

## Petrology and phase relations of the kyanite-eclogites from eastern Turkey

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**Abstract.** Eclogites are found as lenses or layers in the Precambrian gneiss terrain of the Bitlis Massif in eastern Turkey. Kyanite-eclogites from the region of Gablor Hill in the Bitlis Massif exhibit relatively minor alteration, and consist of garnet, omphacite, kyanite, zoisite, calcic amphibole, phengite, rutile and quartz. In terms of geological setting and mineral compositions, Gablor eclogites are very similar to eclogites from high-grade gneiss terrains. Metamorphic conditions during the eclogite crystallisation are determined as  $625 \pm 35^\circ \text{C}$  and  $16 \pm 3 \text{ kbars}$ . The coexistence of white mica, omphacite and kyanite constrains  $a_{\text{H}_2\text{O}}$  between 0.4 and 1. Primary calcic amphiboles from the Gablor eclogites exhibit conflicting textures, indicating stable coexistence with, as well as growth from omphacite and garnet. This is explained by a buffering reaction between amphibole, garnet, omphacite, zoisite and kyanite during the eclogite crystallisation, whereby  $a_{\text{H}_2\text{O}}$  is controlled and buffered by the mineral assemblage.

### Introduction

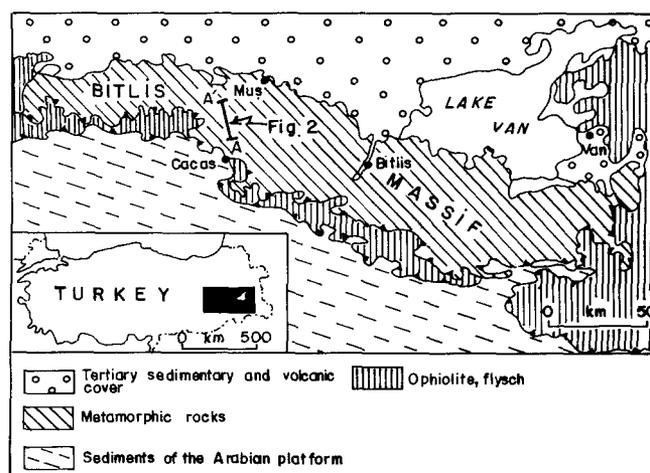
Recent studies have generally demonstrated that kyanite-eclogites, typically found in gneiss terrains, represent basic crustal material metamorphosed in situ within their host gneisses at high pressures (e.g. Bryhni et al. 1977). However, there is much less agreement on the activity of water during their formation (e.g. Fry and Fyfe 1971; Holland 1979a). The assumption of low  $a_{\text{H}_2\text{O}}$  for the formation of eclogites implies that at the same P, T conditions but at higher  $a_{\text{H}_2\text{O}}$  an amphibolite or an amphibole-garnet rock would be stable instead of eclogite. Thus, on this assumption such rocks can form coevally with the eclogite due to local  $a_{\text{H}_2\text{O}}$  and/or later due to retrogressive hydration of the eclogite. A careful study of the relationship of amphibole to anhydrous minerals in eclogite in a single terrain is therefore important. Scarcely altered kyanite-eclogites from the Bitlis Massif in eastern Turkey are closely associated with amphibole-rich eclogites, and are suitable for such a study. Kyanite-eclogites from the Bitlis Massif are also of interest in that they occur in an Alpine orogenic setting and apparently constitute the only occurrence of such rocks in the Balkans and the Middle East. In this paper, the term eclogite is used for rocks consisting essentially of garnet and omphacite

with minor (<10%) amphibole, and amphibole-eclogite for rocks consisting of abundant amphibole (>10%) coexisting with omphacite and garnet.

### Geological setting

The Bitlis Massif is an extensive area of allochthonous metamorphic rocks 300 km long and 40 km wide in southeastern Turkey (Fig. 1). Bitlis metamorphic rocks overlie, with an intervening tectonic zone of ophiolite and Tertiary flysch, the Paleozoic to Tertiary shelf sequences of the Arabian platform (Hall 1976). The southward post-Eocene thrusting of the Bitlis Massif has resulted in internal imbrication, so that the Bitlis Massif now consists of a large number of northward dipping slices of gneiss, amphibolite, metagranite, micaschist, marble and metabasite. Reconstructed stratigraphic sections of the Bitlis Massif usually differentiate between an old basement composed of gneiss and amphibolite of pre-Devonian and probably Precambrian age and a Paleozoic-Mesozoic cover of marble, phyllite and metabasite with low-grade Alpine metamorphism (Boray 1975; Yılmaz 1975; Erdoğan 1982; Helvacı and Griffin 1983; Göncüoğlu and Turhan 1984).

Kyanite-eclogites were discovered by Türkünel (1980) in the basement of the Bitlis Massif in the Gablor area



**Fig. 1.** Geological setting of the Bitlis Massif in southeastern Turkey. The location of the cross-section in Fig. 2 is also shown

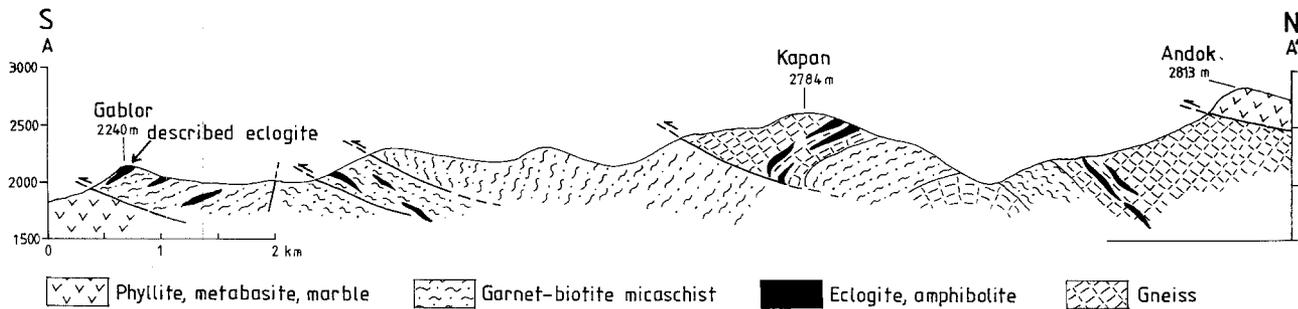


Fig. 2. N-S cross-section through the Bitlis Massif between Muş and Cacas showing its internal structure and the location of the studied kyanite-eclogites

between Muş and Cacas (Figs. 1, 2). Further detailed mapping has shown that the several northward dipping crystalline slices of this region can be grouped into three lithological types (Fig. 2): a) metavolcano-sedimentary unit of the cover sequence, which includes spilite, green and red shale, quartzite and limestone of probable Triassic age metamorphosed in lower greenschist facies, b) garnet-biotite-micaschists intruded by pre-metamorphic granites, c) augengneisses and amphibolites with minor kyanite-eclogites.

#### Field relations of the kyanite-eclogite

Although amphibole-eclogites and amphibolites are common within the gneiss and micaschist slices of the studied region, fresh kyanite-eclogite is only found on the Gablor Hill (Fig. 2). The eclogitic rocks of the Gablor Hill form two lenticular bodies, 200–300 m long and up to 100 m thick, and are embedded in garnet-micaschists which show strong mylonitisation along the eclogite contacts. Garnet-micaschists consist of quartz, plagioclase, biotite, garnet and muscovite. Gablor eclogites are not homogeneous, but show a distinct layering defined by variations in grain size, and more conspicuously, by amphibole-eclogite layers several centimeters thick intercalated with the kyanite-eclogite. Apart from these two large eclogitic bodies, the garnet-micaschists contain 10 cm to 10 m thick lenses and layers of amphibolitised eclogite, layered amphibolite and coarse-grained pegmatoid gabbro. The whole complex of eclogite, amphibolite and micaschist, named the Gablor Group, is cut by microdioritic dykes and quartz veins 0.2 to 0.6 m thick. The microdioritic dykes contain abundant primary muscovite and relict garnet in addition to plagioclase and quartz. A large skarn body probably related to the same magmatism and composed of garnet, clinopyroxene, kyanite, pale amphibole, phlogopite and quartz has also formed within the micaschists.

The Gablor Group lies tectonically over a volcano-sedimentary sequence of shale, limestone, spilite and quartzite metamorphosed in lower greenschist facies, and is overlain by a tectonic slice of garnet-biotite-micaschists (Fig. 2). A second slice of the Gablor Group made up of gneiss, micaschist and amphibolitised eclogite occurs further north (Fig. 2).

Studies of amphibolites from other parts of the Bitlis Massif have also revealed the presence of relict omphacites and/or diopside + oligoclase symplectites suggesting that the old basement of the Bitlis Massif has undergone a Precambrian high pressure metamorphism.

#### Petrography

##### *Kyanite-eclogite*

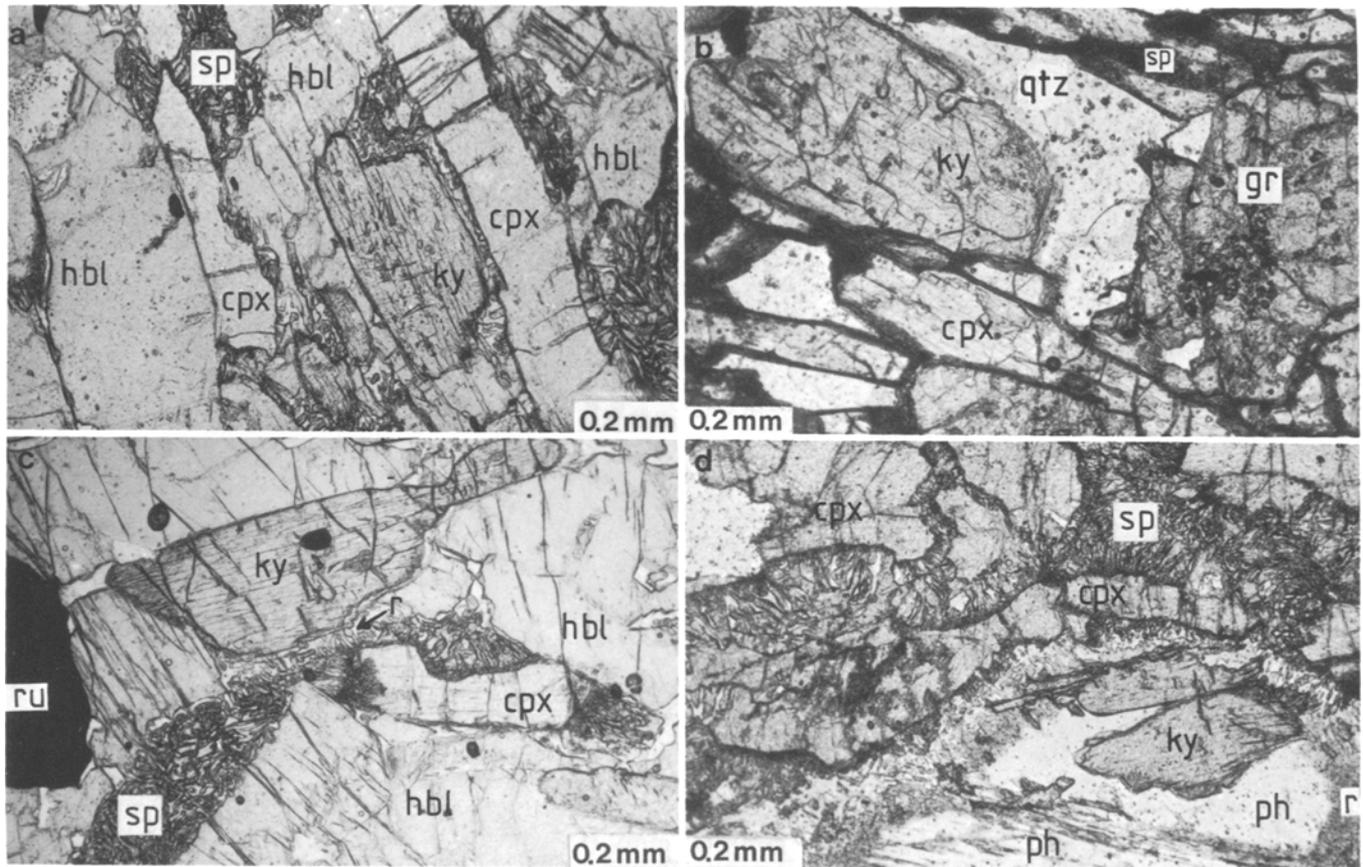
Two main types of kyanite-eclogite are recognised in the field. The common quartz-free kyanite-eclogite, typified by MU12D (Table 1), is a massive, dense, pale bluish-green rock with a porphyroblastic texture. Large, pink garnet crystals up to one centimeter in diameter are set in a pale bluish-green groundmass of omphacite and kyanite. Kyanite also occurs along some surfaces as irregularly oriented laths up to several centimeters long. Colourless to white, acicular crystals of zoisite in parallel alignment, colourless mica flakes and large black amphiboles are noticeable in most hand specimens. Quartz-free kyanite-eclogites are essentially composed of omphacite, garnet, kyanite and calcic amphibole with minor amounts of zoisite, phengite, rutile and pyrite. Colourless to very pale greenish-brown amphibole occurs either as large poikiloblastic crystals several millimeters across, enclosing smaller kyanite, zoisite and omphacite grains (Fig. 3c), or forms an equigranular, oriented groundmass with omphacite and kyanite (Fig. 3a). A distinct linear fabric in the rock is defined by the parallel alignment of elongate omphacite, zoisite and kyanite grains (Fig. 3a). There is also an irregular subparallel banding defined by a few millimeter-thick streaky layers of zoisite, kyanite and calcic amphibole surrounded by more voluminous aggregates of omphacite and kyanite.

Layered quartz-bearing kyanite-eclogites, typified by MU33 (Table 1), are finer-grained pale greenish-grey, equigranular rocks with a granoblastic texture. Garnet, omphacite, zoisite and kyanite crystals, 0.5 to 1 mm large, form a granoblastic aggregate with interstitial quartz (Fig. 3b). Amphibole occurs as rare, pale brown porphyroblastic grains (Table 1). A mineral lineation defined by the parallel alignment of omphacite, kyanite and zoisite crystals (Fig. 3b) and an inconspicuous layering defined by variation in modal quartz is present; some layers contain up to 50% quartz associated with garnet, omphacite, zoisite and kyanite. Quartz-eclogite, MU18, is texturally similar to this type of eclogite, except for the absence of kyanite in the mineral assemblage (Table 1).

The inferred primary minerals in the Gablor kyanite-eclogites are omphacite, garnet, kyanite, calcic amphibole, phengite, rutile and quartz.

##### *Amphibole-eclogite*

There is a continuous range from essentially anhydrous kyanite-eclogites to amphibole-kyanite-eclogites and amphi-



**Fig. 3a–d.** Photomicrographs from the kyanite-eclogites: **a** Parallel aligned equilibrium assemblage of omphacite (*cpx*), kyanite (*ky*) and colourless hornblende (*hbl*) from the amphibole-kyanite-eclogite, MU62. Hornblende and kyanite have small rutile inclusions (dark) and omphacite shows partial breakdown to an oligoclase-diopside symplectite (*sp*). **b** Quartz-kyanite-eclogite (MU33) with the stable assemblage of garnet (*gr*), omphacite (*cpx*), kyanite (*ky*) and quartz (*qtz*). Omphacite is partially broken down to a fine-grained dark symplectite of oligoclase + diopside (*sp*). **c** Kyanite (*ky*), omphacite (*cpx*) and rutile (*ru*) enclosed by colourless hornblende (*hbl*) porphyroblasts in the kyanite-eclogite, MU12D. Note the irregular breakdown of omphacite to the finger-like symplectite (*sp*), and the colourless hornblende + albite reaction rim (*r*) between kyanite and omphacite (*cpx*). **d** Stably coexisting omphacite (*cpx*), kyanite (*ky*) and phengite (*ph*) assemblage in the amphibole-kyanite-eclogite, MU62. Note the phlogopite + feldspar + zoisite reaction rim (*r*) around phengite

**Table 1.** Measured modes of the Gablor eclogites

	MU33	MU18	MU12D	MU62	MU14A	
Omphacite <sup>a</sup>	59.1 (24.4)	48.5 (6.6)	61.2 (25.7)	48.8 (24.0)	78.3 (62.5)	3.9 (3.4)
Garnet <sup>b</sup>	29.1	32.9	16.4 (0.6)	17.9 (0.3)	16.0 (0.3)	4.5
Kyanite <sup>c</sup>	2.4	–	12.0 (0.9)	8.1 (0.3)	–	–
Zoisite	2.0	1.3	–	–	2.0	–
Ca-amphibole	0.1	7.2	8.8	24.6	2.6	77.5
Phengite <sup>d</sup>	–	–	1.2 (0.1)	0.3	–	–
Rutile	0.3	1.1	0.3	0.3	0.7	0.4
Quartz	6.4	8.6	–	–	–	–
Pyrite	0.6	0.4	–	–	0.2	0.2
Plagioclase	–	–	0.1	–	0.2	13.5
	100.0	100.0	100.0	100.0	100.0	100.0

The numbers in the brackets indicate respectively the modal percent of <sup>a</sup> oligoclase + diopside symplectite, <sup>b</sup> kelyphite corona, <sup>c</sup> oligoclase + amphibole symplectite, <sup>d</sup> biotite corona

Two modes under MU14A represent the measured modes of contiguous eclogite and amphibole-eclogite bands within a single thin section

bole-eclogites with up to 80% modal amphibole (Table 1). A typical amphibole-kyanite-eclogite is the specimen MU62, which consists of strongly poikilitic garnet porphyroblasts set in a groundmass of parallel-aligned equigranular omphacite, calcic amphibole and kyanite with minor phen-

gite and rutile (Fig. 3a, Table 1). Texturally and mineralogically the rock is similar to the quartz-free eclogites (e.g. MU12D), and only differs in the abundance of calcic amphibole. Other amphibole-eclogites, like the specimen MU14A consist dominantly of 2–5 mm large interlocking

**Table 2.** Representative mineral compositions

	Omphacite			Calcic amphibole					Garnet			Phengite			
	MU33	MU18	MU12D	MU33	MU33 inc <sup>b</sup>	MU18	MU12D	MU14A	MU33	MU18	MU12D		MU12D		
											core	rim	core	rim	
SiO <sub>2</sub>	54.32	54.54	55.43	46.64	43.47	48.48	47.35	46.29	39.86	39.92	37.46	38.87	49.07	49.40	
TiO <sub>2</sub>	0.02	0.08	0.07	0.38	0.55	0.33	0.27	0.40	0.01	0.00	0.00	0.02	0.32	0.45	
Al <sub>2</sub> O <sub>3</sub>	9.98	10.18	10.05	13.01	16.13	13.70	13.32	13.24	22.38	22.41	21.91	22.38	32.04	31.66	
FeO <sup>a</sup>	1.84	2.47	2.94	5.01	8.58	7.87	7.13	7.58	20.41	22.15	23.32	20.52	1.18	1.65	
MgO	10.69	10.00	10.40	15.22	12.58	14.84	14.64	14.35	10.21	8.02	7.13	10.87	2.39	2.39	
MnO	0.00	0.05	0.02	0.00	0.04	0.03	0.00	0.08	0.30	0.54	0.98	0.39	0.00	0.00	
CaO	16.13	14.78	16.26	10.06	9.71	10.18	9.55	9.83	7.73	7.76	8.54	7.10	0.02	0.05	
Na <sub>2</sub> O	5.50	5.70	5.43	3.93	4.06	3.74	4.11	3.28	0.02	0.00	0.00	0.00	1.52	0.91	
K <sub>2</sub> O	0.00	0.00	0.00	0.41	0.25	0.38	0.46	0.42	0.00	0.00	0.00	0.00	9.30	10.29	
Total	98.48	97.80	100.60	94.66	95.37	99.55	96.83	95.47	100.92	100.80	99.34	100.15	95.84	96.80	
Ions on basis of:															
	4 cations			23 oxygens					8 cations				22 oxygens		
Si	1.95	1.98	1.96	6.76	6.36	6.74	6.76	6.68	2.98	3.01	2.90	2.92	6.45	6.47	
Al <sup>4</sup>	0.05	0.02	0.04	1.24	1.64	1.26	1.24	1.32	0.02	0.00	0.10	0.08	1.55	1.53	
Al <sup>6</sup>	0.37	0.42	0.38	0.99	1.14	0.99	1.00	0.94	1.95	2.02	1.90	1.90	3.42	3.36	
Ti	0.00	0.00	0.00	0.04	0.06	0.03	0.03	0.04	0.00	0.00	0.00	0.00	0.03	0.04	
Fe <sup>3+</sup>	0.01	0.00	0.00	0.00	0.13	0.10	0.03	0.23	0.05	0.00	0.10	0.10			
Fe <sup>2+</sup>	0.05	0.07	0.09	0.61	0.92	0.82	0.82	0.69	1.22	1.40	1.41	1.19	0.13	0.18	
Mg	0.57	0.54	0.54	3.29	2.74	3.07	3.12	3.09	1.14	0.90	0.82	1.22	0.47	0.47	
Mn	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.02	0.04	0.06	0.02	0.00	0.00	
	1.00	1.03	1.01	4.93	5.00	5.01	5.00	5.00					4.05	4.05	
Ca	0.62	0.57	0.62	1.56	1.53	1.52	1.46	1.53	0.62	0.63	0.71	0.57	0.00	0.01	
Na	0.38	0.40	0.37	1.11	1.16	1.01	1.14	0.92	0.00	0.00	0.00	0.00	0.39	0.23	
K	0.00	0.00	0.00	0.04	0.05	0.07	0.08	0.08	0.00	0.00	0.00	0.00	1.56	1.72	
	1.00	0.97	0.99	2.71	2.74	2.60	2.68	2.53	5.00	4.97	5.00	5.00	1.95	1.96	
Total	4.00	4.00	4.00	15.64	15.74	15.61	15.68	15.53	8.00	8.00	8.00	8.00	14.00	14.01	
Jd	37	41	38						Alm	40	47	47	39		
Ac	1	0	0						Spess	1	2	2	1		
Alu	62	59	62						Pyr	38	30	27	41		
									Gross	21	21	24	19		

<sup>a</sup> Total iron as FeO<sup>b</sup> inclusion in garnet

prismatic crystals of pale calcic amphibole enclosing and apparently overgrowing smaller grains of garnet, omphacite and rutile (Table 1). Layers of amphibole-eclogite, ranging in thickness from a few millimeters to several tens of centimeters, are closely interlayered with eclogite. The measured modes of such contiguous amphibole-eclogite and eclogite layers within a single thin-section are given in Table 1. In some amphibole-eclogites, plagioclase occurs as narrow rims between amphibole-amphibole and amphibole-omphacite grains, and as small irregular grains within the amphibole crystals, probably representing former omphacite grains.

#### Corona textures

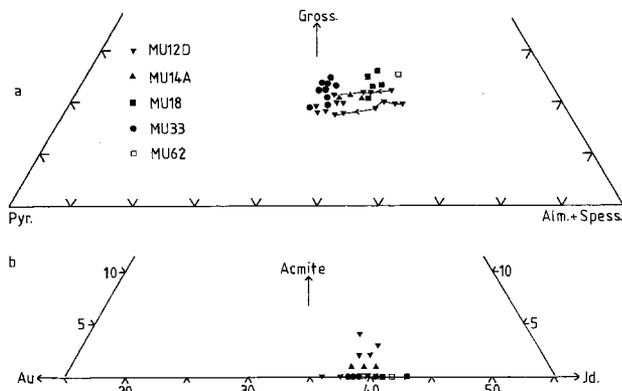
Even the best preserved eclogites show some degree of alteration of the primary minerals. Omphacites are altered along their margins to a symplectite of diopside and oligoclase; the symplectite ranges from very fine-grained to 0.1 mm thick finger-like intergrowths (Fig. 3a-d). Thin (<0.1 mm) coronas of pale-green calcic amphibole and oligoclase have developed along some kyanite-omphacite boundaries; the amphibole in the coronas forms very small

(<0.01 mm) individual crystals growing from kyanite and projecting into the plagioclase (Fig. 3c). Phengite is partially to completely replaced by an intergrowth of biotite, muscovite, feldspar and zoisite (Fig. 3d). Bluish-green hornblende occurs as thin discontinuous kelyphitic rims around garnets. All these corona reactions appear texturally to be broadly contemporaneous and related to the dry uplift of the eclogite through the amphibolite and greenschist facies. The very small size of the amphiboles in the amphibole-oligoclase reaction zones between kyanite and omphacite grains suggests that the large amphibole crystals in the matrix of the eclogites have formed prior to the corona reactions.

#### Minerals

##### Analytical technique

Minerals were analysed using a JEOL JXA-733 computer-controlled electron microprobe. Analyses were performed at 15 kV acceleration potential with a specimen current of  $1.97 \times 10^{-8}$  A, and were processed on-line using the ZAF correction programme. Both synthetic and natural mineral standards were used. Representative analyses are listed in Table 2. The method for estimating Fe<sup>3+</sup> in sodic pyroxene is given in Okay (1978).



**Fig. 4a.** Garnet compositions from the Gablor eclogites plotted on the pyrope-grossular-(almandine+spessartine) diagram in terms of mol%; all spessartine contents are below 1 mol%. The garnet compositions from MU14A are from the eclogite-layer (Table 1). **b** Pyroxene compositions from the Gablor eclogites plotted on part of the acmite-jadeite-augite diagram; symbols as in Fig. 4a

### Garnet

Idioblastic garnet porphyroblasts in the Gablor eclogites are packed with inclusions of all the primary phases of eclogite; individual kyanite poikiloblasts, up to one millimeter in size, are common as inclusions in garnet. The inclusions in some garnets are aligned parallel to the mineral fabric of the rock indicating post-deformational garnet growth.

Garnet compositions from five samples are plotted in Fig. 4 in terms of pyrope, grossular and almandine+spessartine end-members. Four of the analyses are given in Table 2. All analysed garnets are essentially almandine-pyrope-grossular solid solutions. The large poikiloblastic garnets from MU12D show a distinct zoning involving an increase in pyrope component towards the rim at the expense of the almandine component at a fairly constant grossular concentration of about 21 mol% (Fig. 4a). Very similar garnet zoning is observed in the kyanite-eclogites from the Tauern Window in the Eastern Alps (Holland 1979a). No zoning is detected in the smaller garnets from the quartz-kyanite-eclogite MU33; the compositions of these garnets,  $\text{Alm}_{40}\text{Pyr}_{37}\text{Gr}_{22}\text{Sp}_{1}$ , are similar to the rim compositions of the poikiloblastic garnets (Fig. 4a). The range of pyrope contents of the garnets from the Gablor eclogites, 26–42 mol%, is typical for the Group B eclogites (Coleman et al. 1965).

### Omphacite

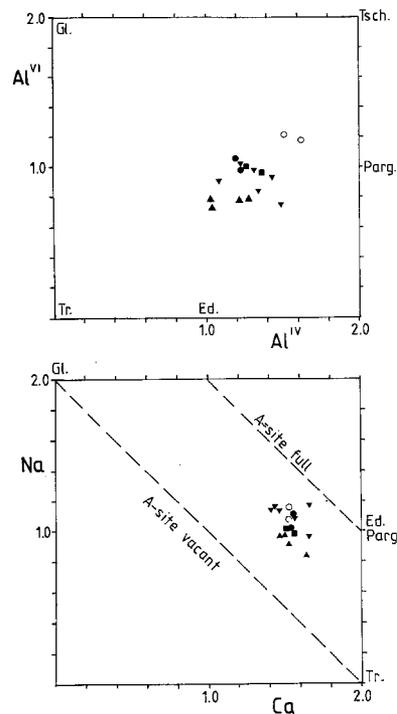
Omphacite in the Gablor eclogites occurs as parallel-aligned colourless prismatic crystals, which are singularly free of inclusions. The omphacite compositions from five rocks, plotted in the acmite-jadeite-augite ternary diagram in Fig. 4b, are fairly uniform, with very low acmite contents (<4%) and with an average composition of  $\text{Au}_{60}\text{Jd}_{39}\text{Ac}_1$ . Omphacites are not zoned, and show only minor tschermakite substitution (Table 2).

### Kyanite

Kyanite grains tend to occur as 1–2 mm large, strongly poikilitic stubby crystals aligned parallel to the omphacite fabric; the inclusions are mainly zoisite. Several millimeters large post-tectonic kyanite porphyroblasts are observed in many samples. Two analyses of kyanite give only minor amounts of  $\text{Fe}_2\text{O}_3$  (0.35 wt%).

### Zoisite

Zoisite occurs as aggregates of parallel-aligned, very elongate (up to 2 mm long and 0.1 mm wide) crystals closely associated and



**Fig. 5.** Compositions of primary calcic amphiboles from the Gablor eclogites. Open circles denote amphibole compositions found as inclusions within garnet in MU33; other symbols as in Fig. 4a

often embedded in kyanite and calcic amphibole. Zoisite crystals are slightly zoned and are free of inclusions. They contain very minor quantities of  $\text{Al}_2\text{Fe}$ -epidote (2–4 mol%).

### Amphibole

Amphiboles from the Gablor eclogites show conflicting textures. In some rocks, e.g. MU12D or MU62, the amphibole forms an equigranular fabric with kyanite and omphacite (Fig. 3a), and is clearly in equilibrium with the anhydrous minerals. In other rocks, e.g. MU33, MU18, or in the different parts of the same rock, e.g. MU12D, amphibole forms several millimeter-large colourless to very pale-brown poikiloblastic crystals enclosing smaller kyanite, omphacite and zoisite grains (Fig. 3c). In layered eclogites, e.g. MU14A, the large pale-green prismatic amphibole crystals in the amphibole-eclogite bands are clearly overgrowing and replacing the anhydrous minerals. Such contrasting amphibole textures seem to be a common feature in eclogites (Coleman et al. 1965).

Although texturally varied, amphiboles from the Gablor eclogites have a fairly uniform composition (Fig. 5, Table 2) and plot in the field of edenite and edenitic hornblende (cf. Leake 1978). A representative mean composition is  $\text{K}_{0.04}\text{Na}_{0.67}\text{Na}_{0.44}\text{Ca}_{1.56}\text{Mg}_{3.29}\text{Fe}_{0.61}^{2+}\text{Al}^{\text{VI}}_{0.99}\text{Ti}_{0.04}\text{Si}_{6.76}\text{Al}^{\text{IV}}_{1.24}\text{O}_{22}(\text{OH})_2$ . Only the pale-green amphiboles from the amphibole-eclogite MU14A show slightly higher  $\text{Fe}^{3+}$  and lower  $\text{Al}^{\text{VI}}$  contents.  $\text{Fe}^{3+}$  in amphibole, estimated by assuming  $\sum \text{Si, Ti, Al, Fe}^{3+}, \text{Fe}^{2+}, \text{Mg} = 13.00$ , and a total ionic charge of 46, is very low or absent (Table 2), which is compatible with the very low acmite contents of omphacites and the absence of iron-oxide in the mineral assemblage.

Amphiboles from the Gablor eclogites are compositionally and texturally very similar to the pale calcic amphiboles from other kyanite-eclogites described as part of the primary eclogite mineralogy (Bryhni 1966; Mottana et al. 1968; Heinrich 1982). The pale colour, common poikiloblastic habit and very low  $\text{Fe}^{3+}$  concentrations seem to be characteristic features of the amphiboles (“carinthines”) from the kyanite-eclogites.

The amphibole inclusions in the garnet porphyroblasts of the Gablor eclogites probably represent an early generation. The gener-

al pale colour of these inclusions, as compared to the dark-green kelyphitic amphibole rims around garnets, suggests that there was little postentrapment reaction between the included amphiboles and the surrounding garnet, and that most of the amphibole inclusions represent the composition of early amphiboles. The pale amphibole inclusions are paragonitic hornblendes (Leake 1978) and have lower Mg/Mg+Fe ratios and Si contents than the matrix amphiboles (Fig. 5, Table 2). No satisfactory analyses can be obtained from the small, colourless to pale-green amphiboles in the reaction zones between kyanite and omphacite.

### Mica

Phengite occurs as large (1–3 mm) individual flakes aligned roughly with the fabric of the eclogite. Phengite crystals commonly enclose kyanite grains and are closely associated with omphacite (Fig. 3 d). Analysed phengites show a range of paragonite (8–20 mol%) and minor margarite (<2 mol%) contents. Basal sections of phengite exhibit a regular zoning, with a decrease of paragonite content towards the rim (Table 2). Reddish brown biotite, close to eastonite in composition, finely recrystallised muscovite, elongate zoisite and colourless chlorite are among the breakdown products of phengite (Fig. 3 d).

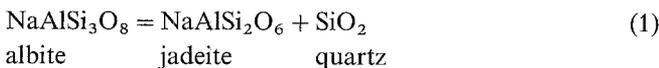
### Other mineral

Dark orange-brown *rutile* is an ubiquitous accessory mineral in the Gablor eclogites. It also occurs as inclusions in garnet and kyanite crystals. *Quartz* grains form strain-free polygonal mosaics, and small inclusions in garnet crystals in the quartz-eclogites; no quartz textures suggesting inversion from coesite, or radial cracks around quartz inclusions in garnets suggesting the former presence of coesite (cf. Chopin 1984) are observed in the Gablor eclogites. *Pyrite* forms small idioblastic crystals in some eclogites.

### Metamorphic conditions

The peak metamorphic temperatures are estimated from the distribution of  $\text{Fe}^{2+}$  and Mg between the garnet rims and contiguous omphacites using the Ellis and Green (1979) calibration.  $K_D$  values for seven contiguous omphacite-garnet pairs from two specimens (MU18 and MU33), which do not show kelyphitic rims around garnets, range from 9.2 to 12.3 (Fig. 6) and indicate temperatures of 580–680°C for 10 to 20 kbar pressure range (Fig. 7). Temperatures can also be estimated from the empirically calibrated garnet-hornblende geothermometer based on the Fe:Mg partitioning between the two minerals (Graham and Powell 1984). Garnet-amphibole pairs from four specimens (MU18, MU33, MU12D, MU14A) give a temperature range of 570–630°C, which compares well with the range of temperatures obtained by the garnet-clinopyroxene geothermometry, suggesting that garnet, pyroxene and amphibole have attained chemical equilibrium.

Pressures can be estimated from the reaction



In the absence of albite, pyroxene is not saturated with respect to the jadeite content, and reaction (1) can only give minimum pressures. Experimental work indicates pseudo-ideality on the jadeite-diopside join for omphacite compositions (Wood et al. 1980); the activity of jadeite in omphacite is therefore taken equal to its mole fraction, and thermodynamic data from Holland (1980) is used for the calculations. For the highest analysed jadeite content in omphacite ( $X_{\text{jd}} = 0.43$  in MU18), reaction (1) yields a mini-

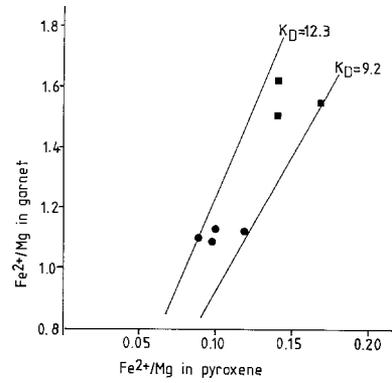


Fig. 6. The distribution of  $\text{Fe}^{2+}$  and Mg between garnet and omphacite (contiguous rim compositions only); symbols as in Fig. 4a

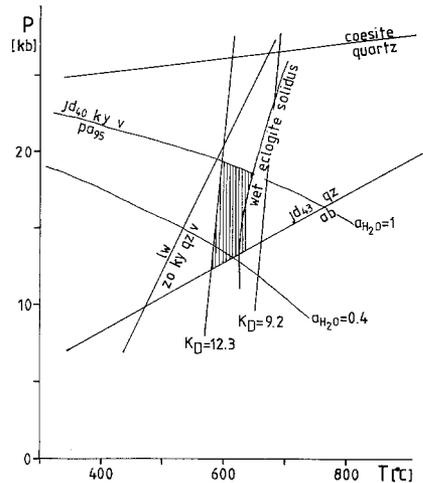
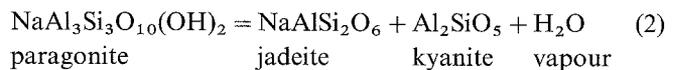


Fig. 7. Pressure-temperature diagram for the Gablor eclogites displaying the metamorphic temperatures from the garnet/pyroxene geothermometer (subvertical lines). Minimum pressures estimated from reaction (1), maximum pressures and range of  $a_{\text{H}_2\text{O}}$  estimated from reaction (2) are also shown;  $pa_{95}$  refers to the paragonite activity in phengite. The conditions of Gablor eclogite crystallisation fall within the vertically ruled area. The lawsonite breakdown curve (Newton and Kennedy 1963), wet eclogite solidus (Hill and Boettcher 1970) and quartz=coesite reaction curve are indicated

imum pressure estimate of about 13 kbar for the temperature range of interest (Fig. 7).

An important pressure and  $a_{\text{H}_2\text{O}}$  sensitive reaction is:



which was experimentally investigated by Holland (1979b). The reaction is applicable to the Gablor eclogites, which have stably coexisting omphacite, kyanite and white mica (e.g. MU12D, Fig. 3 d). However, the calculation of pressure and  $a_{\text{H}_2\text{O}}$  from reaction (2) involves not only estimation of the activity of jadeite in omphacite as above, but also that of paragonite in phengite. The paragonite-muscovite solid solution is known to show strong non-ideality. The paragonite activity in phengite was estimated by first calculating its activity on the ideal site-mixing model, where on the basis of formula  $\text{NaAl}_2\text{Si}_3\text{AlO}_{10}(\text{OH})_2$ , the ideal site-mixing activity is given by:

$$a_{\text{pa}}^{\text{id}} = 9.48 X_{\text{Na}}^4 X^{\text{M}1} [X_{\text{Al}}^{\text{M}2}]^2 X_{\text{Al}}^T [X_{\text{Si}}^T]^3$$

The non-ideality was accounted by estimating the activity coefficient  $\gamma_{Pa}$  from the excess functions given by Eugster et al. (1972):

$$RT \ln \gamma_{Pa} = (1 - X_{Pa})^2 (W_{Pa} + 2X_{Pa}(W_{Mu} - W_{Pa}))$$

where  $W_{Mu} = 4,163.9 + 0.1259 P + 0.3954 T$  (bars, °K)

$$W_{Pa} = 3,082.1 + 0.0822 P + 0.1698 T$$
 (bars, °K)

and  $X_{Pa}$  is the mole fraction of paragonite (K/K + Na) in white mica. The paragonite activity is then given by  $a_{Pa} = \gamma_{Pa} a_{Pa}^{id}$ .

Calculation of the paragonite activity in phengite also requires the knowledge of the pressure and temperature of formation of the eclogite. For a pressure of 16 kbar and a temperature of 625° C (see below), the paragonite activity for the core compositions of phengites from MU12D (cf. Table 2) is 0.95. Taking a jadeite activity of 0.40 in omphacite (cf. Fig. 4b), a paragonite activity of 0.95 and  $a_{H_2O}$  of 1, and using the  $H_2O$  fugacities at high pressures and temperatures given by Delany and Helgeson (1978) and the thermodynamic data from Holland (1979b), reaction (2) indicates a pressure of 18–19 kbars for the temperature range of interest, assuming a  $H_2O$ -rich fluid phase was present during the metamorphism (Fig. 7). A lower  $a_{H_2O}$  limit during the eclogite crystallisation can be calculated from reaction (2) using the lower pressure limit given by the albite = omphacite (jd<sub>4.5</sub>) + quartz reaction. Calculations indicate that  $a_{H_2O}$  was above 0.4 during the eclogite crystallisation (Fig. 7). The paragonite-poor phengite rim compositions (cf. Table 2), indicating either higher pressures (20–21 kbars at  $a_{H_2O} = 1$ ) or lower activities of  $H_2O$ , probably reflect decreasing  $a_{H_2O}$  during the waning stages of the eclogite crystallisation.

Summarising the evidence presented, the Gablor eclogites can be said to have crystallised at temperatures of  $625 \pm 35^\circ$  C, at pressures of  $16 \pm 3$  kbar, with  $a_{H_2O}$  having some value between 0.4 and 1 (Fig. 7).

### Phase relations

The relationship of eclogite to amphibolite, which is essentially that of amphibole to the anhydrous minerals in eclogite, is controversial (Bryhni et al. 1970). There are various possibilities: a) amphibole and the anhydrous minerals of the eclogite could represent an equilibrium assemblage at the peak metamorphic conditions and at a fixed activity of  $H_2O$ , b) amphibole could be in equilibrium (reversible) reaction with the anhydrous minerals, probably caused by episodic influx of hydrous fluids into the "dry" eclogite at or near the peak metamorphic conditions, c) amphibole could be in disequilibrium (irreversible) reaction with the anhydrous minerals. This could happen if hydrous fluids enter the eclogite during its uplift to the surface. The criteria to discriminate between these possibilities are textural and chemical.

In Gablor eclogites the third possibility can be ruled out, as amphibole porphyroblasts have formed before the anhydrous corona reactions, are compositionally similar to amphiboles from HP/HT metabasic rocks, and have equilibrated with garnet and pyroxene at high temperatures. The contrasting textures of amphibole in Gablor eclogites, indicating both stable coexistence with, as well as growth at the expense of the anhydrous minerals, and the regular Fe–Mg partitioning between amphibole, garnet and pyroxene

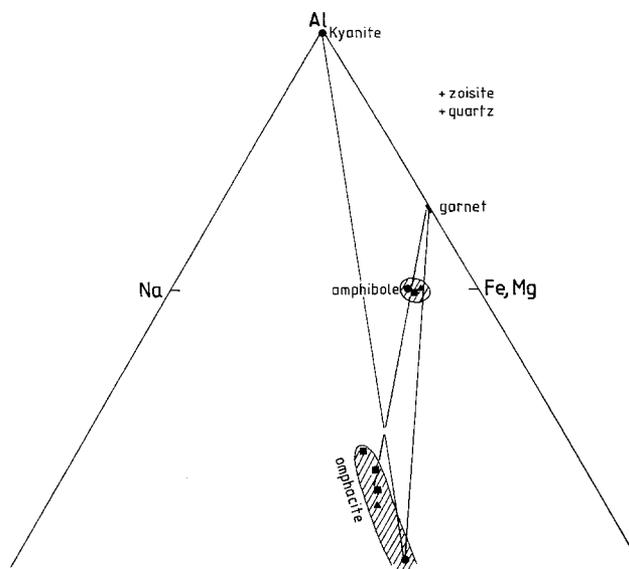
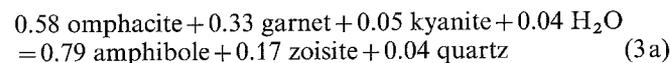
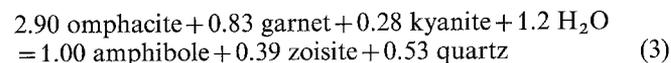


Fig. 8. Projection of mineral compositions from zoisite, quartz and rutile, at a fixed value of  $a_{H_2O}$ , onto the Na–Al\*–(Fe, Mg) plane. Al\* = Al – 2Ca. Ranges of amphibole, pyroxene and garnet compositions from the Gablor eclogites are also shown. Symbols as in Fig. 4a

can only be explained by an equilibrium reaction between garnet, pyroxene and amphibole. The relationship between the three minerals can be evaluated by a phase relations analysis.

The lowest variance mineral assemblage, as found in specimen MU33, is omphacite + garnet + kyanite + zoisite + amphibole + quartz + rutile (Table 1). This mineral paragenesis lies in the eight component system  $SiO_2 - TiO_2 - Al_2O_3 - FeO - MgO - CaO - Na_2O - H_2O$ . The relationship between the phases can be graphically depicted in a Na–Al–Fe, Mg (NAF) ternary diagram (Fig. 8) by projecting from quartz, zoisite and rutile, and assuming a fixed  $a_{H_2O}$ . The NAF diagram in Fig. 8 shows the equivalence of amphibole to omphacite + garnet and to omphacite + garnet + kyanite. Ignoring Fe:Mg partitioning a balanced reaction can be written using the actual mineral compositions from MU33 (cf. Table 2):



Reaction (3a) is written in terms of oxygen units (cf. Thompson et al. 1982, p. 11), which express the changes in modal abundances during the reaction, as the volume of silicates is nearly proportional to the number of oxygen atoms contained. Reaction (3a) involves mainly omphacite, garnet and amphibole, as would be expected from the NAF ternary diagram in Fig. 8. Because amphibole plots between garnet and omphacite in the NAF diagram (Fig. 8), reaction (3) will also occur in kyanite-free eclogites with only very minor balancing exchange substitutions in amphibole.

Because of the unequal partitioning of Fe and Mg between amphibole, pyroxene and garnet, reaction (3) will be a continuous reaction; however, it will also act as a sliding buffer for  $H_2O$ . In Gablor eclogites the contrasting

textures of the amphiboles and the late porphyroblastic growth of kyanite and garnet, thought to have formed at similar  $P-T$  conditions, can be explained through the buffering of  $H_2O$  by the mineral assemblage. The lack of carbonates and the presence of zoisite in the Gablor eclogites indicate that the activity of  $CO_2$  was low ( $X_{CO_2} < 0.1$ , Kerrick 1974). Thus, the buffering of  $a_{H_2O}$  during the eclogite crystallisation, suggested by the mineral textures, indicates that either the  $H_2O$ -rich fluid phase was diluted by other components such as  $H_2S$ ,  $NaCl$  or that there was no fluid phase. Even at reduced values of  $a_{H_2O}$ , mineral reactions will readily occur in eclogites because of the very large positive departures from ideality in the fugacity of  $H_2O$  at high pressures (cf. Delany and Helgeson 1978).

The fluctuations in  $a_{H_2O}$  during the *HP/HT* metamorphism could have been caused by the partial melting of pelites and/or by the crystallisation of deep-seated granitoidic liquids. The presence of muscovite and garnet in the microdiorite dykes, which cut the Gablor eclogites, indicates that the microdiorites were produced through the partial melting of pelites at depths of over 25 km (Green 1976). Skarns within the Gablor Group include kyanite, indicating that the Gablor Group was at considerable depth when it was intruded by the dykes. Thus, the partial melting of pelites would have consumed  $H_2O$ -rich fluids, and the crystallisation of granitoidic liquids would have evolved  $H_2O$ -rich fluids, which would have reacted episodically with the eclogite (cf. Bryhni et al. 1970). The formation of eclogites and S-type granitoids were most likely related events caused by the thickening of the continental crust by overthrusting, leading to high pressure metamorphism and partial melting at deep crustal levels.

The rare Precambrian metamorphic rocks of Turkey probably formed during the Pan-African event (Şengör et al. 1984). The Pan-African rocks of the Arabian-Nubian shield, the nearest large Pan-African terrain to Turkey, are interpreted as cratonised intra-oceanic island arcs, but are generally metamorphosed only to the greenschist facies (Greenwood et al. 1976; Gass 1981). The presence of eclogites of probable Pan-African age in southeastern Turkey is therefore of considerable tectonic significance.

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