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P-T Evolution of Eclogites and Blueschists from the Luk Ulo Complex of Central Java, Indonesia

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Abstract

Rocks of the Lok Ulo Complex crop out over a small area in the vicinity of Karangsambung in central Java. They are part of a belt of Cretaceous accretionary-collision complexes that appear sporadically in an arc extending from Java to Kalimantan and Sulawesi. The complex consists of dismembered ophiolites, sedimentary rocks, and crystalline schists and gneisses occurring as tectonic slabs in a black-shale matrix tectonic mélange. High-pressure rocks such as eclogite, glaucophane rock and blueschist crop out in a thin zone between the low-grade schists and a serpentinite zone along the Muncar and Gua rivers. Some of the eclogite blocks contain tourmaline, which is restricted to the outer shells of—and veins in—such blocks.

The early metamorphic stage (stage I) of the Lok Ulo eclogites comprises garnet (core) and omphacite + Ca-Na amphibole + phengite + rutile + epidote inclusions in the garnet core. Stage II is characterized by garnet (rims of porphyroblasts) + omphacite + rutile + phengite + Ca-Na amphibole. The matrix constituents, which are similar to those of stages I and II, are related to stage III (late or “peak” eclogitic stage). The blueschist overprint of the eclogites occurred during stage IV. The corresponding assemblage is Na amphibole + chlorite + albite + epidote + quartz + titanite + ilmenite. Subsequently, poikiloblastic tourmaline and apatite grew at the expense of chlorite, epidote, and other minerals in some eclogites (stage V).

The P-T path of tourmaline-bearing eclogites is characterized by rising pressures at decreasing temperatures (stage I to stage III: $P = 22.5$ kbar and $T = 365^{\circ}\text{C}$), whereas the normal eclogites show rising temperatures at increasing pressure (stage III: $P = 20.5$ kbar and $T = 410^{\circ}\text{C}$). Thus, these eclogites were subducted to ~70 km depth at a geothermal gradient of ~6 $^{\circ}\text{C}/\text{km}$. Stage IV is limited to the P-T range of 8–10 kbar and 350–400 $^{\circ}\text{C}$ for both eclogite types. The different P-T paths (counterclockwise and clockwise) are explained by metamorphism within a subduction channel. The low geothermal gradient is probably due to a high rate of subduction of a cold oceanic plate.

Introduction

THE CENTRAL INDONESIAN region consists mainly of young, arc-related volcanic rocks, but pre-Tertiary

accretionary complexes, continental fragments, and ophiolite massifs occur as well. All these rocks are the result of collisional processes between the Asian, Australian, and Pacific plates from the Cretaceous to the present (e.g., Wakita, 2000). The present suture between these plates is located

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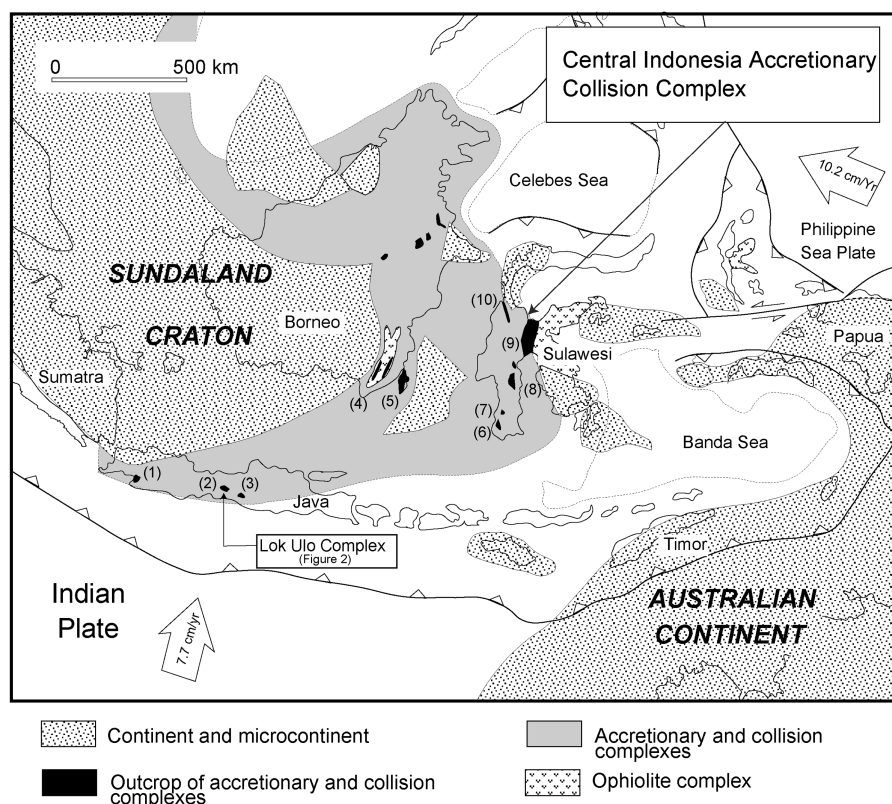


FIG. 1. Distribution of Cretaceous accretionary-collision complexes in central Indonesia. Cretaceous accretionary-collision complexes occur along the eastern and southern margin of Sundaland or between Sundaland and various microcontinents (Paternoster, Buton, etc.). Complexes: 1 = Ciletuh; 2 = Karangsambung; 3 = Jiwo Hills; 4 = Meratus; 5 = Pulau Laut; 6 = Bantimala; 7 = Barru; 8 = Latimojong; 9 = Pompango; 10 = Palu (modified from Metcalf, 1990; Wakita, 2000).

between the southern margin of the Sundaland craton (Asian plate) and the northern and northeastern margins of the Australian craton (Fig. 1).

Cretaceous accretionary-collisional complexes in central Indonesia are distributed sporadically in an arc extending from southwest and central Java, to southeast and east Kalimantan and southern and central Sulawesi. Before the opening of Makassar strait, these complexes may have constituted a common belt (Hamilton, 1979).

One of the major outcrops of the Cretaceous accretionary-collisional complexes is the 50 km² Luk Ulo Complex (Asikin, 1974; Ketner et al., 1976; Suparka, 1988; Wakita et al., 1991, 1994) in central Java (Fig. 1). This complex is exposed around the village of Karangsambung (Fig. 2), involving an assemblage of E-W-trending tectonic

blocks which occur as tectonic slabs in a black-shale matrix mélangé (Asikin, 1974; Ketner et al., 1976). The slabs are composed of a chaotic mixture of dismembered ophiolite, volcanic rocks, sedimentary rocks, high-pressure (HP) metamorphic rocks, as well as ordinary crystalline schists and gneisses. The depositional ages of the cherts range from Jurassic to Late Cretaceous (Wakita et al., 1994). Five K-Ar ages, ranging from 110 to 124 Ma (Ketner et al., 1976; Miyazaki et al., 1998; Parkinson et al., 1998), were obtained from micas of the ordinary schists.

The presence of metamorphic rocks in the Luk Ulo Complex, including eclogites and blueschists, has been known for more than half a century. Surprisingly, no detailed studies have been undertaken on these rocks except the one on a jadeite-

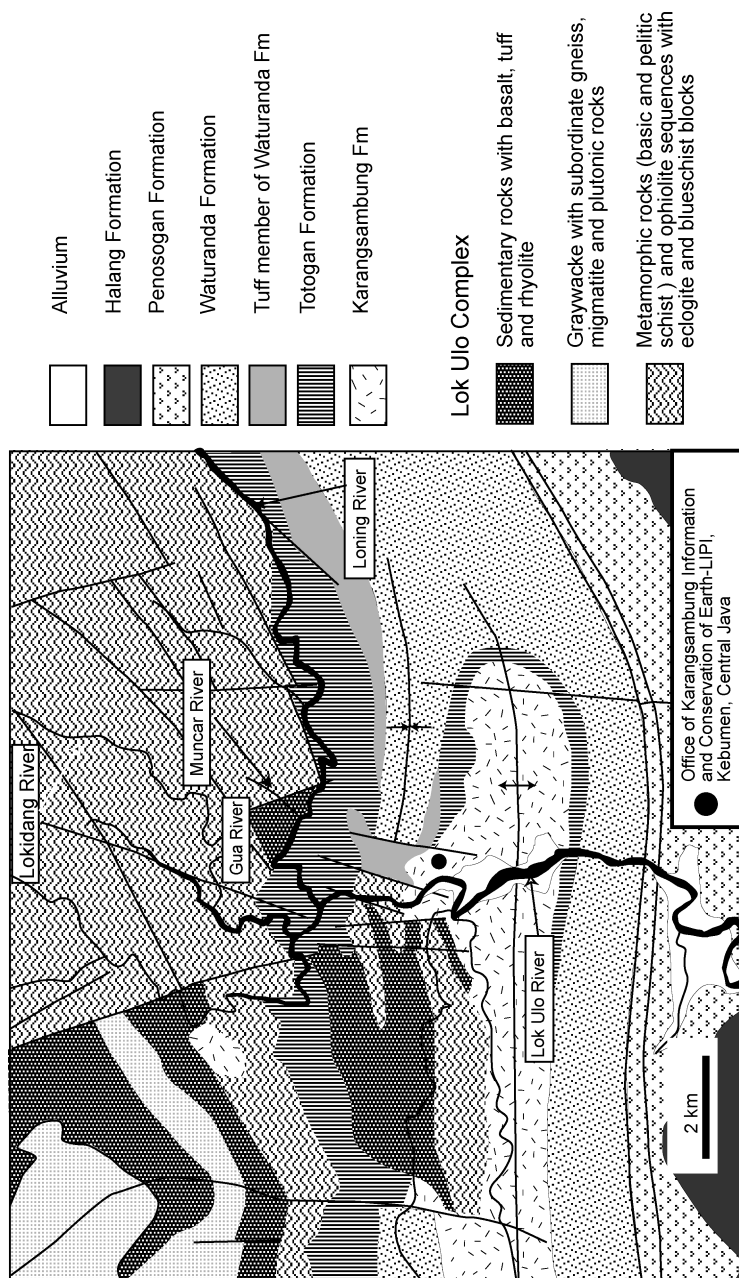


FIG. 2. Geological map of the Karangsambung area (modified after Asikin et al., 1992 with additional data taken from Wakita et al., 1994). The Muncar and Gua rivers are located along a fault zone separating sedimentary blocks, metamorphic rocks, and ophiolite sequences.

glaucophane rock by Miyazaki et al. (1998). In addition, general studies of HP metamorphic rocks from the Lok Ulo Complex were recently presented by Parkinson et al. (1998) and Kadarusman et al. (2005a).

Our detailed petrological study is aimed at deciphering the P-T evolution of eclogites and blueschists in this complex. Such studies can provide important constraints for the tectonic processes of oceanic and/or continental subduction along the plate boundaries of Asia and Australia in the past. Since the discovery of coesite-bearing eclogites from the Bantimala Complex of south Sulawesi by Parkinson and Katayama (1999) and the presence of very deep mantle rocks from the Palu region of central Sulawesi (Kadarusman and Parkinson, 2000), the Central Indonesia Accretionary-Collision Complex (CIACC) has been recognized as one of the world's rare ultrahigh-pressure (UHP) terranes (Liou et al., 2002). However, the relationships among the HP and UHP rocks from the Indonesian region remain unclear. This study will also contribute to the understanding of the relationships of HP rocks from the Lok Ulo Complex and those from other portions of the CIACC.

Geological Setting and Sample Localities

The geology of the Karangsambung area is characterized by the Lok Ulo Complex, which is unconformably overlain by volcanic and sedimentary rocks of the Eocene Karangsambung Formation (Asikin et al., 1992). The rocks of this formation and of Tertiary sequences, subdivided into the Totogan, Waturanda, Penosogan, and Halang formations in ascending order (Fig. 2), are gently folded with an E-W-trending vertical axial plane. The tectonic relationships among the blocks (or slabs) of the Lok Ulo Complex are unclear. Their long axes trend ENE-WSW, parallel to the strike of the Waturanda and Totogan formations (Fig. 2). Large tectonic blocks, consisting of dismembered ophiolites (Suparka, 1988), are distributed in the central part of the terrane (Fig. 2). The best outcrops of these rocks, which are associated with HP metamorphic rocks, are along the Muncar River (Figs. 3B and 3C). In addition, ocean-floor or hydrothermal metamorphism of a succession of basalt, serpentinite, chert, and red limestone took place. These rocks are common constituents of the dismembered ophiolite. Previous petrological studies only concerned HP rock types showing mineral assemblages with jade-

ite and lawsonite (Miyazaki et al., 1998; Parkinson et al., 1998). However, a recent study by Kadarusman et al. (2005a) confirmed that the metamorphic rocks from Lok Ulo Complex not only consist of HP metamorphic rocks but also of very low to low-grade as well as medium-grade low-pressure metabasites and metapelites. Amphibolite-facies schists (predominantly garnet-mica schists) are tectonically intercalated within sediments of larger tectonic blocks (Fig. 3B), whereas small amounts of greenschist, blueschist, garnet amphibolite, eclogite, and glaucophane rock occur as small tectonic blocks in sheared serpentinite along fault zones as discernible by outcrops in the Muncar and Gua rivers. The Lok Ulo Complex may also include continental material from deeper crustal levels found as loose blocks along the Lok-Ulo, Loning and Lokidang rivers. This material consists of metamorphosed coarse-grained pelitic, calc-silicate, and granitic rocks (gneisses, migmatite, quartzites, marbles, felsic granulites) as well as minor bimodal metavolcanics.

We collected samples from loose blocks of eclogite, glaucophane rock, blueschist, greenschist, and amphibolite occurring close to serpentinite and ophiolitic rocks along the Muncar and Gua rivers. We infer that these blocks were once included within the serpentinite. The blocks range in size from 30 cm up to 5 m. In the Muncar River, eclogite blocks are dominant over blocks of blueschist and glaucophane rock; however, in the Gua River it is vice versa.

Petrography of the Samples

The collected HP metabasic rocks were divided into four groups: (1) tourmaline-bearing eclogite (TEC); (2) normal eclogite without tourmaline (EC); (3) glaucophane rock (GR); and (4) blueschist (BS). In the TEC samples KM01, KM10, and KM13B, garnet, omphacite, tourmaline and phengite occur as 1 to 5 mm-sized porphyroblasts (Figs. 4A, 4C, and 5A). The matrix consists of fine-grained omphacite, phengite, bluish amphibole, rutile, titanite, chlorite, epidote, apatite, and accessory ilmenite, albite, and calcite. The modal content of collected TEC is 3–5% garnet, 10–15% clinopyroxene, 10–15% Na-Ca amphibole, 1% rutile, 3–5% phengite, 5–15% chlorite, 3–7% titanite, and 2–5% epidote. Phengite, apatite, quartz, Na amphibole, titanite, and rutile occur as inclusion in garnet. Mineral inclusions in tourmaline are Na-Ca and Na amphibole, epidote, apatite, rutile, titanite, phengite,

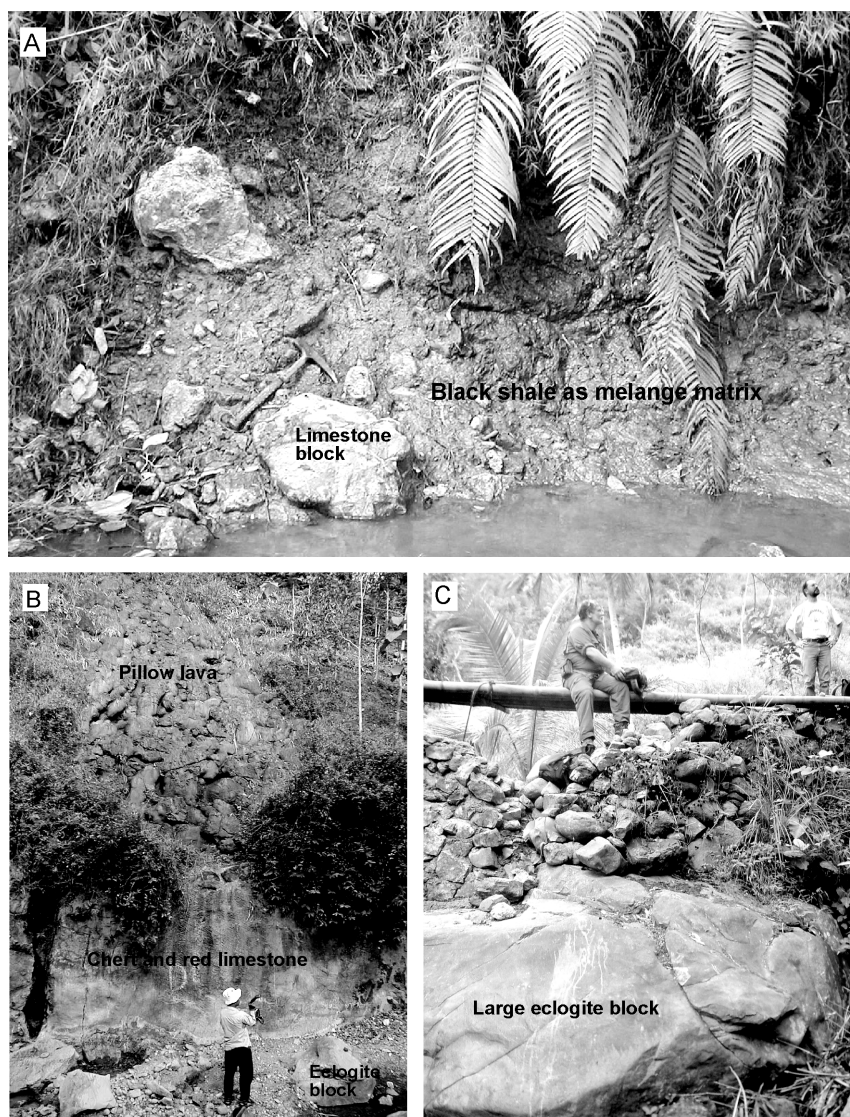


FIG. 3. Field photographs in the Lok Ulo complex. A. Sedimentary rocks as blocks embedded in black shale mélangé matrix; location: Lok Ulo River. B. Loose block of eclogite in front of a block of pillow lava associated with chert and red limestone, Muncar River. C. Large eclogite block in the Muncar River.

chlorite, calcite, fine-grained garnet, and ilmenite (Table 1 and Figs. 4A and 4B).

The mineral composition of the most of EC samples is very similar. However, generally they show two compositionally and texturally different domains. One group of EC samples (KM04, KM17, KSACI, M3A, M3C, M2G) shows garnet, omphacite, phengite, and Na-Ca amphibole as porphyroblasts

(> 0.5 mm; Figs. 4D and 5B). The matrix consists of these minerals, and additionally of chlorite, rutile, titanite, Na amphibole, paragonite, epidote, and accessories of quartz and ilmenite. The difference of grains sizes between porphyroblasts and minerals of the matrix are gradational. The modal content is 10–25% garnet, 10–15% omphacite, 15–30% Na-Ca amphibole, 3–10% white mica (phengite/paragonite),

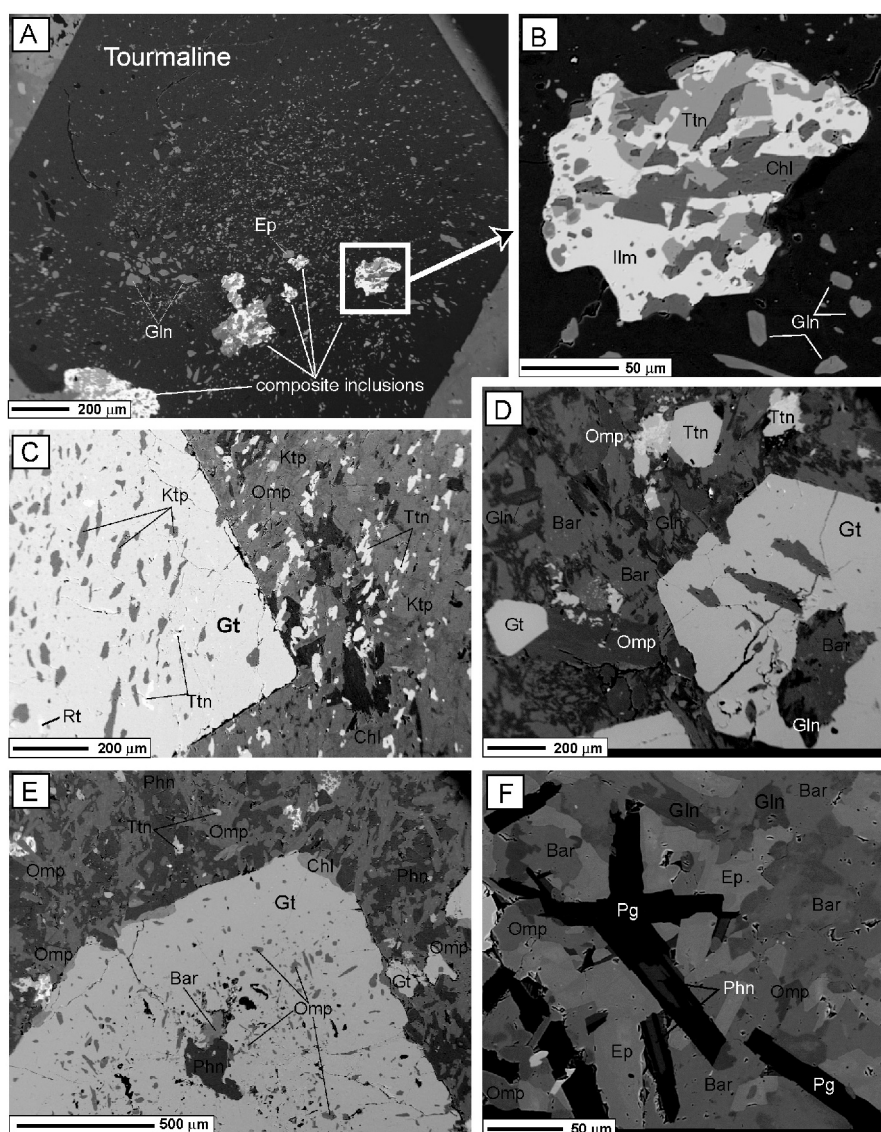


FIG. 4. Backscattered electron images displaying some of the textural characteristics of TEC (A, B, C) and EC (D, E, F) samples. A. Anhedral glaucophane (Gln), epidote (Ep), and composite minerals included in tourmaline (KM13B). B. A composite inclusion consisting of titanite (Ttn), chlorite (Chl), and ilmenite (Ilm). C. Garnet (Gt) porphyroblast with glaucophane, rutile (Rt), and titanite as inclusions. The matrix consists of the stage III assemblage omphacite (Omp), katiophorite (Ktp) and titanite (KM01). D. Eclogite containing garnet, omphacite, barrosite (Bar) as stage II constituents. Barrosite is rimmed by glaucophane as stage IV mineral (KM04). E. Eclogite with garnet porphyroblasts, which contain abundant inclusions of phengite, omphacite, and barrosite. The garnet is embedded in a matrix composed of fine-grained garnet, omphacite, phengite (Phn), and rutile rimmed by titanite (KM11). F. Stage III-IV assemblage showing phengite rimmed by paragonite (Pg), and barrosite replaced by glaucophane (KM17).

2–5% chlorite, 3–5% titanite, 1–5% rutile, 3–5% epidote, 1% quartz, and 1% ilmenite. Omphacite, phengite, barrosite, epidote, Na amphibole, and

rutile are also present as inclusion in garnet. Figure 4D is a backscattered electron (BSE) image of KM17 showing barrosite transformed to glaucophane.

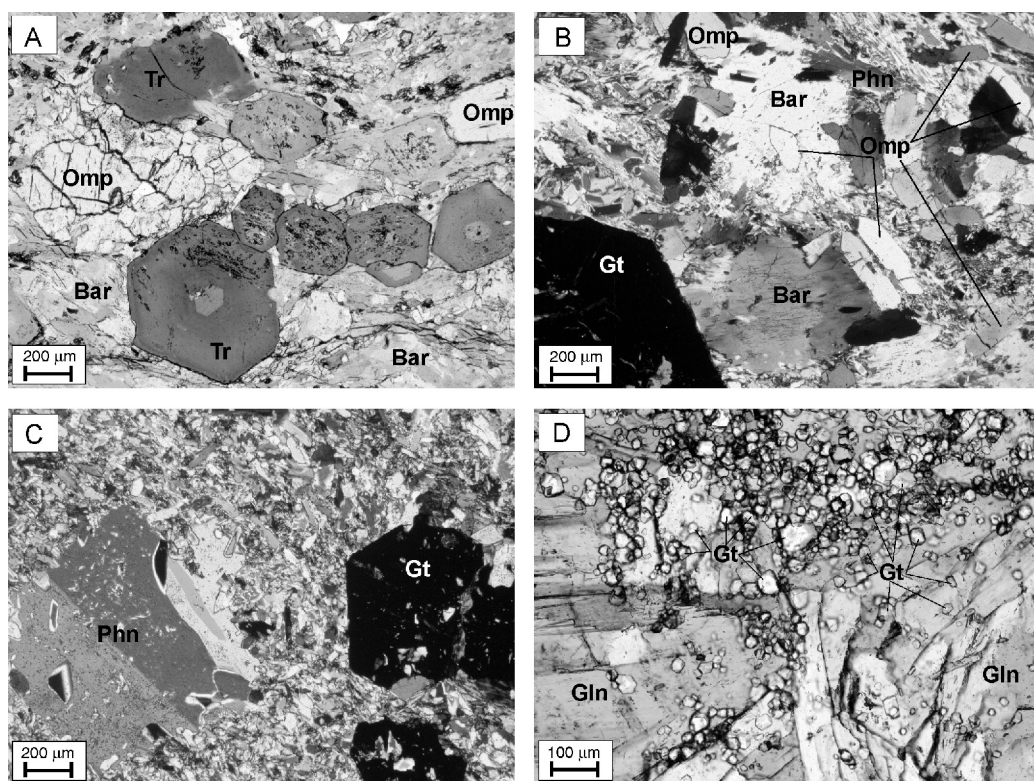


FIG. 5. Photomicrographs (plane-polarized light) of HP rocks from the Lok Ulo Complex. A. Tourmaline with blue core and dark rim grown at the expense of secondary chlorite, resulting from retrogression of garnet and barroisite (KM10). B. Barroisite grown as prophyroblast after garnet and omphacite (M3A). C. Garnet and phengite porphyroblasts. Phengite was corroded by matrix minerals (M3A). D. Large grain of glaucophane enclosing garnet (KM06).

The other group of EC samples (KM11, KM12, M1, M3D) contains only garnet and omphacite as porphyroblast (> 1 mm; Figs. 4E and 5C). The matrix consists of fine-grained (< 0.2 mm) omphacite, garnet, phengite, amphibole, rutile, titanite, epidote, chlorite, and accessories of ilmenite and albite. The modal content is 5–20% garnet, 5–15% omphacite, 3–15% phengite, and 20–35% amphibole, 5–10% chlorite, 3–7% titanite, 1–3% rutile, and 2–5% epidote (Table 1). Omphacite, phengite, amphibole, and rutile occur as inclusions in garnet.

GR samples (KM02 and KM08) contain glaucophane (up to 55%), clinopyroxene (3–5%), phengite (5–7%), epidote (1–3%), chlorite (3–5%), albite (1–3%), titanite, rutile, and ilmenite (total 5%). The constituents of the BS sample KM07 (Fig. 5D) are Na-Ca amphibole (60%), garnet (15%), chlorite (15%), epidote (5%), albite (3%), rutile, and titanite (2%). The amphiboles can be significantly larger

(2–3 mm) than garnet grains (0.3–0.03 mm; Fig. 5D). In the BS sample, epidote is coarse grained (0.5–3.0 mm), whereas in EC and TEC rocks most epidote is fine grained.

EC and TEC blocks are heterogeneous and mineralogically zoned due to retrogression. Outer portions of the blocks contain abundant chlorite, albite, and rare tourmaline as late-stage phases. The presence of compositionally different garnet, clinopyroxene, and amphibole (see the section on Mineral Chemistry) composition in a single rock indicates that the metamorphic overprint at a specific stage was variable. Such rocks also display a complex texture generated during multi-stage metamorphic evolution. We have tried to distinguish these stages and propose here a five stage metamorphic history for the Karangsambung eclogites (Fig. 6).

The mineral assemblage of the early metamorphic stage (stage I = earliest recognizable stage) in

TABLE 1. Mineral Assemblages of Eclogite, Glaucophane Rock, and Blueschist¹

Sample no.	Rock type	Gt	Omp	Ac-		Rt	Qtz	Phn	Prg	Gln	Bar	Ktp	Ab	Chl	Ilm	Ep	Ttn	Ap	Tr
				Au															
KM04	EC	x	x			x		x		x	x			x		x	x		
KM17	EC	x	x			x		x	x	x	x			x		x	x		
KSACI	EC	x	x			x		x			x			x		x	x		
M2G	EC	x	x			x		x			x			x		x	x		
M3A	EC	x	x			x	x	x	x	x	x		x	x		x	x		
M3C	EC	x	x			x		x	x	x	x			x		x	x		
KM11	EC	x	x			x		x			x			x	x		x		
KM12	EC	x	x					x			x	x		x	x		x		
M1	EC	x	x			x		x			x	x		x		x	x		
M3D	EC	x	x			x		x		x	x		x	x			x		
KM01	TEC	x	x	x		x		x				x		x			x	x	x
KM10	TEC	x	x	x		x		x		x		x	x	x			x	x	x
KM13B	TEC	x	x	x								x	x	x	x	x	x	x	x
KM08	GR			x		x		x		x			x	x		x	x		
KM02	GR							x		x		x	x	x	x	x	x	x	
KM07	BS	x				x					x		x	x		x			

¹EC = eclogite; TEC = tourmaline-bearing eclogite; GR = glaucophane rock; BS = blueschist. Mineral abbreviations after Kretz (1973), where available: Ac-Au = aegirine-augite; Phn = phengite; Bar = barroisite; Ktp = katophorite; Tr = tourmaline; Ap = apatite.

our eclogite samples comprises garnet (core) and inclusions in the garnet core, which are omphacite + Ca-Na amphibole + phengite + rutile + epidote + quartz. Stage II, probably representing “near” peak metamorphism, is characterized by the assemblage garnet + omphacite + rutile + phengite + Ca-Na amphibole. These minerals occur as porphyroblasts (actually paleoblasts). The matrix was formed by recrystallization after a deformation event. Thus, matrix constituents are related to stage III (late eclogite stage). These phases are garnet + omphacite + Ca-Na amphibole + phengite + epidote + rutile. The textural difference, related to stage II and III, is not everywhere well developed, inasmuch as in a few eclogites the grain size distribution did not allow a distinction between porphyroblasts and matrix. During stage IV (blueschist overprint), titanite ($\pm$ ilmenite) replaced rutile (forming rinds around rutile), and chlorite formed at the expense of garnet along margins and fractures. Na amphiboles

replaced Ca-Na amphibole. Albite + quartz + epidote pseudomorphs formed after omphacite. These alterations are due to infiltration of aqueous fluids. Subsequently, poikiloblastic tourmaline and apatite grew at the expense of chlorite, epidote, and other minerals (stage V). Based on the distribution of inclusion minerals in the core and rim of tourmaline (see Fig. 6; core: garnet, rutile, phengite, Ca-Na amphibole; as stage III constituents; rim: Na and Ca-Na-amphibole, titanite, chlorite, ilmenite, epidote, and apatite), it may have started to grow after stage III (throughout stage IV). The final growth occurred during stage V.

Mineral Chemistry

The compositions of minerals in our samples were analyzed using a Cameca SX100 electron microprobe with five wavelength-dispersive spectrometers to determine the concentrations of Na, Mg,

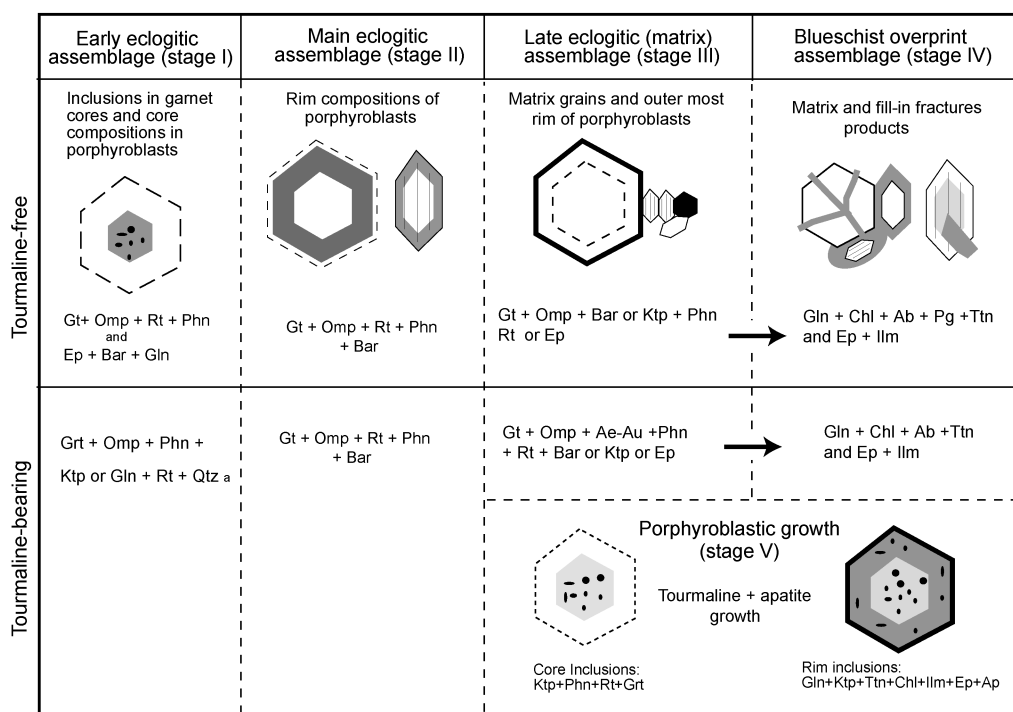


FIG. 6. Five metamorphic stages for EC and TEC samples (in rows) depicted as columns.

Al, Si, K, Ca, Ti, Cr, Mn, Ni, Fe, and Ba. The applied acceleration voltage and electric current were 15 kV and 15 nA, respectively. Beam diameter was about 6 μm , but also 3 μm in the case of small minerals. Counting times for full analyses were 20 s on peak and background each. The PaP correction procedure provided by Cameca was applied. Concentration maps for major elements were prepared by step-wise movement (100 or 200 ms per step) of the thin section under the electron beam of the microprobe and subsequent computer aided evaluation. The energy-dispersive system of the microprobe served as mean of identification of phases during the selection of spots for full analyses.

Garnet

Garnet cores (stage I) in EC samples KSACI, KM04, KM17, M2G, M3D, M3A, and M3C are characterized by contents of 5–13 mol% pyrope, 50.5–61 mol% almandine, 25–31 mol% grossular, and 0.7–14.5 mol% spessartine. Rims of these garnets (stage II) contain 6.5–13 mol% pyrope component, 57.5–61 mol% almandine, 26.5–30 mol% grossular, and 0.1–5 mol% spessartine (Fig. 7A). The apparent

overlap of core and rim compositions is due to a wide range of bulk compositions of the several samples considered. Within a single sample, core and rim compositions are well distinguished, especially on the basis of Mn contents. Most EC and TEC garnets display prograde and retrograde compositional zoning from core to rim, with Mn decreasing from the inner to the outer mantle (bell-shaped Mn-profile, Fig. 7B) and then increase slightly to the outermost rim. The Fe^{2+} contents increase toward the rim, whereas Ca contents show the opposite trend.

Two EC samples (KM11 and KM12) show garnets with higher almandine contents (54–71 mol%), but lower grossular contents (20–29 mol%) than the other EC samples. The composition of EC garnets is different from those in TEC and GR samples (i.e., TEC stage II: pyrope 8–12 mol%, almandine 36–53 mol%, grossular 24–35.5 mol%, and spessartine 10.5–20.5 mol%; BS: pyrope 0.9–3.7 mol%, almandine 25–41.5 mol%, grossular 22–29.5 mol%, and spessartine 30.5–58.5 mol%). In TEC, fine-grained garnet (stage III) preserved in tourmaline contained 2.5–2.8 mol% pyrope, 52–62 mol% almandine, 25–

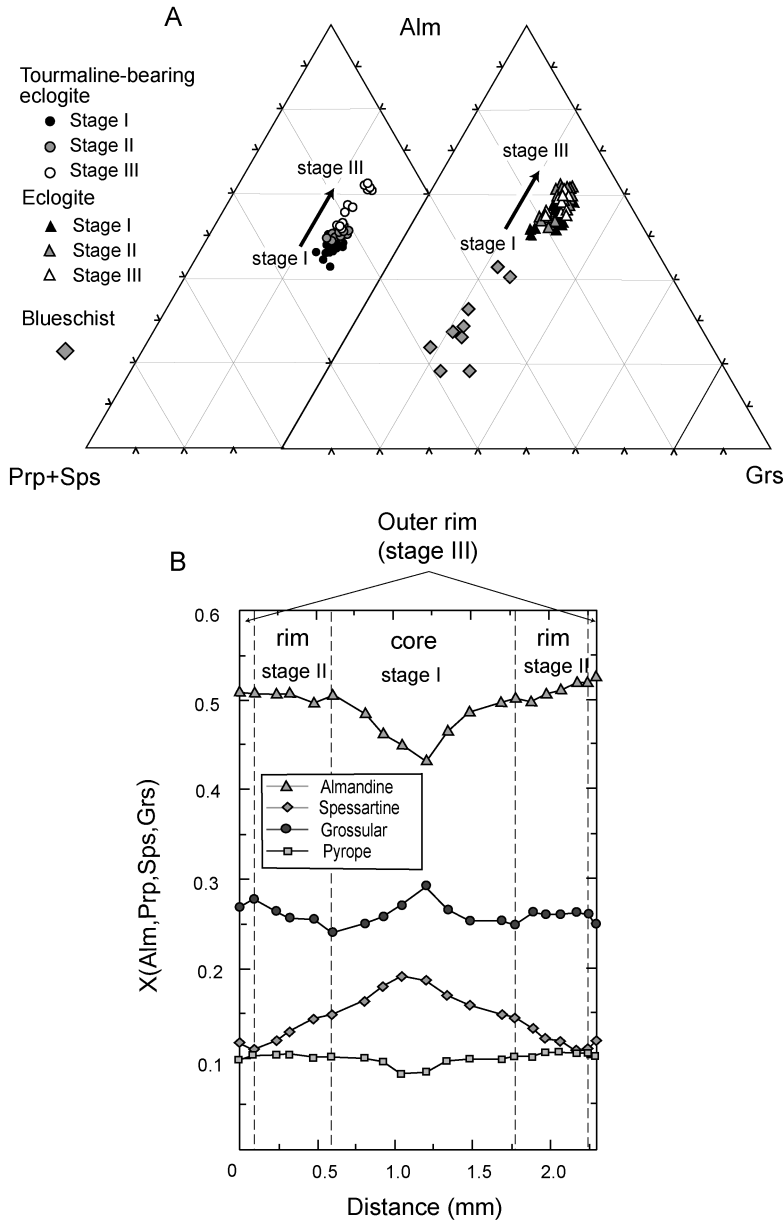


FIG. 7. A. Almandine (Alm)-grossular (Grs)-pyrope+spessartine (Prp+Sps) ternary diagrams of garnet from EC, TEC, and BS samples from the Lok Ulo Complex. B. Zoning profile of garnet from TEC sample KM10. The zonation is characterized by decrease of the spessartine component and increase of the almandine component from core to rim.

28 mol% grossular, and 5–17.5 mol% spessartine. Thus, the almandine contents increase from stage II to stage III. The same was observed for EC garnets (stage III: pyrope 6–12 mol%, almandine 55.5–59

mol%, grossular 28.5–30.5 mol%, and spessartine 1.2–7.8 mol%). The compositions of outermost rims of garnet are similar to fine-grained garnets. Representative analyses of garnet are given in Table 2.

TABLE 2. Representative Analyses of Garnet Recalculated to Structural Formula and Molar Fractions¹

Sample no.:	KM10	KM10	KM10	KSACI	KSACI	KSACI	KM12	KM12	KM12	KM06
Rock name:	TEC	TEC	TEC	EC	EC	EC	EC	EC	EC	BS
Point no.:	#9	#2	#27	#55	#56	#86	#3	#2	#25	#60
Location:	Core	Rim	Outer rim	Core	Rim	Outer rim	Core	Rim	Outer rim	Core
Stage:	I	II	III	I	II	III	I	II	III	IV
SiO ₂	37.56	37.67	37.66	37.92	38.26	37.94	37.40	37.36	38.14	37.08
TiO ₂	0.22	0.14	0.16	0.09	0.11	0.10	0.26	0.17	0.20	0.27
Al ₂ O ₃	20.90	21.15	21.05	21.61	21.68	21.67	20.88	20.87	20.92	19.67
Cr ₂ O ₃	0.03	0.01	0.03	0.00	0.01	0.00	0.02	0.02	0.02	0.02
FeO	21.71	24.62	24.48	27.77	27.50	28.40	24.38	27.40	31.03	9.89
MnO	9.17	4.86	4.99	2.08	0.47	0.17	7.14	2.76	0.34	25.85
MgO	2.16	2.69	2.70	1.80	2.56	2.99	0.87	1.28	1.73	0.22
CaO	9.32	10.03	9.45	10.53	10.52	9.80	9.61	10.34	8.84	8.23
Na ₂ O	0.06	0.04	0.06	0.02	0.06	0.00	0.05	0.04	0.03	0.01
Total	101.11	101.20	100.56	101.82	101.16	101.07	100.62	100.25	101.26	101.24
Si	5.879	5.853	5.894	5.884	5.887	5.928	5.960	5.937	6.052	5.931
Ti	0.026	0.016	0.019	0.011	0.013	0.011	0.031	0.021	0.024	0.033
Al	3.856	3.873	3.882	3.951	3.931	3.991	3.921	3.908	3.912	3.708
Cr	0.003	0.001	0.004	0.000	0.001	0.000	0.002	0.003	0.003	0.002
Fe ³⁺	0.141	0.126	0.114	0.049	0.068	0.131	0.077	0.089	0.086	0.290
Fe ²⁺	2.701	3.055	3.108	3.554	3.599	3.579	3.172	3.552	4.032	1.033
Mg	0.503	0.624	0.629	0.417	0.586	0.696	0.206	0.304	0.410	0.051
Ca	1.563	1.669	1.584	1.751	1.734	1.640	1.641	1.760	1.503	1.411
Mn	1.216	0.639	0.661	0.273	0.062	0.023	0.964	0.372	0.046	3.502
Na	0.018	0.013	0.018	0.005	0.019	0.001	0.017	0.012	0.008	0.002
Grossular	0.2724	0.2782	0.2640	0.2918	0.2891	0.2761	0.2735	0.2934	0.2506	0.2352
Pyrope	0.0838	0.1040	0.1049	0.0696	0.0977	0.1172	0.0344	0.0506	0.0684	0.0086
Amandine	0.4502	0.5091	0.5180	0.5924	0.5998	0.6007	0.5287	0.5920	0.6720	0.1722
Spessartine	0.1916	0.1065	0.1102	0.0455	0.0103	0.0040	0.1606	0.0620	0.0077	0.5837

¹Electron microprobe analyses were recalculated to double formula units considering 10 cations in the six- and eightfold sites. Fe³⁺ = 4-Al-Cr.

Clinopyroxene

Primary clinopyroxenes in the investigated samples are either omphacite or aegirine-augite. Fe³⁺ contents were calculated by normalization to 6 oxygens and four cations. Normalized pyroxene end-member components for presentation in Figure 8 were calculated on the basis of $X_{Jd} = Al^{VI}/(Na+Ca)$, $X_{acm} = Fe^{3+}/(Na+Ca)$, and the $X_{Au} = (Ca)/(Na+Ca)$ (Morimoto et al., 1988). These components show a

strong variation in both EC and TEC. Representative analyses of clinopyroxene are given in Table 3.

X_{Jd} and X_{acm} of EC omphacites (stage II) range between 0.26 and 0.43 (Fig. 8) and 0.04 and 0.23, respectively. X_{Jd} values of omphacite inclusions in garnet (stage I) range from 0.34 to 0.39, and do not vary systematically with respect to their position within the garnet grains. Compositions of omphacite (stage II) in TEC are almost similar to those of EC omphacite except for the somewhat higher aegirine-

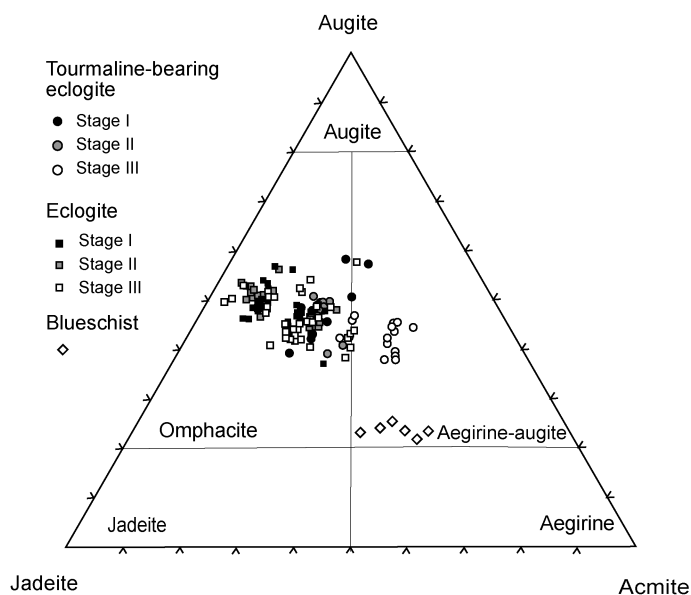


FIG. 8. Chemical composition of clinopyroxene in the jadeite-augite-aegirine triangular diagram. All primary pyroxenes in the eclogites (EC and TEC) fall into the field of omphacite and aegirine-augite, whereas clinopyroxene from GR rock plots in the aegirine-augite field. Diagram after Morimoto et al. (1989).

augite component ($X_{Jd} = 0.17\text{--}0.42$, $X_{Ae} = 0.17\text{--}0.38$). Fine-grained omphacite (stage III) of EC rocks are characterized by X_{Jd} values between 0.20 and 0.46. X_{Ae} values show a wide range in between 0.04 and 0.30. BS clinopyroxene has the composition of aegirine-augite ($X_{Jd} = 0.28\text{--}0.38$; see Fig. 8). A significant difference in composition exists between the core and rim of stage-II omphacite in both EC and TEC samples. In general, this difference is characterized by increasing Na and Al (jadeite component) and decreasing Ca, Mg, and Fe contents from core to rim.

Amphibole

Analyzed amphiboles comprise Na amphiboles (glaucofane) and Na-Ca amphiboles (barroisite-katophorite). The Fe^{3+} and Fe^{2+} contents of these amphiboles were estimated on the assumption $Si + Al + Ti + Cr + Fe + Mn + Mg = 13$ and 23 oxygens in total. Representative analyses of amphiboles are listed in Table 4. The compositional range of amphibole in each rock and stage are depicted in Figure 9, based on the nomenclature of amphiboles by Leake et al. (1997), as a function of Si per formula unit (pfu) versus $X_{Mg} = Mg/(Fe^{2+} + Mg)$.

Na amphiboles from EC samples are glaucophanes that are present as inclusions in garnet

(stage I) and as a late matrix constituent (stage IV). The glaucophanes from both stages are almost identical in composition ($Si = 7.60\text{--}7.88$ pfu, and $X_{Mg} = 0.68\text{--}0.72$, Fig. 9A). Na-Ca amphiboles of EC samples vary from Mg-katophorite to barroisite (Figs. 9B and 9C). Barroisite was present during stages I to III, indicating that this phase was stable during eclogite metamorphism. Mg-katophorite occurred instead of barroisite as a stage III mineral in only a few samples (KM11, KM12 and M1).

Amphiboles from TEC samples are glaucophane (stages I and IV) and Mg-katophorite (stage III). Glaucophane of stage IV shows $X_{Mg} = 0.66\text{--}0.73$ and $Si = 7.69\text{--}7.85$ pfu (almost identical to corresponding EC amphiboles). However, no barroisite was found in the TEC samples.

The analyzed Na-Ca amphiboles from the BS sample are restricted to barroisite in composition (Fig. 9B). In GR samples, both Na amphibole (glaucophane) and Na-Ca amphibole (Mg-katophorite) are present. The latter amphibole was the one that formed earliest. X_{Mg} (0.54–0.63) of GR glaucophane is lower than that of EC and TEC glaucophane. The same is true for Mg-katophorite compared with X_{Mg} in the TEC and EC samples. On the contrary, X_{Mg} of barroisite in the BS sample is higher than this value in the EC barroisite.

TABLE 3. Representative Analyses of Clinopyroxene Recalculated to Structural Formula and Molar Fractions¹

Sample no.:	KM10	KM10	KM10	KSACI	KSACI	KSACI	KM12	KM12	KM12	KM08
Rock name:	TEC	TEC	TEC	EC	EC	EC	EC	EC	EC	BS
Point no.:	#48	#49	#45	#53	#54	#89	#4	#5	#32	#9
Location:	Core	Rim	Outer rim	Core	Rim	Outer rim	Core	Rim	Outer rim	Core
Stage:	I	II	III	I	II	III	I	II	III	
Mineral name:	Aegirine-augite			Omphacite						
SiO ₂	54.81	54.88	55.17	56.21	56.49	55.94	55.08	55.30	55.25	55.50
TiO ₂	0.11	0.08	0.11	0.07	0.07	0.08	0.08	0.08	0.05	0.07
Al ₂ O ₃	9.00	8.34	7.12	10.12	10.03	11.04	9.24	9.22	7.50	7.15
Cr ₂ O ₃	0.00	0.00	0.03	0.01	0.00	0.01	0.03	0.03	0.02	0.02
FeO	8.72	8.86	10.70	5.74	5.38	5.33	9.80	9.49	12.21	16.85
MnO	0.30	0.27	0.21	0.02	0.03	0.00	0.00	0.00	0.06	0.07
MgO	7.45	7.83	7.33	8.51	8.77	8.01	6.19	6.77	6.02	3.72
NiO	0.02	0.00	0.01	0.07	0.00	0.00	0.05	0.04	0.00	0.00
CaO	12.55	12.95	12.27	14.03	14.10	13.27	12.37	12.40	11.18	6.24
Na ₂ O	7.38	7.13	7.65	6.81	6.90	7.35	7.65	7.82	8.24	11.08
K ₂ O	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.01	0.00
Total	100.35	100.35	100.62	101.61	101.77	101.03	100.48	101.16	100.56	100.70
Si	1.959	1.964	1.975	1.972	1.974	1.965	1.974	1.962	1.984	1.985
Ti	0.003	0.002	0.003	0.002	0.002	0.002	0.002	0.002	0.001	0.002
Al	0.379	0.351	0.300	0.418	0.413	0.457	0.390	0.386	0.318	0.301
Cr	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.001	0.001	0.000
Fe ³⁺	0.209	0.211	0.275	0.096	0.102	0.109	0.188	0.224	0.284	0.493
Fe ²⁺	0.051	0.054	0.046	0.072	0.055	0.047	0.105	0.057	0.083	0.011
Mn	0.009	0.008	0.007	0.001	0.001	0.000	0.000	0.000	0.002	0.002
Mg	0.397	0.418	0.391	0.445	0.457	0.419	0.331	0.358	0.323	0.198
Ni	0.000	0.000	0.000	0.002	0.000	0.000	0.002	0.001	0.000	0.000
Ca	0.481	0.497	0.471	0.528	0.528	0.499	0.475	0.471	0.430	0.239
Na	0.512	0.494	0.531	0.463	0.468	0.500	0.532	0.538	0.574	0.768
K	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Diopside	0.3831	0.4022	0.3952	0.4292	0.4492	0.4191	0.3409	0.3739	0.3292	0.2116
Hedenbergite	0.0495	0.0523	0.0461	0.0695	0.0544	0.0474	0.1087	0.0597	0.0844	0.0118
Jadeite	0.2994	0.2816	0.2535	0.3646	0.3638	0.3889	0.3407	0.3108	0.2879	0.2731
Opx	0.0077	0.0088	0.0000	0.0092	0.0043	0.0001	0.0000	0.0000	0.0000	0.0000
Tschermakite	0.0383	0.0338	0.0220	0.0260	0.0238	0.0329	0.0237	0.0363	0.0141	0.0133
Rest	0.2220	0.2213	0.2858	0.1015	0.1045	0.1116	0.1927	0.2286	0.2888	0.4974

¹Electron microprobe analyses were recalculated to a structural formula based on four cations and 12 valencies. The molar fraction of the six components were computed according to Massonne (1992).

Phengite and paragonite

Micas are present in all studied samples. Paragonite commonly coexists with phengite. The latter

phase might have crystallized earlier than paragonite because phengite occurs enclosed in garnet cores and in paragonite (Fig. 4F). Representative

TABLE 4. Representative Analyses of Amphiboles¹

Sample no.:	KM10	KM10	KM10	KM01	KM01	KSACI	KSACI	M2G	M2G	KM12	KM12	KM08	km02	km02	km07
Rock name:	TEC	TEC	TEC	TEC	TEC	EC	EC	EC	EC	EC	EC	GR	GR	GR	BS
Point no.:	#21	#24	#29	#10	#13	#55	#57	#17	#20	#12	#6	#3	#12	#17	#47
Stage:	I	IV	III	III	I	II	III	III	IV	III	II	IV	IV	IV	IV
Mineral name:	Kfp	Gln	Ktp	Ktp	Ktp	Bar	Bar	Bar	Gln	Ktp	Bar	Gln	Gln	Gln	Bar
SiO ₂	45.38	56.95	46.13	46.60	45.29	50.40	49.68	50.91	56.32	48.81	49.56	54.76	53.84	47.83	52.56
TiO ₂	0.42	0.06	0.41	0.37	0.42	0.22	0.22	0.22	0.07	0.30	0.32	0.22	0.14	0.37	0.16
Al ₂ O ₃	13.01	9.33	12.49	12.23	13.39	9.84	11.62	10.46	12.12	10.42	9.96	8.21	9.01	11.10	5.65
FeO	14.14	13.06	14.25	13.31	12.96	11.35	12.13	11.35	9.72	17.25	17.26	16.52	18.85	18.84	12.30
MnO	0.27	0.21	0.23	0.35	0.34	0.00	0.00	0.05	0.03	0.02	0.00	0.10	0.09	0.19	0.52
MgO	11.33	10.17	11.32	11.75	11.70	13.47	11.93	12.85	11.12	9.22	9.98	9.57	8.03	8.73	15.50
CaO	7.89	1.05	7.83	7.49	7.81	8.74	7.75	7.93	2.08	5.82	5.82	2.40	1.53	5.36	8.26
Na ₂ O	4.82	7.22	4.44	4.81	4.83	3.67	4.58	4.26	6.74	5.68	5.33	6.95	7.54	6.24	3.67
K ₂ O	0.89	0.03	0.80	0.69	0.79	0.26	0.27	0.29	0.06	0.41	0.53	0.10	0.17	0.45	0.28
Total	98.13	98.10	97.90	97.60	97.53	97.95	98.17	98.32	98.25	97.92	98.76	98.83	99.20	99.12	98.90
Si	6.56	7.85	6.65	6.71	6.54	7.14	7.06	7.19	7.68	7.09	7.09	7.67	7.58	6.90	7.33
Ti	0.05	0.01	0.04	0.04	0.05	0.02	0.02	0.02	0.01	0.03	0.03	0.02	0.01	0.04	0.02
Al	8.82	9.38	8.82	8.83	8.87	8.81	9.03	8.95	9.63	8.91	8.81	9.05	9.09	8.83	8.28
Fe ³⁺	0.62	0.51	0.68	0.63	0.62	0.31	0.21	0.23	0.29	0.49	0.71	0.62	0.77	0.75	0.86
Fe ²⁺	1.09	0.99	1.04	0.97	0.94	1.03	1.23	1.12	0.82	1.61	1.36	1.31	1.45	1.52	0.58
Mn	0.03	0.03	0.03	0.04	0.04	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.02	0.06
Mg	2.44	2.09	2.43	2.52	2.52	2.85	2.53	2.71	2.26	2.00	2.13	2.00	1.68	1.88	3.22
Ca	1.22	0.16	1.21	1.16	1.21	1.33	1.18	1.20	0.30	0.91	0.89	0.36	0.23	0.83	1.23
Na	1.35	1.93	1.24	1.34	1.35	1.01	1.26	1.17	1.78	1.60	1.48	1.89	2.06	1.75	0.99
K	0.16	0.01	0.15	0.13	0.15	0.05	0.05	0.05	0.01	0.08	0.10	0.02	0.03	0.08	0.05
XMg	0.69	0.68	0.70	0.72	0.73	0.73	0.67	0.71	0.73	0.55	0.61	0.60	0.54	0.55	0.85

¹Electron microprobe analyses were calculated to a structural formula unit based on 23 oxygens. XMg = $Mg^{2+}/(Mg^{2+} + Fe^{2+})$

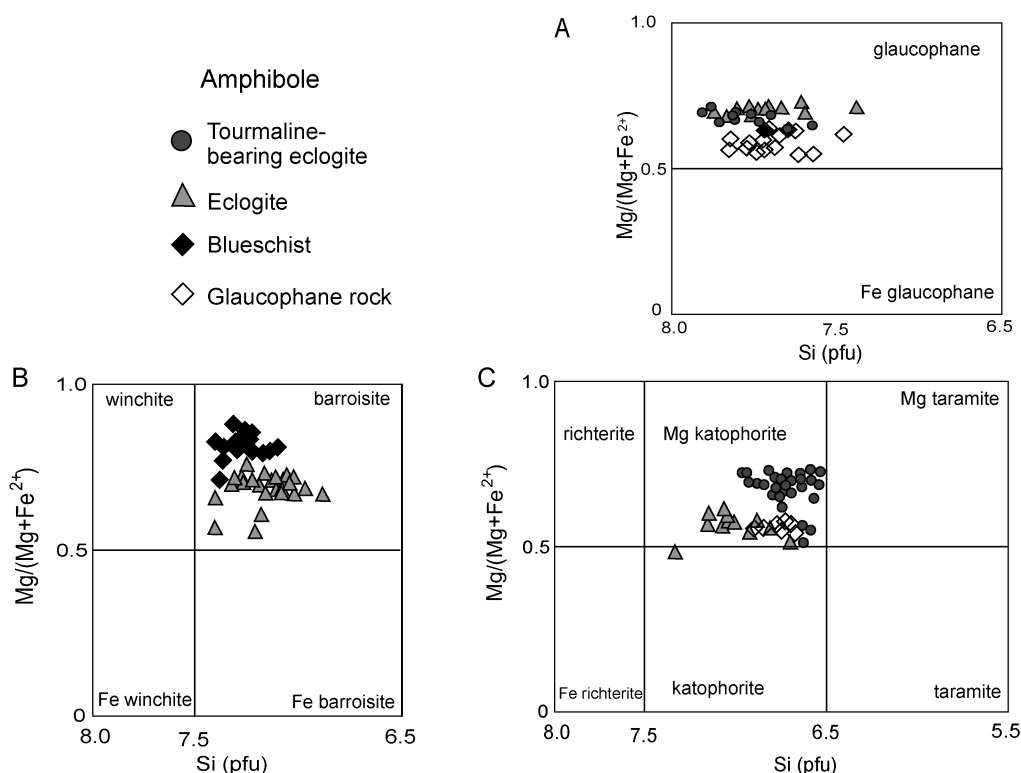


FIG. 9. Si (pfu) versus $Mg/(Mg+Fe^{2+})$ diagram for amphibole after Leake et al. (1997). A. Na amphibole in TEC (stage IV), EC (stage IV) and GR rocks. B. Na-Ca amphiboles in EC (stage I, II, III) and BS rocks. C. Ca-Na amphiboles in TEC (stage I, II, III), EC (stage III), and GR rocks.

analyses of phengite and paragonite are listed in Table 5. Fe^{3+} contents were calculated by normalization of the mica structural formula to 12.1 cations pfu (based on 22 O) + interlayer cations. The Si and Na contents of phengite of our EC samples define a nearly linear trend from 6.52 to 6.81 Si pfu and $X_{Na} = (Na/(Na+K))$ from 0.12 to 0.07 (Fig. 10). Phengites in TEC samples are compositionally restricted (6.60–6.70 Si pfu in sample KM10 and 6.84–6.91 Si pfu in sample KM01). X_{Na} ranges between 0.05 and 0.15. In general, phengite in both EC and TEC rock types lacks strong compositional zoning, except for slightly increasing Si and Mg contents from core to rim. BS phengites have Si contents and X_{Na} values between 6.49 and 6.79 pfu and 0.04 and 0.10, respectively. Total Al contents in phengites of all samples (EC, TEC, BS) display a good negative correlation with increasing Si contents due to the Tschermak's substitution, but X_{Fe} ($X_{Fe} = Fe^{2+}/(Mg+Fe^{2+})$) does not show a simple linear correlation. BS phengites show significantly higher X_{Fe}

than those from EC and TEC samples. The Si and Na contents of paragonite in EC samples range between 6.01 and 6.07 (probably slightly high) and 0.90 to 0.97 pfu, respectively.

Epidote

All analyzed epidotes are plotted in Figure 11. Representative analyses of epidote are given in Table 6. Iron was assumed to be Fe^{3+} . Some epidote in EC samples shows zoning, with higher birefringent cores, indicating higher Fe^{3+} contents compared with the rims. The clinozoisite/zoisite component in terms of $Al\# = (100 \times Al/(Fe^{3+} + Al))$ in epidote of EC, TEC, and BS samples ranges between 74 and 89, 70 and 76, and 67 and 75, respectively (Fig. 11).

Tourmaline

Representative analyses of tourmaline, which in general is very rare in eclogites, are presented in Table 7 on the basis of 29 oxygens. The weight percent of

TABLE 5. Representative Analyses of Phengite and Paragonite¹

Sample no.: Rock name: Point no.: Stage:	Phengite												Paragonite												
	KM10			KSAC1			KSAC1			KSAC1			KM12			KM12			KM08			KM17			M3A
	TEC #26 I	TEC #40 II	TEC #86 III	EC #57 I	EC #58 II	EC #87 III	EC #57 I	EC #58 II	EC #87 III	EC #16 I	EC #19 II	EC #29 III	GR #1 III	EC #9 III	EC #18 III										
Mineral name:																									
SiO ₂	50.34	51.67	51.544	50.19	50.51	49.48	49.23	49.39	50.05	50.29	48.36	48.43													
TiO ₂	0.60	0.23	0.211	0.32	0.43	0.35	0.37	0.35	0.48	0.35	0.05	0.04													
Al ₂ O ₃	27.03	24.74	24.575	29.20	28.55	28.54	27.82	26.57	26.43	24.73	40.55	39.65													
Cr ₂ O ₃	0.01	0.02	0.000	0.02	0.02	0.02	0.01	0.03	0.01	2.84	0.04	0.00													
FeO	3.71	3.94	3.583	2.10	2.04	2.19	4.23	4.45	4.33	5.00	0.28	0.32													
MnO	0.08	0.02	0.088	0.00	0.01	0.00	0.00	0.02	0.00	0.00	0.01	0.02													
MgO	3.85	4.37	4.364	3.07	3.31	3.43	3.15	3.27	3.25	3.16	0.17	0.24													
CaO	0.08	0.00	0.020	0.00	0.02	0.01	0.02	0.03	0.07	0.02	0.17	0.12													
BaO	0.00	0.00	0.00	0.17	0.10	0.10	0.00	0.00	0.00	0.21	0.00	0.00													
Na ₂ O	0.54	0.17	0.186	0.85	0.86	0.85	0.55	0.49	0.55	0.41	8.04	7.74													
K ₂ O	10.74	11.07	11.192	10.22	10.11	10.10	10.69	10.24	9.91	9.00	0.76	0.83													
Total	96.96	96.24	95.76	96.15	95.98	95.06	96.06	94.84	95.08	96.01	98.42	97.39													
Si	6.652	6.882	6.911	6.636	6.679	6.623	6.579	6.670	6.727	6.698	6.008	6.066													
Ti	0.059	0.024	0.021	0.032	0.042	0.035	0.037	0.036	0.049	0.035	0.004	0.004													
Al	4.211	3.884	3.883	4.550	4.450	4.502	4.383	4.228	4.186	3.883	5.939	5.853													
Cr	0.001	0.002	0.000	0.002	0.002	0.002	0.001	0.003	0.001	0.299	0.004	0.000													
Fe ²⁺	0.255	0.335	0.353	0.233	0.226	0.245	0.291	0.350	0.434	0.408	0.029	0.033													
Fe ³⁺	0.155	0.104	0.049	0.000	0.000	0.000	0.182	0.153	0.053	0.148	0.000	0.000													
Mn	0.009	0.003	0.010	0.000	0.002	0.000	0.000	0.002	0.000	0.000	0.001	0.002													
Mg	0.758	0.867	0.872	0.605	0.653	0.685	0.628	0.658	0.651	0.628	0.031	0.046													
Ca	0.011	0.000	0.003	0.000	0.003	0.002	0.003	0.004	0.010	0.003	0.023	0.016													
Ba	0.000	0.000	0.000	0.009	0.006	0.005	0.000	0.000	0.000	0.021	0.000	0.000													
Na	0.139	0.045	0.048	0.219	0.221	0.220	0.143	0.127	0.143	0.105	1.936	1.880													
K	1.810	1.880	1.914	1.724	1.706	1.724	1.822	1.764	1.699	1.530	0.121	0.133													
Muscovite	0.4737	0.4474	0.4441	0.5167	0.4893	0.5049	0.5209	0.4865	0.4610	0.4039	0.0317	0.0211													
Phlogopite	0.0500	0.0500	0.0500	0.0283	0.0265	0.0453	0.0500	0.0500	0.0500	0.0500	0.0081	0.0019													
Mg-Al celadonite	0.2481	0.3179	0.3254	0.2327	0.2555	0.2321	0.1988	0.2199	0.2212	0.2126	0.0078	0.0236													
Fe-Al celadonite	0.0835	0.1229	0.1317	0.0895	0.0884	0.0830	0.0921	0.1172	0.1474	0.1381	0.0072	0.0171													
Paragonite	0.0707	0.0235	0.0246	0.1121	0.1141	0.1129	0.0728	0.0670	0.0772	0.0642	0.9310	0.9268													
Rest	0.0740	0.0383	0.0242	0.0208	0.0262	0.0217	0.0654	0.0594	0.0432	0.1311	0.0141	0.0095													

¹Electron microprobe analyses were calculated to double formula unit (42 valencies). The molar fractions of the six components were computed according to Massonne (1992).

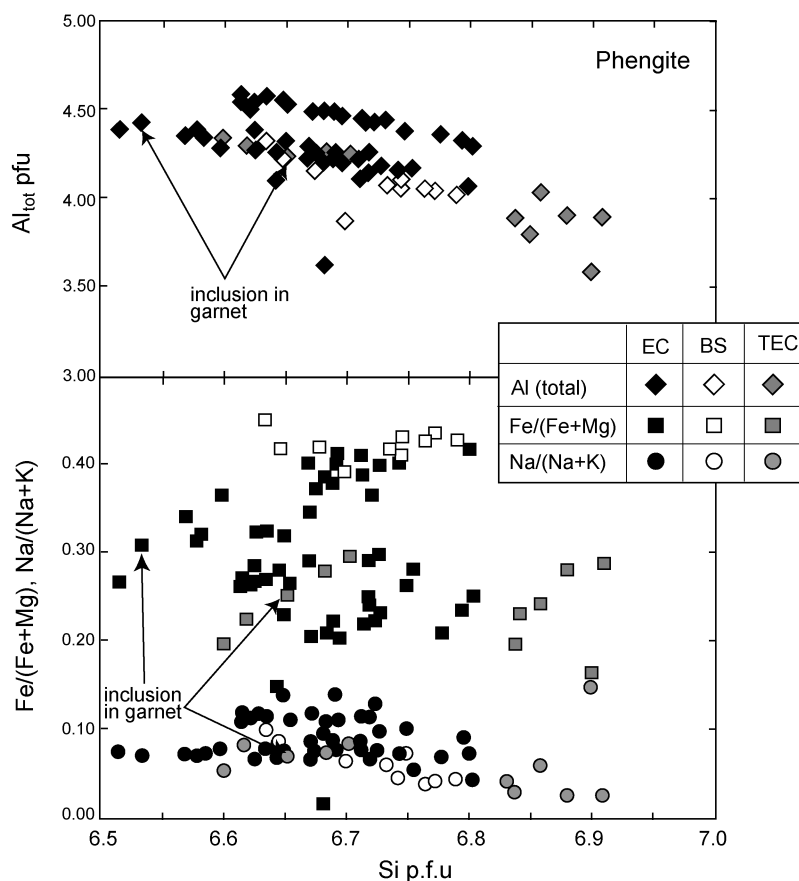


FIG. 10. Variation diagrams of selected chemical parameters for phengite in EC, TEC, and BS rocks showing Si pfu versus $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$, $\text{Na}/(\text{Na}+\text{K})$, and Al_{tot} pfu.

B_2O_3 was calculated assuming 3 boron atoms in the structural formula and Fe^{2+} as Fe total. Tourmaline compositions corresponding to dravite-schörl solid solution are rich in Na with $\text{Na}_{0.89-0.99}\text{Ca}_{0.02-0.12}\text{K}_{\sim 0.01}$ in the X site (alkali group in Fig. 12A). X_{Mg} values are between 0.47 and 0.72 (Table 7). Si and Al range from 5.91 to 6.01 pfu and 5.48 to 5.95 pfu, respectively. The blue-greenish core and brownish mantle of tourmaline (Fig. 5) show nearly identical compositions. The only significant differences between core and rim (Table 7) are TiO_2 (core: 0.16–0.29 wt%, rim: 0.66–1.07 wt%) and Na contents (core: 0.96–1.0 pfu, rim: 0.88–0.94 pfu). Tourmaline in Karangsembung eclogite has a composition similar to tourmaline in eclogite from the Elekdag area, northern Turkey (Altherr et al., 2004) both plotting in the same group as tourmaline from metapelites or calc-silicate rocks (Fig. 12B; Henry and Guidotti, 1985).

Chlorite and albite

Chlorite compositions are variable and depend on rock type and textural position (Table 8). In our EC and TEC samples, chlorite is present as a matrix constituent, replacing barrosite and omphacite, filling fractures, and forming coronas around garnet. Chlorites in BS samples are generally more magnesian ($X_{\text{Mg}} = 0.63\text{--}0.72$) than chlorite in TEC and GR samples ($X_{\text{Mg}} = 0.51\text{--}0.68$ and $0.49\text{--}0.53$, respectively). X_{Mg} values of chlorites in EC show a wide compositional spread ($X_{\text{Mg}} = 0.37\text{--}0.72$) because chlorite replacing garnet shows lower X_{Mg} values than chlorite from the matrix.

Albite, occurring as anhedral grains, is rare in a few EC and TEC samples, but is abundant in all GR and BS samples. All albites range in composition from Ab_{98} to Ab_{100} (Table 9; see also Table 10 for titanite).

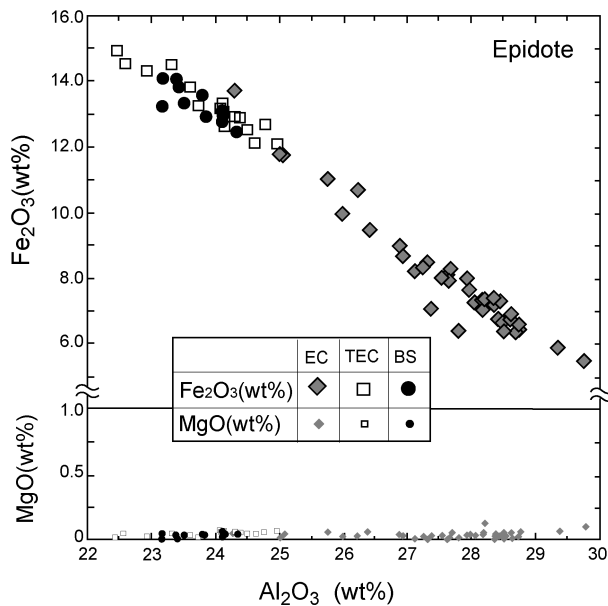


FIG. 11. Variation diagram of selected chemical parameters for epidote in EC, TEC, and BS rocks, showing Al_2O_3 (wt%) versus MgO (wt%) and Fe_2O_3 (wt%).

Pressure-Temperature Evolution

On the basis of the previously outlined textural features and mineral compositions, we have defined five stages. For each stage, we have either calculated P-T conditions using thermodynamic methods, or used mineral assemblages to constrain P-T ranges. With this information, P-T paths were constructed to understand the geodynamic processes responsible for the formation of the Lok Ulo Complex.

Geothermobarometric methods

The geothermobarometric computation, considering various multivariant mineral equilibria, was undertaken with the computer software PTGIBBS (Brandelik and Massonne, 2004) mainly for metamorphic stages I to III. We applied the internally consistent data set by Berman (1988), augmented by compatible thermodynamic data (see Massonne and Kopp, 2005). Complex activity formulations were used for components in garnet (Massonne, 1992), omphacite (Massonne, 1992) and phengite (Massonne, 1997). For other mineral components, mostly simple activity relations (see below) were applied. Calculated exchange equilibria for the components

almandine (Alm), grossular (Grs), and pyrope (Prp) in garnet (Gt), diopside (Di) and hedenbergite (Hd) in omphacite (Omp), and muscovite (Ms), Mg-Al-celadonite (MgAlCel), and Fe^{2+} -Al-celadonite (FeAlCel) in phengite (Phn), were, for instance: (1) $\text{Alm}_{\text{Gt}} + 3 \text{Di}_{\text{Omp}} = \text{Prp}_{\text{Gt}} + 3 \text{Hd}_{\text{Omp}}$; (2) $3 \text{MgAlCel}_{\text{Phn}} + \text{Prp}_{\text{Gt}} + 2 \text{Grs}_{\text{Gt}} = 3 \text{Ms}_{\text{Phn}} + 6 \text{Di}_{\text{Omp}}$; (3) $\text{Alm}_{\text{Gt}} + 6 \text{MgAlCel}_{\text{Phn}} + 2 \text{Grs}_{\text{Gt}} = 3 \text{FeAlCel}_{\text{Phn}} + 6 \text{Di}_{\text{Omp}} + 3 \text{Ms}_{\text{Phn}}$; (4) $3 \text{MgAlCel}_{\text{Phn}} + 6 \text{Hd}_{\text{Omp}} + 3 \text{Ms}_{\text{Phn}} = 6 \text{FeAlCel}_{\text{Phn}} + 2 \text{Grs}_{\text{Gt}} + \text{Prp}_{\text{Gt}}$; (5) $6 \text{Hd}_{\text{Omp}} + 3 \text{Ms}_{\text{Phn}} = \text{Alm}_{\text{Gt}} + 3 \text{FeAlCel}_{\text{Phn}} + 2 \text{Grs}_{\text{Gt}}$; (6) $3 \text{Di}_{\text{Omp}} + 3 \text{Hd}_{\text{Omp}} + 3 \text{Ms}_{\text{Phn}} = \text{Alm}_{\text{Gt}} + 3 \text{MgAlCel}_{\text{Phn}} + 2 \text{Grs}_{\text{Gt}}$; (7) $\text{Alm}_{\text{Gt}} + 3 \text{MgAlCel}_{\text{Phn}} = 3 \text{FeAlCel}_{\text{Phn}} + \text{Prp}_{\text{Gt}}$; (8) $3 \text{FeAlCel}_{\text{Phn}} + 2 \text{Grs}_{\text{Gt}} + \text{Prp}_{\text{Gt}} = 3 \text{Ms}_{\text{Phn}} + 3 \text{Hd}_{\text{Omp}} + 3 \text{Di}_{\text{Omp}}$.

Seven invariant points (IPs) for fixed mineral compositions result for each compositional set, considering the above equilibria. These points would fall together for ideal conditions (perfect thermodynamic data and true equilibrium compositions). However, a certain scatter within the limits of error (1_ accuracy of the P estimate in the range of 1 to 2 kbar, as assumed by Massonne and Kopp, 2005) are tolerable. A wide scatter was taken as indication that the selected mineral compositions (includes the

Sample no.:	KSACI	KM17	KM02	KM08	KM13B	KM13B
Rock name:	EC	EC	BS	BS	TEC	TEC
Point no.:	#56	#7	#4	#7	#3	#36
Stage:	III	III	III	III	III	III
SiO ₂	38.60	38.81	38.25	38.22	37.86	37.78
TiO ₂	0.13	0.05	0.11	0.10	0.06	0.19
Al ₂ O ₃	28.15	27.19	24.34	23.73	22.66	23.96
Cr ₂ O ₃	0.01	0.00	0.02	0.02	0.03	0.03
Fe ₂ O ₃	8.05	8.76	12.94	14.03	15.05	13.24
Mn ₂ O ₃	0.19	0.06	0.24	0.32	0.28	0.03
MgO	0.03	0.03	0.03	0.01	0.00	0.06
CaO	23.73	24.14	23.17	22.93	23.00	22.19
Na ₂ O	0.01	0.07	0.00	0.00	0.04	0.01
Total	98.90	99.10	99.09	99.37	98.98	97.49
Si	2.98	3.00	3.00	3.00	3.00	3.01
Ti	0.01	0.00	0.01	0.01	0.00	0.01
Al	2.56	2.48	2.25	2.19	2.11	2.25
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe ³⁺	0.47	0.51	0.76	0.83	0.90	0.79
Mn ³⁺	0.01	0.00	0.01	0.02	0.02	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.01
Ca	1.96	2.00	1.95	1.93	1.95	1.89
Na	0.00	0.01	0.00	0.00	0.01	0.00
XAl=(Al/(Al+Fe ³⁺))	0.85	0.83	0.75	0.73	0.70	0.74

¹Electron microprobe analyses were calculated to a structural formula unit based on 25 valencies.

calculated Fe²⁺-Fe³⁺ contents as well) are not in equilibrium.

In addition to the thermodynamic calculations, we used calibrations for the Fe²⁺-Mg partitioning between omphacite and garnet due to equilibrium (1) for stage I to stage III. We applied the calibration of Ellis and Green (1979) and Krogh Ravna (2000), considering the calculated Fe²⁺ contents for both minerals. Assuming a 1σ error as low as ± 20°C for the above applied geothermometers, related to equilibrium (1), and compositions of minerals (nearly) in equilibrium, the obtained temperatures for a single metamorphic stage are compatible among the various methods.

For obtaining information on the P-T conditions of stage III we also used the subsequent equilibrium: (9) 3 Jd_{omp} + 1 Prp_{gt} + 2 SiO₂ + 1 H₂O = 1 Pg_{pg} + 1 Gln_{amp}, proposed by Miyazaki et al. (1998)

to consider the presence of omphacite rich in jadeite (Jd) component, paragonite (Pg), and amphibole (Amp) rich in glaucophane (Gln) component. However, the P-T position of equilibrium (9) depends on water activity. Activity models for the mineral components in equilibrium (9) are based on those defined by Holland and Powell (1990) as proposed by Miyazaki et al. (1998).

Results

After the selection of specific compositions, assumed to represent those of coexisting minerals, from 12 eclogite samples (2 TEC and 10 EC samples), we calculated P-T data for 17 and 57 compositional combinations of garnet-omphacite-phengite (stages I, II, and III) from TEC and EC, respectively, applying the program PTGIBBS and the calibrations

TABLE 7. Representative Analyses of Tourmaline¹

Sample no.:	KM01	KM13B	KM10	KM10
Rock name:	TEC			
Point no.:	#26	#1	#66	#73
Location:	Green rim	Dark rim	Brown rim	Blue core
Stage:	V	V	V	V
B ₂ O ₃ *	10.76	10.60	10.76	10.85
SiO ₂	36.56	36.50	36.71	36.97
TiO ₂	0.86	1.01	0.88	0.17
Al ₂ O ₃	31.19	29.59	30.69	32.19
Cr ₂ O ₃	0.00	0.03	0.04	0.01
FeO	6.95	9.93	6.89	6.64
MnO	0.01	0.00	0.00	0.04
MgO	8.78	7.28	8.96	8.71
CaO	0.39	0.45	0.44	0.14
Na ₂ O	2.86	2.90	2.95	3.13
K ₂ O	0.01	0.05	0.04	0.00
NiO	0.01	0.04	0.05	0.02
Total	98.37	98.38	98.40	98.86
B	3.00	3.00	3.00	3.00
Si	5.91	5.99	5.93	5.92
Al	5.94	5.72	5.85	6.08
Ti	0.10	0.12	0.11	0.02
Cr	0.00	0.00	0.01	0.00
Fe ²⁺	0.94	1.36	0.93	0.89
Mn	0.00	0.00	0.00	0.01
Ni	0.00	0.00	0.01	0.00
Mg	2.11	1.78	2.16	2.08
Ca	0.07	0.08	0.08	0.02
Na	0.89	0.92	0.92	0.97
K	0.00	0.01	0.01	0.00

¹The weight percent of B₂O₃ is calculated assuming 3 boron atoms in the structural format on the basis of 29 oxygens.

by Ellis and Green (1979) and Krogh Ravna (2000). Selected results of the calculations are given in Table 11. These results refer exclusively to mineral compositions given in Tables 2, 3, 5, and 6 and to PTGIBBS calculations in which the obtained invariant points did not strongly scatter. Among these invariant points (IPs), we have taken IP1 (intersection of the P-T curves of equilibria 1, 2, and 6) which is thought to be the most reliable (see Massonne and Kopp, 2005). The 74 P-T data for IP1

TABLE 8. Representative Analyses of Chlorite¹

Sample no.:	KM01	KSACI	M1	KM02	KM07
Rock name:	TEC	EC	EC	GR	BS
Point no.:	#51	#79	#34	#40	#56
Stage:	IV	IV	IV	IV	IV
SiO ₂	27.88	27.22	27.54	26.60	28.84
TiO ₂	0.02	0.03	0.02	0.03	0.01
Al ₂ O ₃	18.71	20.82	19.00	19.00	18.81
Cr ₂ O ₃	0.01	0.02	0.02	0.01	0.05
FeO	19.54	18.26	22.91	27.65	18.55
MnO	0.55	0.02	0.26	0.39	0.99
MgO	21.18	22.06	19.11	16.41	23.05
Total	87.89	88.42	88.86	90.08	90.29
Si	5.69	5.46	5.65	5.53	5.70
Al	4.50	4.93	4.59	4.65	4.38
Cr	0.00	0.00	0.00	0.00	0.01
Ti	0.00	0.00	0.00	0.00	0.00
Fe	3.33	3.07	3.93	4.80	3.06
Mn	0.10	0.00	0.05	0.07	0.17
Mg	6.44	6.60	5.84	5.08	6.79
xSi	0.84	0.73	0.82	0.76	0.85
xMg	0.65	0.68	0.60	0.51	0.68
xFe	0.34	0.32	0.40	0.48	0.31

¹Electron microprobe analyses were calculated to a structural formula unit based on 28 oxygens.

lie in the range 283–453°C and 15.3 to 23.5 kbar. The temperatures obtained with the calibration of Ellis and Green (1979) are consistently higher. The observed differences (39–102°C) are consistent with the statement by Massonne and Kopp (2005) that this temperature difference scatters around 70°C (for the temperature range 450 to 750°C). The difference between the temperatures obtained using the calibration by Krogh Ravna (2000) and PTGIBBS ranges between –25 to 100°C. The P-T data resulting from the computations with PTGIBBS are plotted in Figure 13.

Despite the significant scatter of P-T estimates obtaining with PTGIBBS (Table 11), a systematic prograde change in P-T conditions from stage I to stage III results. The TEC samples (stage I: P = 19.4–22.5 kbar and T = 339–448°C, stage II: P = 16.7–24.7 kbar and T = 343–438°C, and stage III: P = 21.3–23.5 kbar and T = 333–396°C; Fig. 13A)

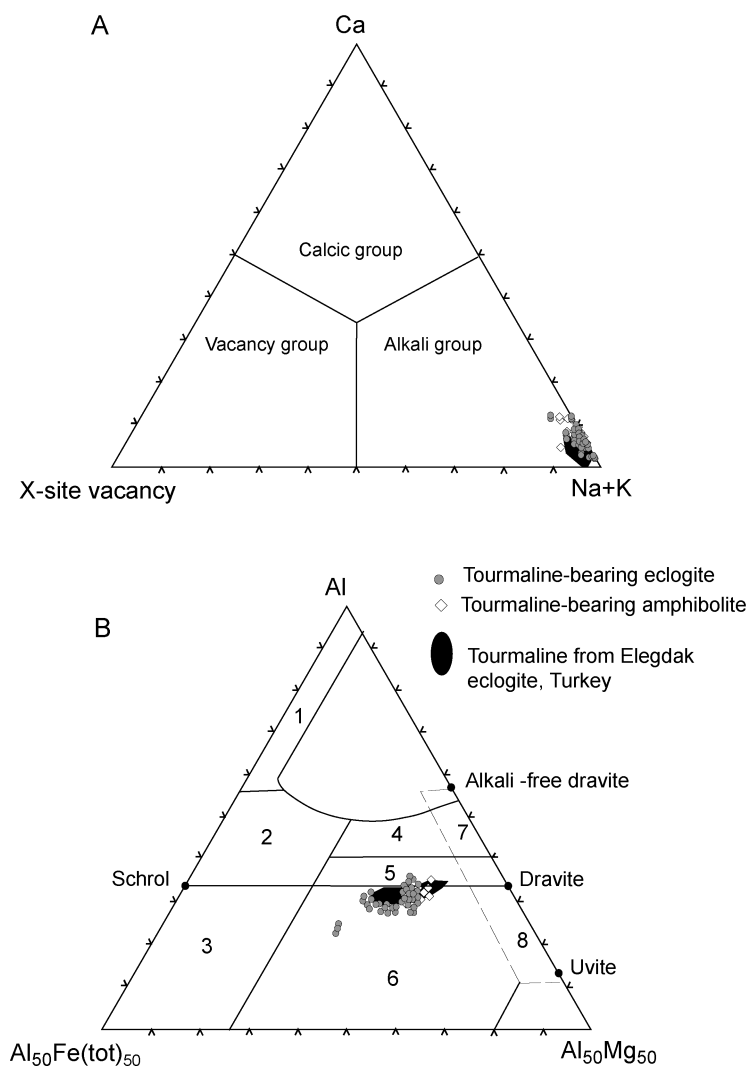


FIG. 12. Classification of tourmaline in TEC samples and amphibolites (Kadarusman, unpubl. data) of the Lok Ulo Complex. A. based on the principal constituent in the X-site (Hawthorne and Henry, 1999). B. Based on the Al-Fe(tot)-Mg diagram of Henry and Guidotti (1985) for petrogenetic indicator classification. Note that compositions of tourmaline in eclogite from the Elekdag area, North Turkey (Altherr et al., 2004) are also plotted in these diagrams.

yielded rising pressures and decreasing temperatures, whereas the EC rocks (stage I: $P = 15.3\text{--}21.1$ kbar and $T = 283\text{--}415^\circ\text{C}$, stage II: $P = 16.4\text{--}21.9$ kbar and $T = 329\text{--}442^\circ\text{C}$, and stage III: $P = 18.4\text{--}22.8$ kbar and $T = 359\text{--}453^\circ\text{C}$; Fig. 13B) show a P-T history with rising temperature and pressure from stage I to stage III.

The retrograde path toward stage IV (blueschist-facies overprint) leads in the eclogites (EC and TEC)

to the assemblage glaucophane + epidote + chlorite + titanite + albite + quartz. This assemblage is limited to the P-T range of the albite-stable, garnet-free, low-temperature portion of the epidote-blueschist facies (e.g., Evans, 1990). The corresponding P-T conditions are 8–10 kbar and 350–400°C (Figs. 13A and 13B; thus, the retrograde path for TEC rocks is part of a counterclockwise P-T path, whereas the EC rocks show a clock-wise P-T loop)

TABLE 9. Representative Analyses of Feldspar

Sample no.:	KM02	KM10
Rock name:	GR	EC
Point no.:	#9	#39
Stage:	IV	IV
SiO ₂	68.22	68.15
TiO ₂	0.00	0.01
Al ₂ O ₃	19.22	19.67
Cr ₂ O ₃	0.00	0.00
Fe ₂ O ₃	0.44	0.32
Mn ₂ O ₃	0.01	0.00
MgO	0.00	0.02
CaO	0.09	0.08
Na ₂ O	12.89	12.42
K ₂ O	0.03	0.02
Total	100.89	100.69
Si	2.98	2.99
Ti	0.00	0.00
Al	0.99	0.99
Fe*	0.02	0.01
Mn	0.00	0.00
Mg	0.00	0.00
Ca	0.00	0.00
Na	1.09	1.05
K	0.00	0.00
Total	5.08	5.04
Anorthite	0.00	0.00
Albite	0.99	1.00
K-Feldspar	0.00	0.00

TABLE 10. Representative Analyses of Titanite

Sample no.:	KM02	KM01	KSAC1
Rock name:	GR	TEC	EC
Point no.:	#1	#52	#60
Stage:	III	III	III
SiO ₂	30.89	30.59	30.40
TiO ₂	38.70	38.04	39.27
Al ₂ O ₃	1.15	1.32	0.95
Cr ₂ O ₃	0.00	0.01	0.00
Fe ₂ O ₃	0.98	0.55	0.36
Mn ₂ O ₃	0.00	0.09	0.02
MgO	0.00	0.00	0.02
CaO	28.63	28.50	27.90
Na ₂ O	0.02	0.05	0.00
K ₂ O	0.00	0.00	0.01
Total	100.39	99.15	98.93
Si	1.00	1.00	1.00
Al	0.04	0.05	0.04
Cr	0.00	0.00	0.00
Ti	0.94	0.94	0.97
Fe3	0.02	0.01	0.01
Mn3	0.00	0.00	0.00
Ca	0.99	1.00	0.98
Na	0.00	0.00	0.00
K	0.00	0.00	0.00

Discussion and Conclusions

Pressure-temperature evolution and tectonic environment

which also relate to the GR rocks as they show an assemblage similar to that of stage IV of the eclogites. However, BS rocks, which contain garnet, may indicate a higher temperature portion of the epidote-blueschist facies. Temperatures for the appearance of almandine-rich garnet in BS rocks have been estimated to 400–460°C at pressure of 6–7 kbar (Yokoyama et al., 1986; Patrick and Evans, 1989). The P-T conditions of stage IV are also defined by the reaction clinozoisite + glaucophane + quartz + H₂O = tremolite + chlorite + albite, which was experimentally investigated by Maruyama et al. (1986). These authors gave minimum pressure of 7 kbar at temperatures above 300°C.

The above-outlined P-T estimates point to metamorphic peak pressures (stage III) around 20–22 kbar (Fig. 13) for both investigated eclogite types EC and TEC, broadly confirming previous estimates by Miyazaki et al. (1998) for jadeite-glaucophane rock of the Lok Ulo Complex. However, these authors estimated higher metamorphic peak temperatures for their jadeite-glaucophane rock of 490–570°C. More importantly, we were able to reconstruct P-T paths for the eclogites. These paths comprise a “prograde” branch (stages I to III), characterized by significant pressure increase, and a “retrograde” branch (stages III to IV) as the result of pressure release. In addition, the P-T evolution can be both clockwise and counterclockwise. We

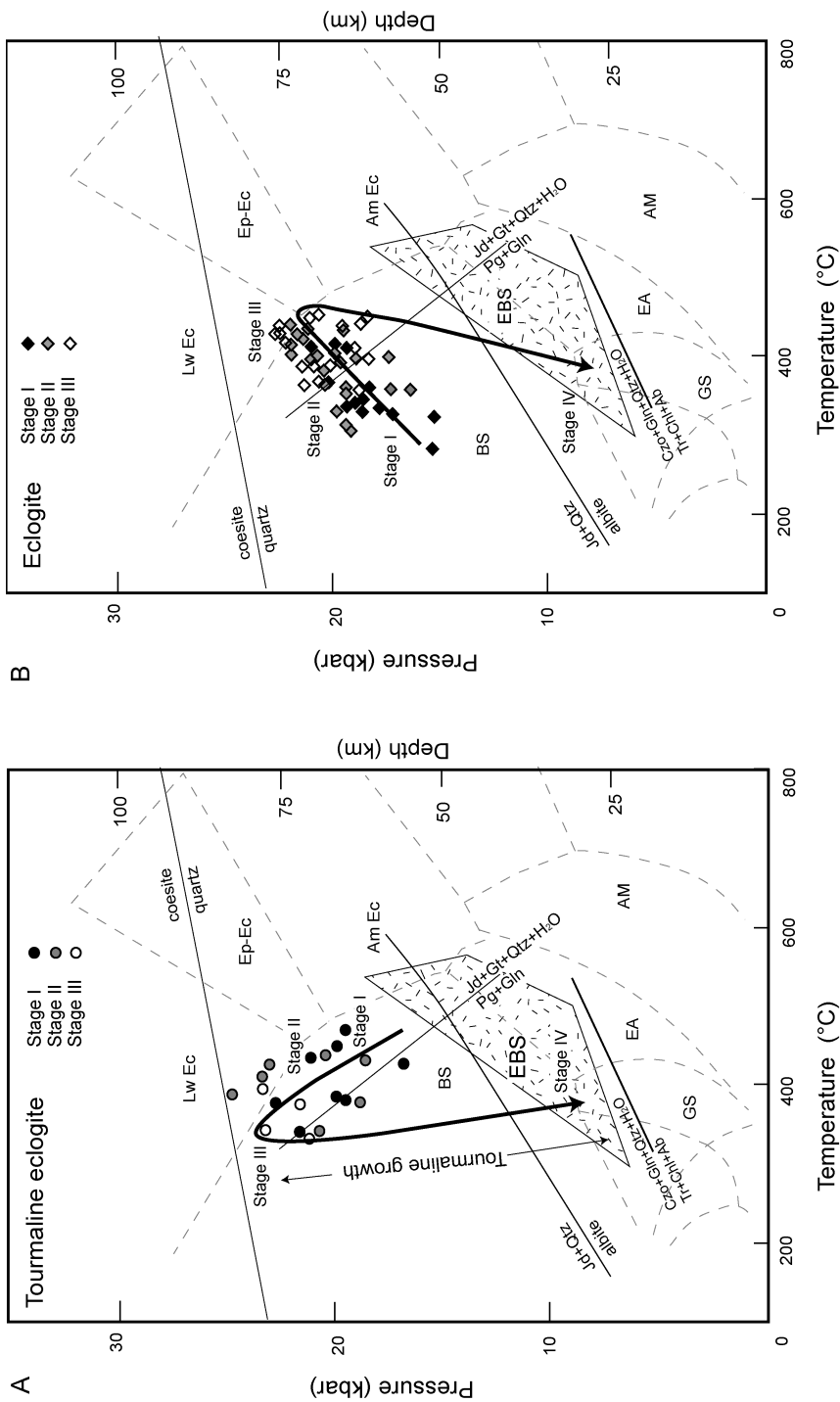


FIG. 13. P-T paths (bold) for Lok Ulo eclogites. A. TEC. B. EC. Symbols show the calculated P-T conditions, using PTCIBBS (Brandelik and Massonne, 2004), for stages I, II, and III. Underlying petrogenetic grid referring to metamorphic facies was taken from Maruyama et al. (1996). Abbreviations of facies names as by these authors. Stability field of epidote blueschist (EBS) as calculated by Evans (1990). In addition, the following reaction curves are shown: coesite = quartz (Mirwald and Massonne, 1980); albite = jadeite + quartz (Holland, 1980); jadeite + pyrope + quartz + H_2O = paragonite + glaucophane (as proposed by Miyazaki et al., 1998); clinozoisite + glaucophane + quartz + H_2O = tremolite + chlorite + albite (Maruyama et al., 1986).

TABLE 11. Selected Results of Applied Geothermobarometry of Various Eclogite Samples and Stages¹

Sample no. (type)	Stage	Pair no. (Grt-Cpx-Phn)	Method			
			PTGIBBS, P (kbar)	BM2004 T (°C)	EG1979 T (°C)	KR2000 T (°C)
KM10 (TEC)	I	#9-#48-#26	19.8	385.5	447.2	465.7
KM10 (TEC)	II	#2-#49-#40	23.3	410.4	476.9	454.9
KM10 (TEC)	III	#27-#45-#40	23.5	396.2	454.3	436
KM01 (TEC)	I	#35-#40-#33	19.8	448.3	527.5	540
KM01 (TEC)	II	#36-#47-#34	21.9	403.9	462.8	462.7
KM01 (TEC)	III	#16-#31-#25	21.3	333.2	375.8	395.3
KSACI (EC)	I	#55-#53-#57	18.3	359.6	431.9	365.1
KSACI (EC)	II	#56-#54-#58	20.4	381.8	439.2	356.6
KSACI (EC)	III	#86-#89-#87	21.2	389.2	446.8	362.8
M2G (EC)	I	#25-#29-#35	18.8	344.0	405.5	366.6
M2G (EC)	II	#26-#30-#36	19.4	354.1	414.0	345.7
M2G (EC)	III	#50-#47-#52	19.9	403.7	487.5	423.2
KM12 (EC)	I	#3-#4-#16	15.3	325.0	427.5	411.3
KM12 (EC)	II	#2-#5-#19	19.4	314.2	398.2	339.3
KM12 (EC)	III	#25-#32-#29	20.7	368.7	452.5	365.8
M3C (EC)	I	#72-#78-#99	20.4	366.1	433.9	401.5
M3C (EC)	II	#74-#83-#100	21.9	402.1	472.2	399.0
M3C (EC)	III	#76-#91-#101	22.6	430.6	497.3	419.2
M3D (EC)	II	#3-#16-#31	21.9	415.9	506.8	463.9
M3D (EC)	III	#1-#17-#32	22.5	441.1	480.1	447.5

¹BM2004 = Brandelik and Massonne, 2004; EG1979 = Ellis and Green, 1979; KR2000 = Krogh Ravna, 2000.
Calculated temperature of EG1979 and KR2000 based on pressure resulting from PTGIBBS.

think that these findings can be best explained by a subduction-channel environment. Numerical modeling of the mass flow in a subduction channel demonstrates that both clockwise and counterclockwise P-T paths are possible, and that rocks that have experienced these different paths can come close together during exhumation (Gerya et al., 2002; Stöckhert and Gerya, 2005). If a rock approaches the boundary to the overlying hot mantle during subduction (pressure increase), heating can result. If a rock moves away from this boundary, even cooling can happen during subduction (counterclockwise path). The mass flows deduced from the modeling experiments also show that a considerable rock volume can be exhumed and that only a portion of subducted metabasic rocks, transformed to eclogites, disappears in the deep mantle. As the peak P-T conditions for the EC rocks were about $P = 20.5 \pm 2.5$ kbar and $T = 410 \pm 50^\circ\text{C}$, these rocks were

subducted to ~70 km depth with a geothermal gradient of ~6°C/km. Such a low gradient can be explained by a high rate of subduction of a cold oceanic plate (Peacock, 1992).

The remaining problem in case of the Lok Ulo Complex is why the deeply subducted eclogites were finally mixed with rocks (e.g., dismembered ophiolite) that apparently never experienced high pressures. The exposed rocks rather point to a mélange zone that was located not too deep in the Earth. Thus, it is likely that rocks of a former subduction-channel environment (those which were at a specific time relatively close to the surface) and near-surface rocks were intensively tectonically mixed. This mixing probably occurred at low temperatures in the presence of hydrous fluids, explaining the estimated maximum temperatures of some rocks of the mélange ($T < 400^\circ\text{C}$) and the disintegration of the various rock units (formation of tectonic blocks) and

partially intense retrogression (e.g., along block surfaces). The reason for the formation of the mélange zone in the Cretaceous is, however, a matter of speculation. Nevertheless, it is very likely that the corresponding tectonics happened along a convergent margin where oceanic crust was subducted below a continental plate. This situation might have been similar to the present one (subduction of the Indo-Australian plate below the Sumatra-Java arc system).

Tourmaline in eclogites

Eclogites containing tourmaline are rare in nature. Thus far, they have been described from only a few localities (Smith, 1971; Kagiannidou et al., 1987; Altherr et al., 2004). Tourmaline is a chemically robust phase capable of retaining information regarding protracted metamorphic or even pre-metamorphic histories by chemical zoning and mineral inclusions (Bebout and Nakamura, 2003). Once formed, tourmaline does not readily readjust its composition by volume diffusion (Henry and Dutrow, 1996). The significance of newly detected tourmaline in eclogites of the Lok Ulo Complex is related to the timing of formation of tourmaline, i.e. infiltration of B-rich fluids and, thus, of fluid-rock interaction processes during subduction or exhumation of HP rock in the subduction environment. Experimental studies have shown that boron partitioning and boron isotope fractionation vary as a function of temperature and the coordination number of boron, but the pressure dependence is not clear (Ota et al., 2006). Generally, it is poorly understood how the boron-related fluid-rock interaction occurs in natural systems. Our new findings contribute to understand corresponding processes.

According to the reported textural relationships and the derived P-T path (Fig. 13), the infiltration of external B-bearing aqueous fluids occurred during the exhumation of some eclogites (after stage III) at relatively low temperatures ($T < 400^{\circ}\text{C}$). This infiltration resulted in tourmaline formation was restricted to the outer shells of eclogite blocks and veins cutting such blocks. Hydrous fluids also caused the formation of coexisting Na and Na-Ca amphiboles, which, however, in contrast to tourmaline, have been well described from blueschists and low-temperature eclogites (e.g., Brown, 1977; Ernst, 1979; Pognante and Kienast, 1987; Krogh et al., 1994; Tsujimori, 2002). The sources of these fluids are deeper and, thus, hotter portions of the subduction channel where water is released by prograde

mineral reactions. By this process, boron, which has been originally enriched in altered oceanic crust and sediments, might enter the fluids by breakdown of micas (Sperlich et al., 1996; Nakano and Nakamura, 2001; Ota et al., 2006). In cooler portions of the subduction channel, boron in the fluids reacts with the eclogitic minerals to form tourmaline. In addition, other hydrous minerals such as chlorite and epidote, grown at an early stage of tourmaline formation, later reacted with the B-bearing fluids, causing further growth of tourmaline (stage IV), also explaining the compositional zonation of this boron-mineral.

Relationship to HP-UHP rocks from other regions of Central Indonesia

The HP and UHP metamorphic rocks from the CIACC are distributed sporadically in at least 10 locations (see above, Fig. 1). However, the HP and UHP metamorphic rocks of only five of them (Meratus complex, Lok Ulo complex, Bantimala complex including Barru complex, Pompango complex, and Palu Complex: see Miyazaki et al., 1996, 1998; Parkinson, 1998; Parkinson et al., 1998; Kadarusman and Parkinson, 2000; Kadarusman et al., 2005a, 2005b) were petrologically studied in detail. Although Parkinson et al. (1998) first attempted to correlate them within the framework of the Cretaceous accretionary complex, and additionally speculated that all had experienced the same tectonic history, the relationships among HP and UHP rocks from the CIACC remain unsolved, due to large differences of the rock types, P-T conditions, rock associations, and ages in each location. The Meratus and Pompango schist complexes contain rocks that are clearly of continental margin parentage (Parkinson, 1998; Wakita et al., 1998), and thus differ significantly from the three other studied complexes. In addition, eclogites were not reported from either location. The maximum pressure for the Pompango Complex was estimated to be only 6 kbar. No detailed P-T study for the HP metamorphic rocks from the Meratus Complex were undertaken (Parkinson, 1998; Parkinson et al., 1998). However, the Meratus and Pompango schist complexes have Cretaceous ages (Pompango: ~111 Ma, Parkinson, 1998; Meratus: 110–180 Ma, Wakita et al., 1998), similar to those of the Lok Ulo Complex.

The presently investigated terrane is compared with two other complexes (Bantimala Complex and Palu Complex). According to our study and Miyazaki et al. (1998), the Lok Ulo Complex

contains low-temperature eclogites and jadeite-glaucophane-quartz rocks that have experienced metamorphic pressures less than 24 kbar and temperatures below 570°C. In contrast to these rocks, eclogites and coesite-bearing jadeite-rich rocks, reported from the Bantimala Complex of southern Sulawesi, were metamorphosed at pressures above 24 kbar and temperatures above 580°C (Miyazaki et al., 1996). Parkinson et al. (1998) even estimated P-T conditions >27 kbar and 720–760°C. The eclogites from the Palu Complex, northwestern Sulawesi, show higher temperatures (980–1060°C at $P > 20$ kbar) than all other eclogites from the CIACC. In addition, HP granulites ($P = 12$ –17 kbar, $T = 700$ –750°C) and garnet lherzolites ($P = 19$ –38 kbar, $T = 1025$ –1210°C) are associated with these eclogites (Kadarusman and Parkinson, 2000; Kadarusman et al., 2005b). Furthermore, the Lok Ulo and the Bantimala complexes are Cretaceous in ages (Lok Ulo: K-Ar: 110–124 Ma, Bantimala: K-Ar: 111–137 Ma; Miyazaki et al., 1996, 1998; Parkinson et al., 1998; Wakita, 2000), whereas the Palu Complex is much younger (Sm-Nd: 20–27 Ma, Kadarusman et al., 2001).

Thus, the above differences of the HP and UHP complexes of central Indonesia suggest that they were not formed by a simple subduction-collision event in a single zone. The CIACC could be the result of multiple subductions and collision between oceanic plates and microcontinents from Cretaceous to Neogene time. Alternatively, Massonne (2005) proposed another process, recognizing that also in the Paleozoic Variscan orogen two HP events (at about 395 Ma and 340 Ma) occurred with low to medium-temperature eclogites being formed during the older event and high-temperature eclogites associated with high-pressure granulites and garnet lherzolites during the younger HP-UHP event. For the Variscan case, this was interpreted as due to the collision of two continental plates starting at the older HP event. Afterward crustal thickening occurred, extending over a wide area, until lithospheric delamination happened, in which lower portions of continental crust were involved (younger HP-UHP event). Transferring this situation to central Indonesia, the geodynamic model by Massonne (2005) would require a continent-continent collision (Sundaland margin and Australian-derived continent or microcontinent), the beginning of which would be marked by Cretaceous accretionary complexes such as the Lok Ulo Complex.

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