in the text.

to 1 mm in diameter, occur in a very fine grained matrix made up of amphibole, plagioclase, ilmenite and clinopyroxene. The main foliations (S1) are defined by alternating layers of plagioclase, green hornblende and light grey clinopyroxene. Local cataclasis and brittle fracturing orientated oblique to earlier ductile metamorphic fabrics (the main foliation) characterised of late D2 deformation and are associated with retrograde metamorphism. This D2 deformation is probably associated with S2 foliations (Fig. 3). The rocks consist mainly of porphyroblastic garnet, clinopyroxene, green amphibole, plagioclase and rutile/ilmenite. No orthopyroxene and spinel grains were observed. Mineral assemblages are typical of the amphibolite facies (Jamieson, 1980).

Clinopyroxene is pale green and/or gray in colour, occurs as rounded crystals, lining up in the foliation. Hornblende crystals are green in colour. Garnet porphyroblasts are reddish pink in colour, with a grain size between 0.4 cm up to 1.5 cm across. Porphyroblastic garnet is fractured indicating the effects of later deformation and some of the fractures are filled by green amphibole. Pressure shadows are developed at the edge of the porphyroblastic garnet. None of the garnet porphyroblasts display helicitic porphyroblastic fabrics. Some reaction rims are developed at the margins of the garnets, mainly defined by interlocking plagioclase and hornblende grains (Fig. 3). These reaction rims are probably related to the subsolidus metamorphic reaction or due to the retrograde metamorphism. No cumulate fabrics are developed in the rocks. This, suggests that the rocks do not represent igneous cumulate rocks. The garnet amphibolite mineral assemblage (cpx + hornblende + garnet + plagioclase + rutile) clearly indicates the amphibolite facies were later replaced by minerals of the green schist facies (?actinolite + plagioclase + epidote), suggesting a retrograde metamorphic event. Late prehnite/pumpellyite veins cut the fabrics of the rock.

## MINERAL CHEMISTRY

### Clinopyroxene

Clinopyroxenes have a salite composition, according to Deer *et al.* (1992) nomenclature, ranging from $En_{30-33}Fs_{15-22}Wo_{31-53}$.$X_{Mg}$ values between ~ 75–88. Chemistry of the clinopyroxene indicates that the rocks are alkaline to peralkaline in composition (Fig. 4). $SiO_2$ ranges between ~ 43 wt% to 48 wt%. $Al_2O_3$ and CaO contents between ~ 7.5–12 wt% and ~ 11–22 wt% respectively. $TiO_2$ concentrations are ~ 1.0 wt% and MgO ranges between ~ 8–10 wt%. $Na_2O$ contents are ~ 3.0 wt%. $K_2O$ content is always below microprobe detection level.

### Amphibole

No zoning texture has been observed in amphiboles. Only core compositions of amphibole have been analysed. Amphibole compositions vary systematically within the samples. Following Deer *et al.* (1992) classification, amphiboles are mostly pargasite in composition (Fig. 5). Plot of $Al^{VI}$ versus Na[M4] show that amphibolites fall within the sodic-calcic amphibole and calcic-amphibole field (Fig. 6). Figure 7 indicates that the hornblendes follow the high-temperature trend, between the metamorphic and magmatic hornblende field. Majority of amphibole clusters have $Al^{IV}/Al^{VI}$ ratios > 2.0 and thus they are 'low pressure' sodic-calcic amphibole, presumably crystallised between ~ 4–5 kbar. This estimated pressure may reflect the pressures during the formation of the garnet amphibolite. Titanium contents range from ~ 0.2–0.3 atoms per formula unit (~ 1–2 wt%). These Ti ranges are close to the Ti contents (~ 0.22 atoms per formula) in amphiboles from garnet amphibolite of the upper structural level of Mowomba Metamorphic Sole, Central Sulawesi (Parkinson, 1991).

### Garnet

Optically unzoned porphyroblastic garnets are an abundant constituent in the garnet amphibolite after amphibole and clinopyroxene. Optically, garnet is homogeneous and often display brownish and/or pale red colour. Although the garnets are optically unzoned, core and rim compositions for all garnets have been analysed. Compositional variations of the garnets are shown in Figure 8a. All garnets are almandine-rich and spessartine-poor [$Alm_{40.9-38.9}Sps_{1.1-2.7}Pyr_{23.4-27.1}Gros_{34.9-30.2}$] but these garnets are relatively almandine-poor compared to the garnet compositions of the Mowomba metamorphic sole and the Peleru Mélange, Central Sulawesi (Parkinson, 1991) (Fig. 8b). Rim compositions of garnet are relatively rich in Ca and Mg, and poor in Fe compared to the core composition. Increasing substitution of CaO by MgO indicates progressively higher temperatures (Malpas, 1979) and/or pressures (Green and Ringwood, 1967; Miyashiro, 1973) of metamorphism, and that core-rim zonation is in response to the prograde metamorphic stage (Banno *et al.*, 1986). Ganguly and Kennedy (1974) investigated the mixing properties of natural garnet aluminosilicate end-members and concluded that mixing of pyrope-grossular end members when *X*pyr = 0.15–0.20 occurred at temperatures above approximately 550°C (the "critical mixing temperature"), which

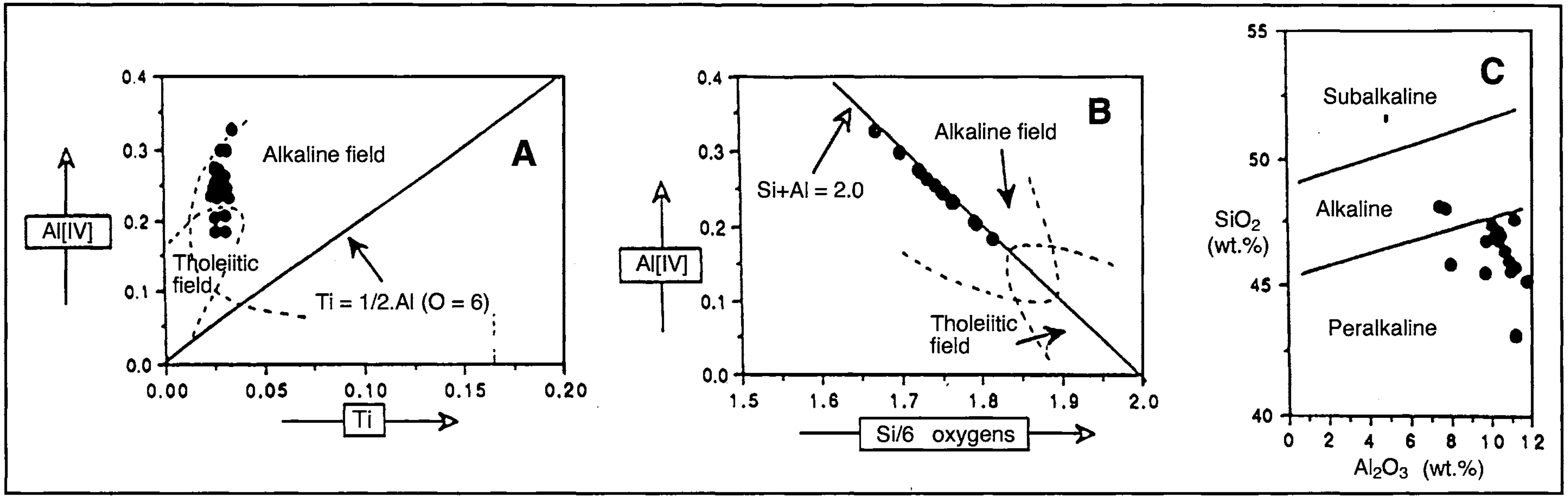


**Figure 4.** Plots of (A) Ti versus Al[IV]; (B) Si versus Al[IV] and (C) $Al_2O_3$ versus $SiO_2$ of clinopyroxene compositional variations in garnet amphibolite from Pungulupi river, Tungku area. Alkalic and tholeiitic basalt fields from Maruyama (1977) and Leterrier *et al.* (1982); Ocean floor basalts field from Nisbet and Pearce (1977). Alkaline, subalkaline and peralkaline fields from Le Bas (1962).

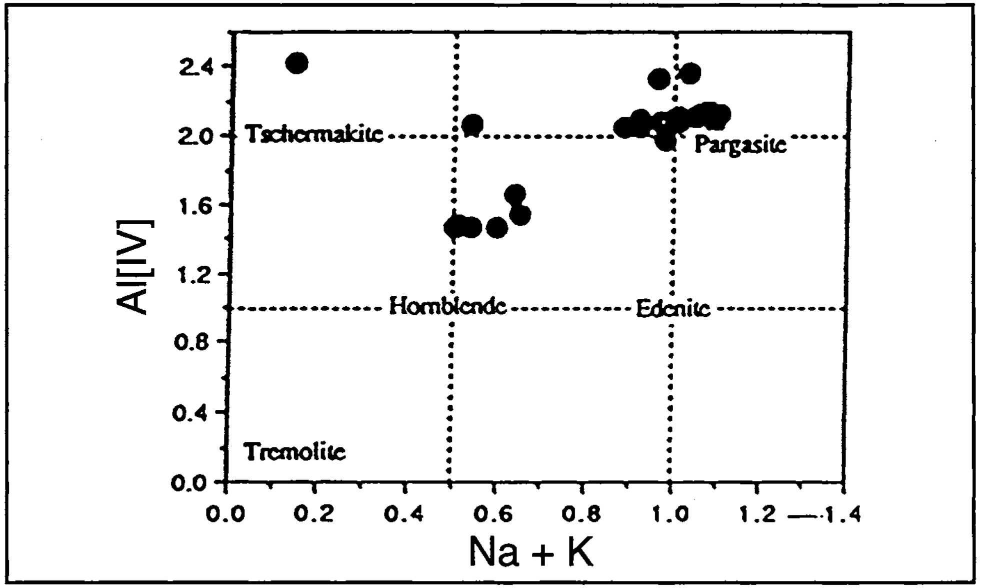


**Figure 5.** (Na + K) versus Al[IV] plot of amphibole compositions in garnet amphibolite from Sungai Pungulupi, Tungku area; displayed on Deer *et al.* (1992) diagram.

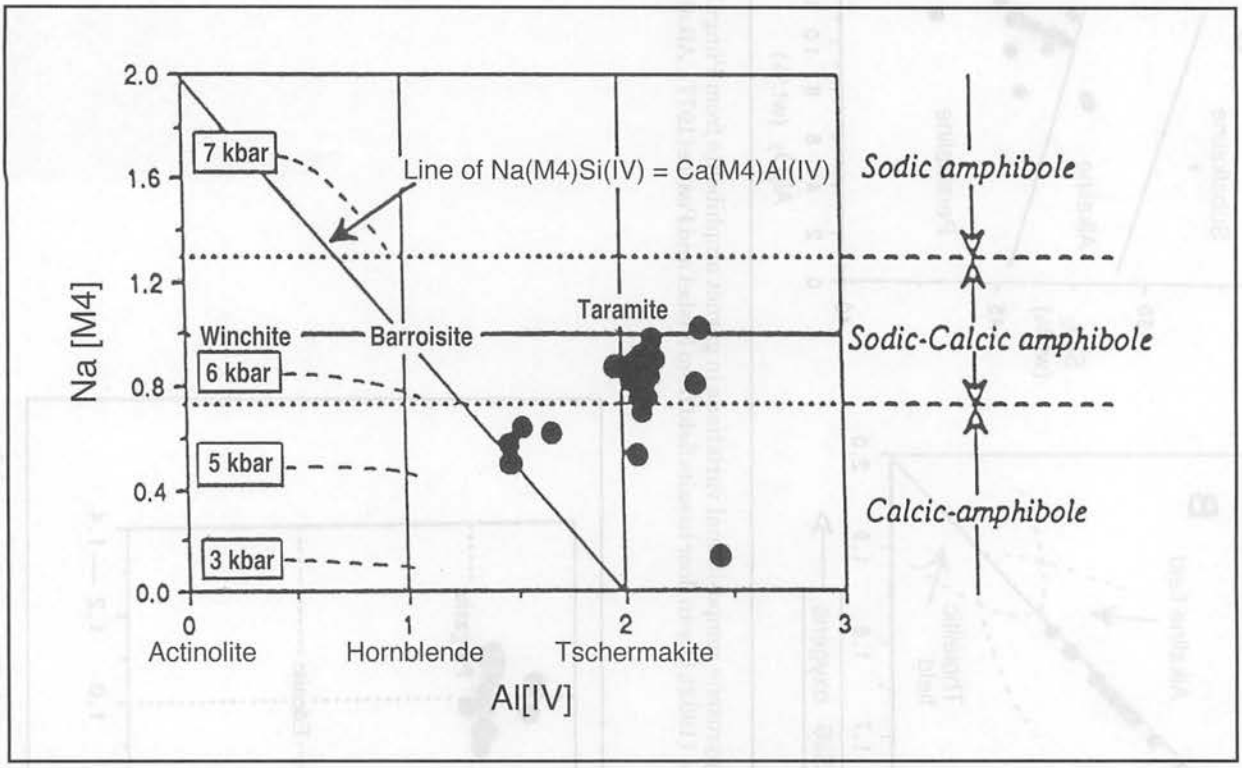


**Figure 6.** Al[IV] versus Na[M4] plot of amphibole compositions in the garnet amphibolite from Sungai Pungulupi, Tungku areas; displayed on Brown's (1977) diagram.

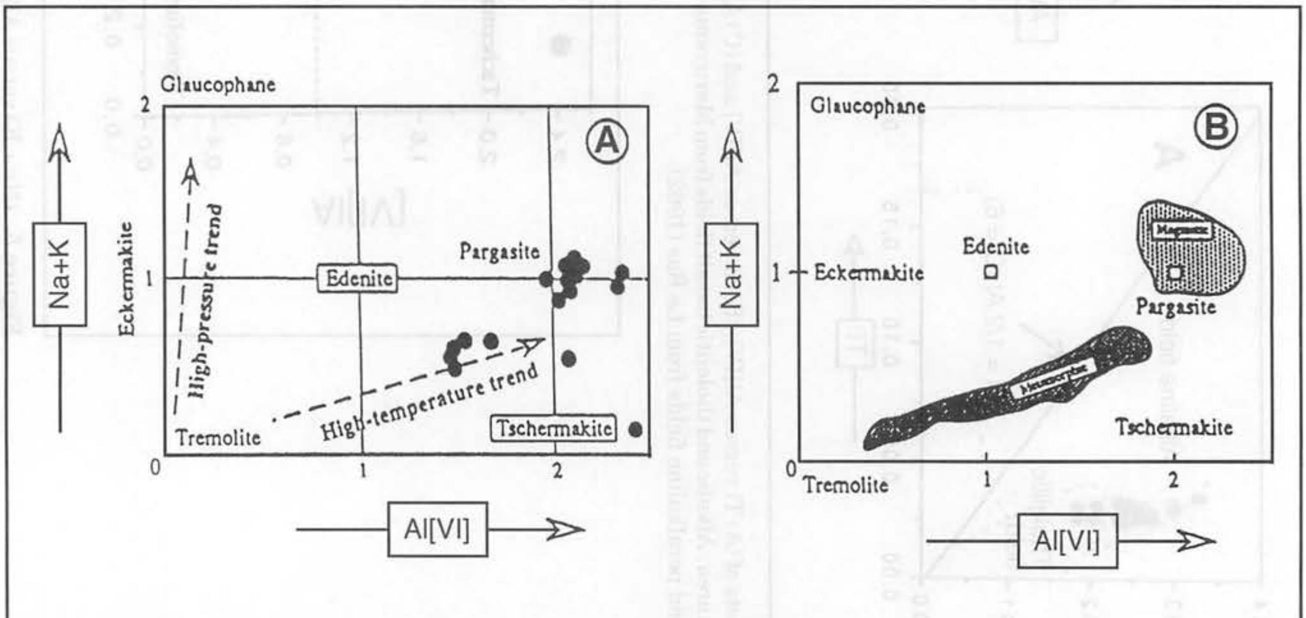


**Figure 7.** Al[VI] versus (Na + K) plot of (A) amphibole composition in garnet amphibolite compared to (B) metamorphic and magmatic amphibole fields (Jamieson, 1981).

constrains temperatures of garnet growth. $TiO_2$ contents are less than 0.24 wt% and relatively low compared to those in the garnet amphibolites from the Mowomba metamorphic sole ($TiO_2$: 0.21–0.54 wt%). $K_2O$ content is always below microprobe detection level.

### Plagioclase

Plagioclase compositions were difficult to determine because of the secondary effects of albitisation and alteration to fine aggregates of epidote, white mica, clays and maybe pumpellyite. All analysed plagioclase in garnet amphibolites is unzoned, thus the analyses were carried out on the core of the plagioclase. Composition of plagioclase typically ranges from oligoclase ($An_{20-22}$) to andesine ($An_{33-43}$). However, a few plagioclase clusters have compositions between labradorite ($An_{52-68}$) and bytownite ($An_{71-73}$), probably these plagioclase compositions represent the primary phase. Oligoclase and andesine occur in garnet amphibolites from Mowomba metamorphic sole (Parkinson, 1991). A semi-empirical amphibolite geothermometer for coexisting hornblende/ plagioclase pairs, proposed by Plyusnina (1982), yield temperatures of c. 600°–750°C and pressures of c. 3–4 kbar for hornblende plagioclase core compositions in metapyroxenites.

## P-T CONDITIONS

### Garnet-Hornblende Geothermometry

The garnet hornblende Fe-Mg exchange geothermometer of Graham and Powell (1984), has been applied to the coexisting garnet-hornblende pairs in the garnet amphibolites. The criteria of Graham and Powell (1984) were used to select

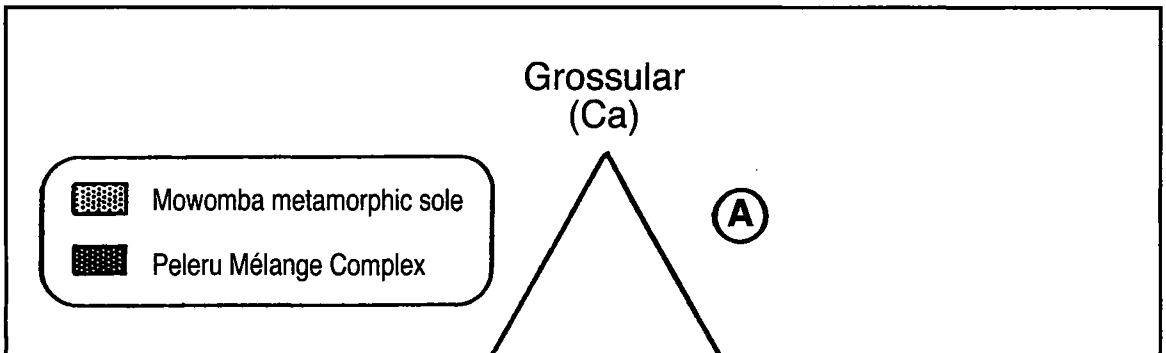


**Figure 8.** (A) Composition of garnet in garnet amphibole from Sungai Pungulupi, Tungku area, Dent Peninsula, Sabah; (B) Composition of garnet in metabasites from Mowomba Metamorphic Sole and Peleru Mélange Complex, Central Sulawesi for a comparison.

suitable grains for analysis. These include: attainment of textural equilibrium (implying attainment of chemical equilibrium) lack of significant internal compositional zonation, low Mn in garnet ($X_{Mn}$ < 0.1) and low Na[M4] in hornblendes. Such criteria are only met by amphibolites near to the peridotite contact (Parkinson, 1991). Peak metamorphic temperatures of the garnet amphibolites, ranging from 850°C to 900°C were derived using this method. Rim analyses yielding slightly higher temperatures (950°C–1,060°C) than core analyses, are consistent with the normal zonation in the garnets (Hollister, 1966).

### Garnet-Clinopyroxene Geothermometry

Garnet-clinopyroxene pairs are also used to determine the P-T condition of metamorphism for the Tungku garnet amphibolite. This geothermometry has been proposed by Raheim and Green (1974) and later modified by Ellis and Green (1979). Both of these geothermometers have been tested to calculate the temperature of the rock with pressures of 5 and 10 kbar. Use of Raheim and Green (1974) geothermometer yielded temperature ranges from ~ 800°C to 950°C for estimated pressure of 5 kbar, and temperatures of ~ 860°C to 990°C for estimated pressure of 10 kbar. However using Ellis and Green (1979) geothermometer, the temperature ranges from 730°C to 960°C for pressure of 5 kbar and ranges from 740°C to 1,080°C for pressure of 10 kbar. Generally, all geothermometers do not show much differences in temperature ranges, thus, it can be estimated that the peak metamorphic condition of the garnet amphibolite are T = 800–1,050°C and P = 5–10 kbar. This P–T conditions are almost similar with the P-T conditions of the hornblende garnet metapyroxenites from the Ballantrae Ophiolite Complex Scotland (Treloar *et al.*, 1980).

## WHOLE-ROCK GEOCHEMISTRY

Two samples of garnet amphibolite pebbles (EKc, EKf) from the Sungai Pungulupi, Tungku area, Dent Peninsula, SE Sabah were selected for major and trace element analysis by wavelength dispersive X-ray fluorescence spectrometry techniques using the Philips PW 1480 XRF spectrometer at RHUL. Results are presented in Table 1.

### Major Element Geochemistry

Bulk rock analyses of Tungku samples have a tholeiitic composition (Fig. 9). The $SiO_2$ contents range from ~ 44–45 wt% and $TiO_2$ about 1.7 wt%. $K_2O$ ranges from 0.01 wt% to 0.17 wt% and $P_2O_5$ contents are from 0.12–0.14 wt%. MgO concentrations from ~ 7–10 wt%. CaO concentrations are about 14 wt%. $Al_2O_3$ and $Fe_2O_3$ range from ~ 15–17 wt% and from 13–14 wt% respectively. Detailed interpretations of whole rock major element data from medium-grade metamorphosed rocks presents considerable problems, especially when shearing and deformation has accompanied the metamorphism (Searle and Malpas, 1982). Even low-grade metamorphism can cause large, coherent changes in major element chemistry (Garcia, 1978).

Major elements ($TiO_2$, $P_2O_5$, $Al_2O_3$) have a similar concentrations to those of garnet amphibolites from the Mowomba Metamorphic Sole and the Peleru Mélange, Central Sulawesi (Parkinson, 1991) and metapyroxenite from the Ballantarae Ophiolite, Scotland (Thirlwall and Bluck, 1984). Major elements such as MgO, $Fe_2O_3$, $Na_2O$ and $K_2O$ contents are slightly lower in garnet amphibolite (this study) compared to the garnet amphibolites from the Central Sulawesi Complex. CaO concentrations are high relative to the Central Sulawesi Complex.

### Trace Element Geochemistry

In general, variations in trace elements of metamorphic rocks are more reliable indicators of igneous petrogenesis than their major element variations. However, abundances of large-ion lithophile elements (LILE: Rb, Sr, Ba, K) in metamorphic rocks are subject to considerable modification during metamorphism, due to the

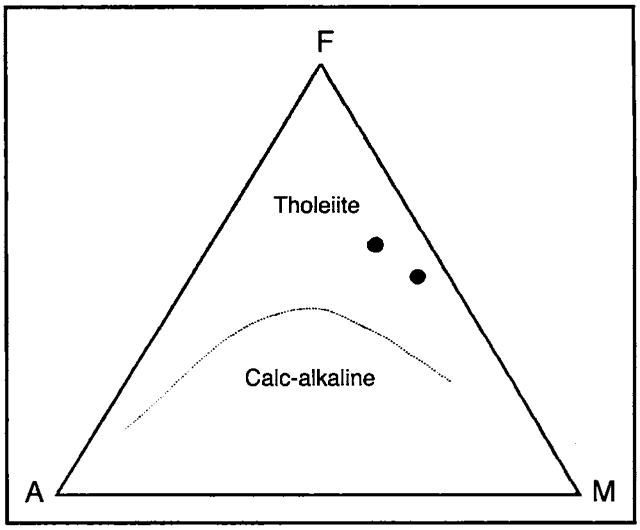


**Figure 9.** AFM diagram of the garnet amphibolite from Sungai Pungulupi, Tungku area. The approximate boundary between tholeiite and calc-alkaline fields is from Irvine and Baragar (1971).

**Table 1.** Whole-rock geochemical analyses for garnet amphibolites (EK) from Sungai Pungulupi, Tungku area compared to garnet amphibolites of Mowomba Metamorphic Sole, Central Sulawesi (MO36A, MO56B, MO61A) and garnet amphibolites of Peleru Mélange Complex, Central Sulawesi (MO69A, MO74B, PE72A. Data source from Parkinson (1991). Oxides in wt% and trace element in ppm. Total iron as $Fe_2O_3$ ($Fe_2O_3$* = $Fe_2O_3$ + FeO x 1.111). *Mg* = Mg/(Mg + $Fe^{2+}$), Mg = MgO/40; Fe = $Fe_2O_3$ x 0.9/72. Data presented on a volatile-free basis.

| Oxides/Elements | SAMPLE NO. | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | EKc | EKf | MO36A (Sole) | MO56B (Sole) | MO61A (Sole) | MO69A (Mélange) | MO74B (Mélange) | PE72A (Mélange) |
| $SiO_2$ | 43.55 | 44.67 | 43.66 | 49.48 | 47.02 | 41.38 | 52.09 | 46.45 |
| $TiO_2$ | 1.66 | 1.72 | 2.03 | 1.32 | 1.72 | 1.98 | 1.70 | 1.62 |
| $Al_2O_3$ | 16.86 | 15.01 | 14.94 | 15.82 | 15.72 | 15.84 | 14.35 | 18.20 |
| $Fe_2O_3$* | 13.92 | 12.79 | 15.40 | 8.87 | 11.81 | 14.92 | 9.32 | 11.51 |
| MgO | 6.82 | 9.95 | 10.63 | 10.62 | 12.26 | 11.65 | 8.30 | 6.54 |
| MnO | 0.26 | 0.21 | 0.29 | 0.16 | 0.25 | 0.31 | 0.21 | 0.21 |
| CaO | 14.40 | 14.42 | 10.14 | 11.53 | 7.57 | 11.63 | 9.29 | 11.54 |
| $Na_2O$ | 2.18 | 1.23 | 2.54 | 2.15 | 3.41 | 1.48 | 3.83 | 3.36 |
| $K_2O$ | 0.17 | 0.01 | 0.15 | 0.94 | 0.07 | 0.38 | 0.56 | 0.38 |
| $P_2O_5$ | 0.14 | 0.13 | 0.12 | 0.30 | 0.20 | 0.12 | 0.11 | 0.11 |
| Total | 99.95 | 100.14 | 99.90 | 101.19 | 100.03 | 99.69 | 99.76 | 99.92 |
| LOI | 0.11 | 0.23 | – | – | – | – | – | – |
| | | | | | | | | |
| $Al_2O_3/TiO_2$ | 10.16 | 8.73 | 7.36 | 11.98 | 9.14 | 8.00 | 8.44 | 11.23 |
| $CaO/TiO_2$ | 8.67 | 8.38 | 4.99 | 8.73 | 4.40 | 5.87 | 5.46 | 7.12 |
| *Mg* | ~ 49 | ~ 61 | ~ 59 | ~ 71 | ~ 67 | ~ 60 | ~ 64 | ~ 53 |
| | | | | | | | | |
| Ni | 229 | 118 | 135 | 53 | 14 | 26 | 129 | 50 |
| Cr | 684 | 447 | 381 | 412 | 323 | 461 | 389 | 226 |
| V | 195 | 396 | 160 | 218 | 81 | 209 | 149 | 256 |
| Sc | 41 | 56 | 28 | 25 | 20 | 38 | 24 | 46 |
| Pb | –0.4 | 0.0 | 0.6 | 0.1 | 10.4 | 1.7 | 2.5 | 0.6 |
| Sr | 113.0 | 27.4 | 117.2 | 99.5 | 42.0 | 25.3 | 186.8 | 117.3 |
| Rb | 0.5 | 0.3 | 1.4 | 20.8 | 5.6 | 1.2 | 2.5 | 1.5 |
| Ba | 5 | –2 | 49 | 77 | 123 | 61 | 223 | 79 |
| Th | –1.7 | 0.9 | 2.1 | – | 0.2 | 2.6 | 1.0 | 0.5 |
| Zr | 43.5 | 93.2 | 168.4 | 128.4 | 94.2 | 130.6 | 100.1 | 83.4 |
| Nb | 0.1 | 1.2 | 5.2 | 3.4 | 0.2 | 4.9 | 4.4 | 1.3 |
| Y | 16.7 | 42.8 | 47.1 | 43.2 | 27.2 | 52.0 | 45.3 | 40.8 |
| La | 0.3 | 2 | 15 | 9 | 16 | 18 | 13 | 20 |
| Ce | 4 | 6 | 16 | 14 | 28 | 25 | 33 | 18 |
| Nd | 4 | 7 | 18 | 8 | 5 | 19 | 17 | 11 |
| Cu | 82 | 27 | 15 | 102 | 55 | 15 | 59 | 46 |
| Zn | 57 | 71 | 79 | 39 | 39 | 65 | 62 | 79 |
| Cl | 197 | 75 | – | – | 2 | 7 | – | – |
| Ga | 15 | 17 | 19 | 9 | 24 | 21 | 17 | 16 |

recrystallization of micas and feldspars (Searle and Malpas, 1982). The great variations in these alkali elements in most of the analysed samples indicate that they have clearly been mobilised to a large degree during metamorphism of the garnet amphibolite (Sungai Pungulupi metabasites).

Rare earth elements (Nd, Y), high field strength (HFS) elements (NB, Ti, P, Zr) and compatible elements (Cr, Ni, V) are thought to be relatively immobile during alteration and/or metamorphism and thus probably reflect primary igneous abundances (Pearce and Cann, 1973; Pearce, 1975; Pearce and Norry, 1979; Pearce, 1980; Pearce *et al.*, 1984). These diagrams have been used to determine the tectonic affinity of the Sungai Pungulupi metabasites. Various plots of Cr, Y, Ti and Zr (Fig. 10) reveal that EKf and EKc metabasites have similar chemical characteristic of ratios of these elements to MORB, LREE, LIL- and HFS-elements concentrations are relatively low in the analysed samples compared to the garnet amphibolite from Mowomba Metamorphic Sole and Peleru Mélange (Table 1), reflecting that these rocks are more depleted in incompatible elements. However, concentrations of incompatible elements in Sungai Pungulupi metabasites are relatively high compared to the cumulate ultramafic and mantle sequence rocks. This suggests that the abundances of incompatible element in the Sungai Pungulupi metabasites within the range between the mantle sequence rocks and the granulite/amphibolite grade of the basal peridotite and the metamorphic sole.

The abundances of compatible element (Ni, Cr, V, Sc) in Sungai Pungulupi metabasites are close to the cumulate ultramafic and mantle sequence rocks, and relative high in comparison to the garnet amphibolite from Mowomba Metamorphic Sole and Peleru Mélange, suggesting that the rocks probably represent transition mafic rocks which lie between the basal periodotite and the metamorphic sole. Generally, the trace elements abundance in Sungai Pungulupi metabasites are similar to those in the hornblende garnet metapyroxenites from the Ballantrae Ophiolite, Scotland (Treloar *et al.*, 1980).

## Spider Diagrams

Spider diagram patterns (normalised to chondrite data from Sun *et al.*, 1979) for two samples

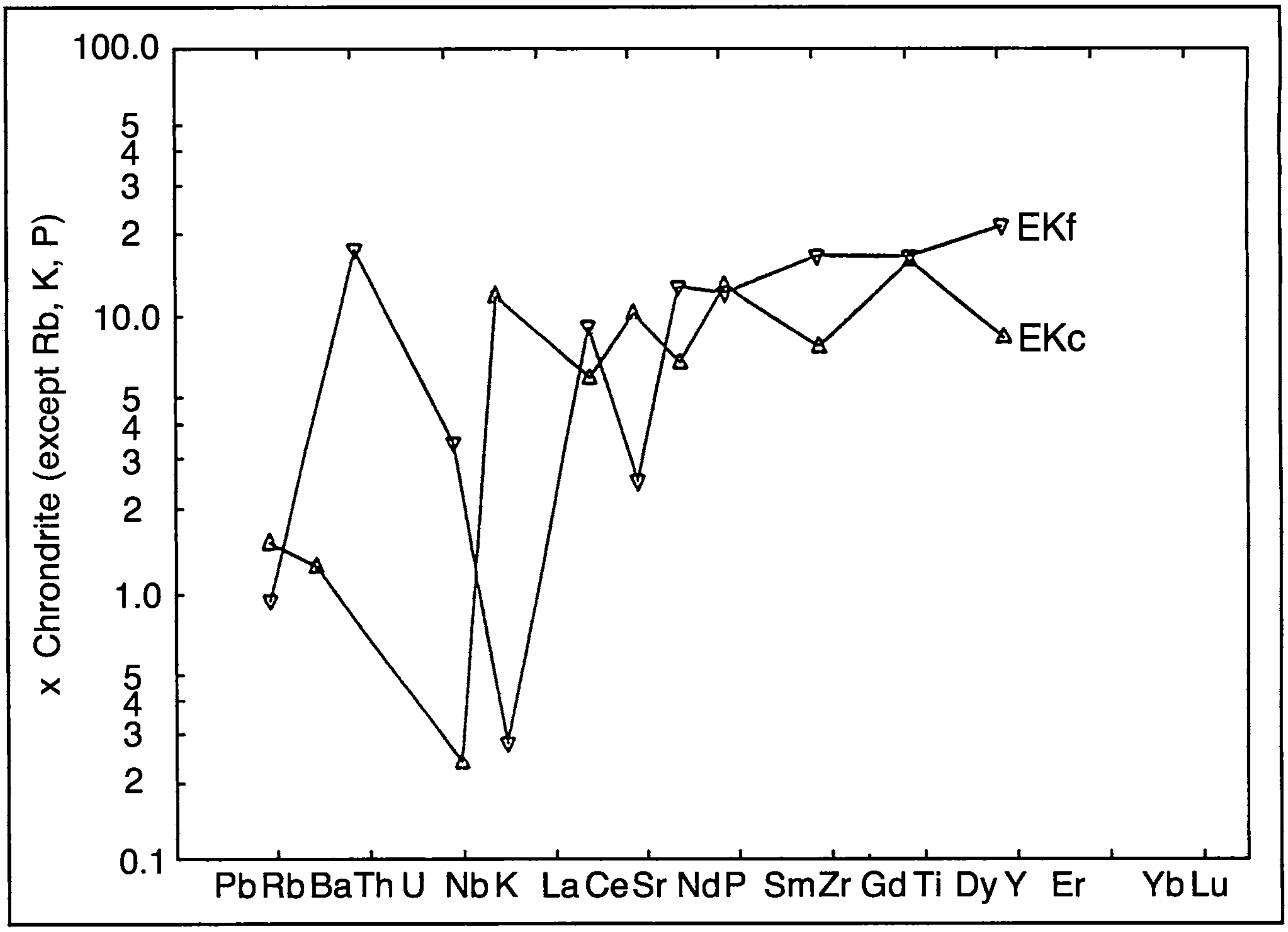


**Figure 10.** Spider diagram of garnet amphibolites from Sungai Pungulupi, Tungku area. Sample/chondrite (except Rb, K, P) normalization and element arrangement are according to Sun (1980).

of garnet amphibolite from Sungai Pungulupi (Sungai Pungulupi metabasites) are presented in Figure 10. Sample EKf (fine grained size) is characterised by a LREE-depleted, a positive Sr and K anomalies and a negative Zr anomaly. Positive LIL-elements (Ba, Rb, K, Ce) anomaly probably due to the enrichment by metamorphic fluids introduced into the samples. Generally, garnet amphibolite is characterised by a relative depletion in LILE, relatively flat HFSE trend (10–20x chondrite, sample EKf) and light REE (La, Ce) depletion (sample EKc), suggesting a MORB deviation (Saunders *et al.*, 1980). Sample EKc is depleted in Nb and enriched in LILE (especially K, Rb, Ba) characteristics of island arc tholeiites (Floyd, 1991). Sample EKf which has depletion in K and enriched in Nd reflects chemical feature of E-MORB and/or alkaline rocks (Sun *et al.*, 1979). However, as stated earlier, abundancies of LILE are subject to considerable modification during metamorphic recrystallisation and the interpretation of an island arc derivation for these rocks should be treated with some caution.

## TECTONIC SETTING

Tectonic discriminant diagrams of Pearce and Cann (1973, 1975), Pearce and Norry (1979), Pearce (1980), Pearce *et al.* (1984) and others have been used to determine the tectonic provenance of the garnet amphibolites stable high field strength (HFS) elements (Zr, Y, Nb, Ti) and compatible elements (Cr, V) were commonly used for this purpose, because these elements are relatively immobile during the alteration and/or low grade metamorphism (Pearce, 1980). Several discriminant plots using these elements are shown in Figure 11. Most of the tectonic discriminant diagrams indicate the analysed garnet amphibolites always fall within MORB/OFB and WPB fields.

## K-AR AGE DATING

One hornblende separated from garnet amphibolite yielded an age of 76 ± 21 Ma (late Early Cretaceous to Early Eocene). The relatively large error ranges because of the abnormally high percentage of atmospheric Ar40 (93%), the large error of age (± 21 Ma) and the relatively low K content (0.03 wt%) suggests that the age for this amphibolite is probably not completely incompatible with other ages. However, at least, this age may represent the age of metamorphism for the garnet amphibolite (Omang, 1993).

## DISCUSSION AND INTERPRETATIONS

### Origin and Significance of the Garnet Amphibolite

As described in previous section, the garnet amphibolite from Tungku area is characterised by porphyroblastic texture. Mylonitic texture can also be seen in the rock. Foliation (S1) in garnet amphibolite is defined by alternating layers of plagioclase and hornblende with clinopyroxene occurs as rounded crystals (light brown/grey) lining up in the foliation. Mineral assemblages are mainly of garnet porphyroblast (almandine) composition + Calcic-pyroxene (Salite) + Calcic amphibole (Pargasitic hornblende) + Sodic-Calcic amphibole + Calcic plagioclase. Mineral chemistry of amphibole indicates that this garnet amphibolite represent high temperature metamorphic and magmatic rocks. Chemistry of clinopyroxene in garnet amphibolite indicates that this rock is derived from igneous protolith of MORB derivation, as indicated by low $Al^{IV}$ and Ti contents (Loucks, 1990). Whole rock trace element geochemistry also suggests the garnet amphibolites were derived from MORB origin. P-T conditions of this rock is similar to that of the basal peridotite of White Hills peridotite, Newfoundland (Jamieson, 1980).

### Correlation with Age of Genesis of Darvel Bay Ophiolite

As stated by Omang (1993), the age of dolerite dykes (*c.* 100 ± 10 Ma) associated with the Darvel Bay Ophiolite is interpreted as the minimum age of the igneous formation of the Darvel Bay Ophiolite. The maximum age of the garnet amphibolite (*c.* 97 Ma) overlaps with the minimum age of the Darvel Bay Ophiolite and the minimum age of the garnet amphibolite (*c.* 55 Ma) is almost similar to the maximum age of the older clastic sediments deposited in the Crocker basin in Sabah (Tongkul, 1991). If these garnet amphibolites (Tungku metabasite) are related to the emplacement of the Darvel Bay Ophiolite, this means that the garnet amphibolite was formed less than 5 Ma year after the formation of the Darvel Bay Ophiolite. An age difference within 5 Ma year for the formation of a metamorphic sole beneath an ophiolite complex is commonly found (Spray, 1984; Parkinson, 1991).

### Tectonic Significance of the Garnet Amphibolite

Metamorphic mineral assemblages, metamorphic texture/fabrics, whole-rock geochemistry, PT-conditions and probably the K-

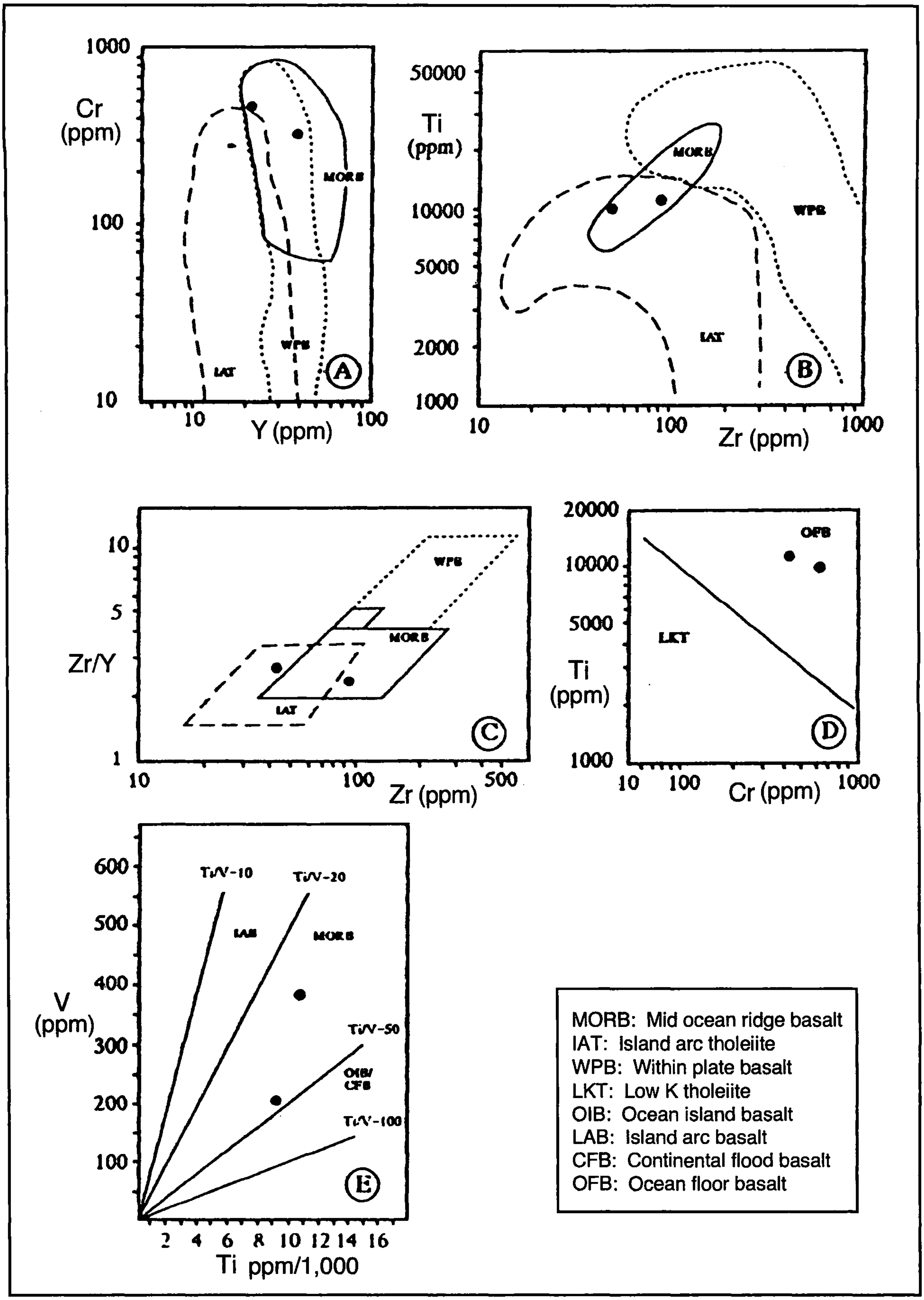


**Figure 11.** Tectonic discriminant diagrams of the Tungku garnet amphibolite. (A) Y-Cr diagram of Pearce *et al.* (1984); (B) Zr-Ti diagram of Pearce (1980); (C) Zr-Zr/Y diagram of Pearce and Norry (1979); (D) Cr-Ti diagram of Pearce (1975); (E) Ti/1000-V diagram of Shervais (1982).

Ar age dating indicate the garnet amphibolite represents the transition zone rocks between the basal peridotite and metamorphic sole. Thus, it suggested that the occurrence of the garnet amphibolites (Tungku metabasites) must be related to the early stage emplacement of the Darvel Bay Ophiolite which probably took place during Late Cretaceous time. The occurrence of the Tungku metabasites (metapyroxenite and garnet amphibolite pebbles) in the Sungai Pungulupi, Tungku area provide a record for the formation of the basal mylonitized peridotite and metamorphic soles in Sabah, relating to the subducted and/or obducted Mesozoic oceanic lithosphere of the Proto South China Sea.

## CONCLUSIONS

The main conclusions are:

1. Garnet amphibolite pebbles in the Sungai Pungulupi, Tungku area are considered to form part of a metamorphic sole relating to the early emplacement of the Darvel Bay Ophiolite Complex.
2. K-Ar age dating on a single sample of this rock yielded an age of 76 ± 21 Ma (late Early Cretaceous to Early Eocene). This age probably reflects the cooling age of the rock and probably represents the earlier stage for the Darvel Bay Ophiolite emplacement.

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