Jadeite–chloritoid–glaucophane–lawsonite blueschists in northwest Turkey: unusually high *P/T* ratios in continental crust

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ABSTRACT Sodic metapelites with jadeite, chloritoid, glaucophane and lawsonite form a coherent regional metamorphic sequence, several tens of square kilometres in size, and over a kilometre thick, in the Orhaneli region of northwest Turkey. The low-variance mineral assemblage in the sodic metapelites is quartz + phengite + jadeite + glaucophane + chloritoid + lawsonite. The associated metabasites are characterized by sodic amphibole + lawsonite ± garnet paragenesis. The stable coexistence of jadeite + chloritoid + glaucophane + lawsonite, not reported before, indicates metamorphic pressures of 24 ± 3 kbar and temperatures of 430 ± 30 °C for the peak blueschist facies conditions. These *P–T* conditions correspond to a geotherm of 5 °C km^{-1}, one of the lowest recorded in continental crustal rocks. The low geotherm, and the known rate of convergence during the Cretaceous subduction suggest low shear stresses at the top of the downgoing continental slab.

Key words: jadeite, chloritoid, blueschist, geotherm, Turkey, subduction.

INTRODUCTION

Petrological data provide the best record of the thermal structure of the subducted former continental or oceanic crust, represented as blueschist and eclogite terranes in orogenic belts. Knowledge of the shear and radioactive heating, rate of subduction and thermal structure of the former subduction zones depends to a large extent on the precise and accurate characterisation of the peak *P–T* conditions and *P–T–t* paths of the down-going slabs (e.g. Peacock, 1992). A common problem in this context is the estimation of metamorphic pressure in the blueschist belts, particularly in the lawsonite–blueschist facies, which covers a large *P–T* field above *c.* 8 kbar and below *c.* 500 °C (Evans, 1990). Metabasites in lawsonite–blueschist facies are dominated by the low variance sodic amphibole + lawsonite ± sodic pyroxene assemblages, which usually allow only a minimum estimate of the metamorphic pressures based on the jadeite content of the sodic pyroxene. Metapelitic lithologies, rare in the blueschist facies, have been shown to have great value in the precise estimation of the peak *P–T* conditions in the eclogite facies (e.g. Chopin, 1981a; Schreyer, 1985). Here, I describe sodic metapelites from northwest Turkey, which contain coexisting jadeite and chloritoid along with glaucophane and lawsonite. The stable coexistence of jadeite and chloritoid indicates geotherms as low as 5 °C/km for the Cretaceous blueschist metamorphism with implications for the subducted continental crust.

Blueschists in northwest Turkey form an east–west trending metamorphic belt, *c.* 250 km long and *c.* 50 km wide, called the Tavşanlı Zone, immediately south of the main Neo-Tethyan suture (Fig. 1). The coherent blueschist sequence in the Tavşanlı Zone consists of metapelitic schists at the base, marbles in the middle and a series of metabasite, metachert and phyllite at the top (Okay, 1984). The blueschists represent a subducted and subsequently exhumed passive continental margin sequence. Stratigraphic comparison with unmetamorphosed sequences farther south in the Taurides suggests a Infra-Cambrian–Palaeozoic depositional age for the basal metaclastic rocks, and a Mesozoic age for the marbles and the overlying metabasite-metachert sequence. Phengite Rb–Sr and Ar–Ar data from the blueschists indicate a Late Cretaceous (80 ± 5 Ma) age for the H*P*/L*T* metamorphism (Sherlock *et al.*, 1999). The coherent blueschist sequence is tectonically overlain by a Cretaceous accretionary complex of basalt, radiolarian chert and pelagic shale. The accretionary complex exhibits generally a low-grade incipient blueschist metamorphism. Large tectonic slabs of ophiolite, predominantly peridotite, lie over the coherent blueschists or the accretionary complex (Okay, 1984).

GEOLOGICAL SETTING

Chloritoid–jadeite schists occur in the western part of the Tavşanlı Zone around the town of Orhaneli. Blueschists in the Orhaneli region are predominantly metapelitic schists and marbles. The schists consist of quartz-rich greyschists at the base, and white, phengite-rich schists at the top below the marbles (Lisenbee, 1971). The greyschists form grey, finely banded, hard, medium-grained rocks representing sodic metapelites (Okay & Kelley, 1994). The minimum thickness of the schist sequence is *c.* 800 m. The

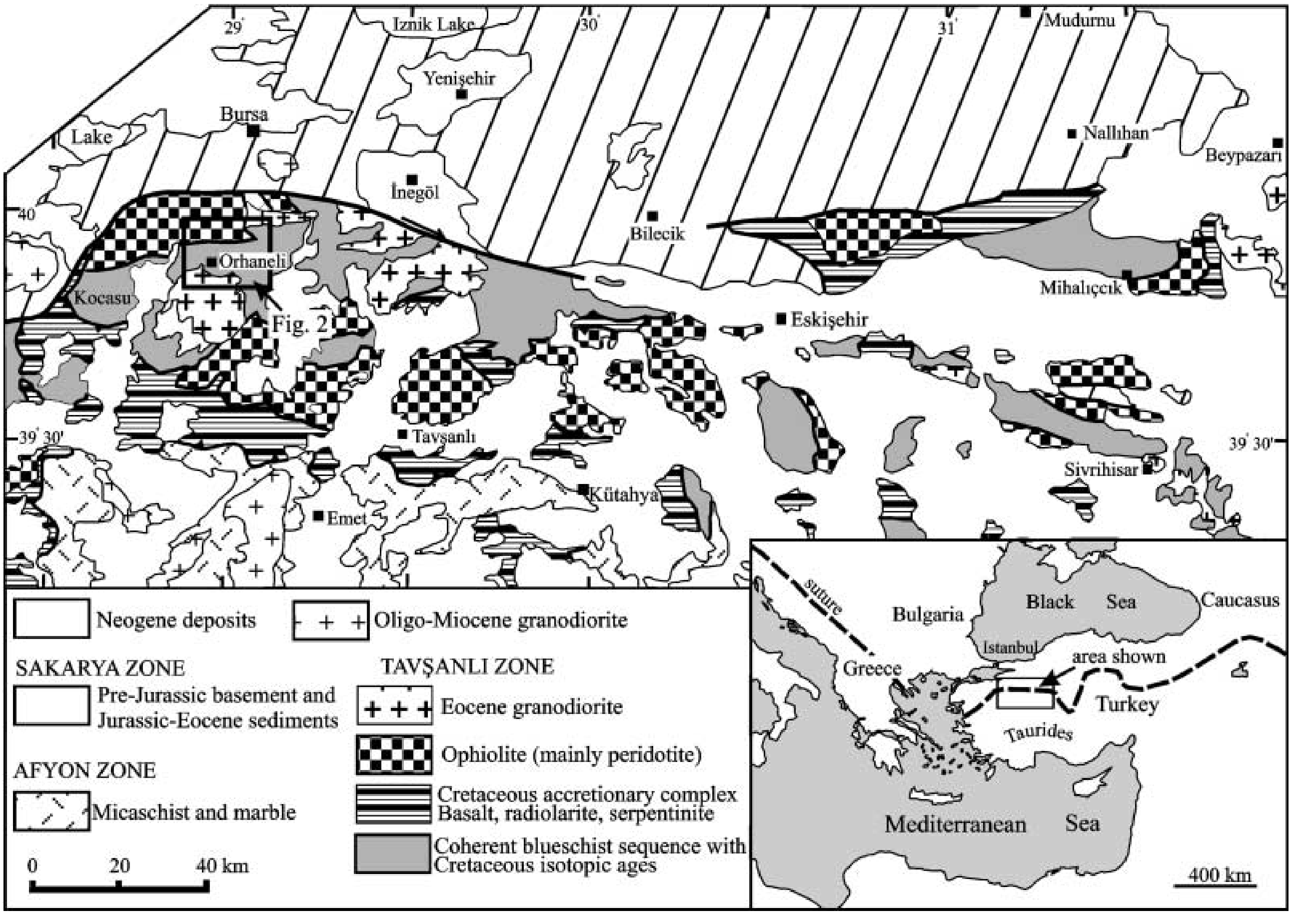

Fig. 1. Tectonic map of northwest Turkey showing the regional distribution of the blueschists.

schists are overlain by white marbles of over 400 m in thickness. Marble and calcschist bands, several metres thick, also occur within the schists. The schists show a strong ductile deformation with the development of penetrative foliation and mineral lineation. Isoclinal folds are present from the scale of thin section to 200–300 m with generally east–west trending fold axis (Lisenbee, 1971). Thin marble layers in the schists are stretched out in the fold limbs and are seldom continuous for more than a few hundred metres. The mineral stretching lineation defined by sodic amphibole and chloritoid in the schists, and by calcite in the marbles trends parallel to the axis of the isoclinal folds. Rare metabasite layers interfolded with the calcschists occur north of the village of Deliballar (Fig. 2). A late crenulation cleavage is well developed in the micaceous lithologies.

The coherent blueschist sequence is tectonically overlain by the Burhan ophiolite, which is made up of north–south trending dunite, harzburgite and gabbro bands, up to several kilometres in thickness (Lisenbee, 1971). The peridotite is cut by an east–west trending swarm of dolerite dykes. Narrow tectonic slivers of garnet-amphibolite, similar to the metamorphic soles described from the base of ophiolites worldwide (e.g. Spray, 1984), occur at the base of the Burhan ophiolite (Fig. 2). Locally, the sub-ophiolite metamorphic rocks show a weak blueschist facies overprint marked by development of small lawsonite aggregates in plagioclase, and by thin rims of sodic amphibole around hornblende crystals (Okay *et al.*, 1998; Önen & Hall, 2000). Hornblende from the garnet–amphibolite north of Deliballar has been dated by Ar–Ar method as 101 ± 4 Ma (Harris *et al.*, 1994).

The blueschists in the Orhaneli region are cut by two Eocene granodioritic plutons with well-marked contact metamorphic aureoles (Fig. 2). The Orhaneli and Topuk granodiorites are undeformed post-tectonic intrusions dated as 53 and 48 Ma, respectively (Harris *et al.*, 1994). Blueschist minerals are completely destroyed within a one-kilometre-wide contact metamorphic aureole with the growth of new minerals, including andalusite, cordierite, alkali feldspar and

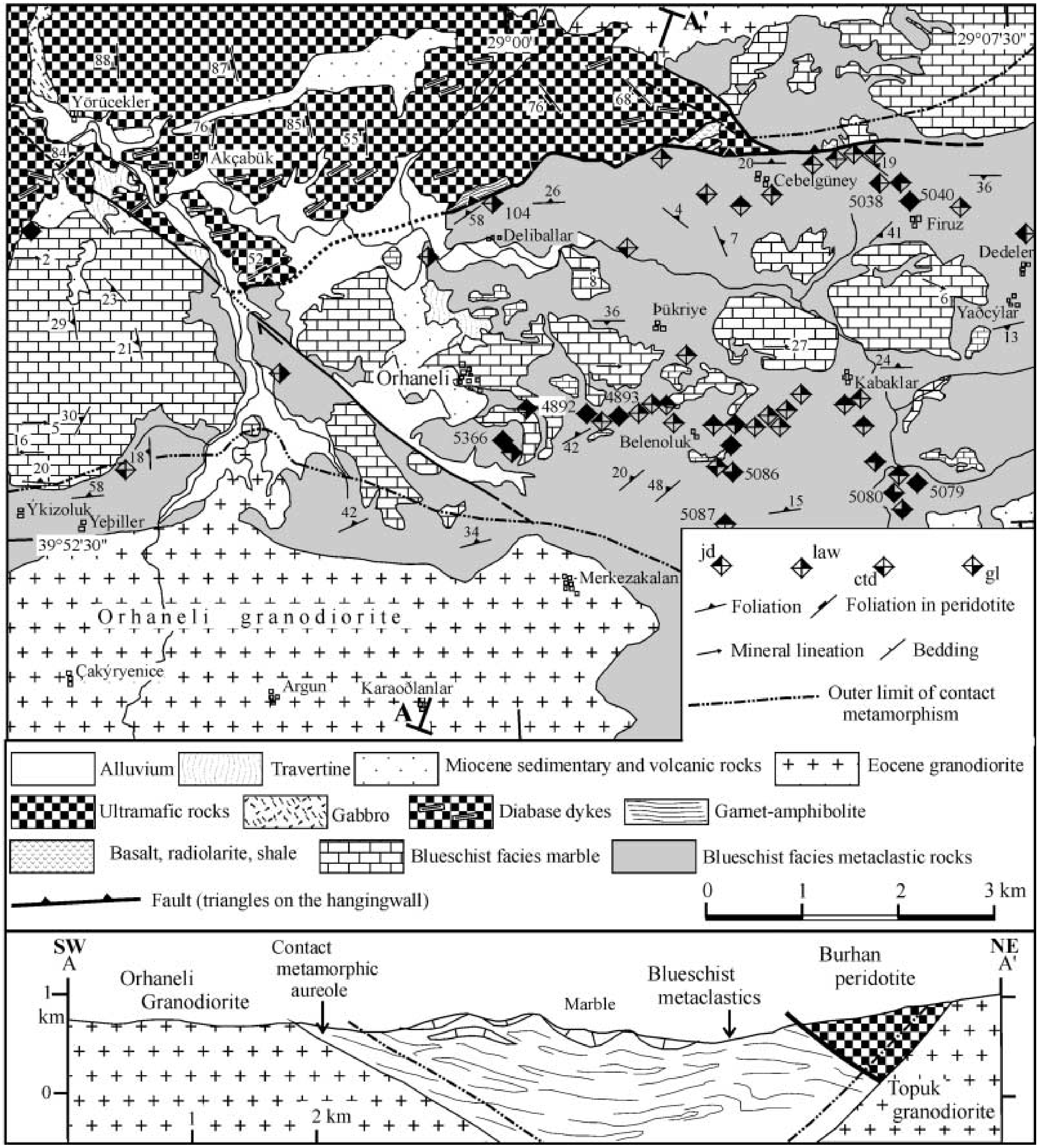

Fig. 2. Geological map and cross-section of the Orhaneli region (modified from Lisenbee, 1971) with the sample locations. The sample numbers are keyed to Table 1. For location see Fig. 1.

biotite. The contact metamorphic mineral assemblages and the Al-content of amphibole in the Orhaneli granodiorite indicate that the pluton was emplaced in the blueschists at a depth of *c*. 10 km during the Early Eocene (Harris *et al*., 1994). The blueschists, the ophiolite and the granodiorites are unconformably overlain by continental Miocene sedimentary and volcanic rocks.

PETROLOGY AND MINERAL CHEMISTRY

Petrography

One hundred and eighteen schist samples were petrographically studied from the Orhaneli region. The common minerals in the greyschists, in order of abundance, are quartz, white mica, jadeite, chloritoid, sodic amphibole, lawsonite and chlorite. Minor minerals include tourmaline, apatite, rutile, graphite, retrograde albite and magnetite.

Quartz and white mica constitute over half of the mode in the greyschists (Table 1). Quartz grains commonly show undulose extinction and recrystallization to smaller grain aggregates. White mica, predominantly phengite, forms aggregates of slender crystals defining the foliation. Only one out of 10 analysed samples contained paragonite closely associated with phengite, similar to the textures described by Shau *et al.* (1991) and Okay & Kelley (1994). Jadeite commonly occurs as equant porphyroblasts up to 1 mm in length. In many sections it appears dark due to small opaque inclusions (Fig. 3). In some sections jadeite porphyroblasts are rimmed and partially replaced by sericitic white mica. Bluish green chloritoid forms elongate prismatic grains, *c.* 0.5 mm long, aligned parallel to the foliation. Sodic amphibole occurs as idioblastic crystals, *c.* 0.5 mm long. In several samples it shows zoning with pale blue cores and colourless rims. Lawsonite shows its typical prismatic habit. In many thin-sections the four minerals, jadeite, chloritoid, sodic amphibole and lawsonite, occur in close proximity and are inferred to be in textural equilibrium (Fig. 3). In the least retrograded samples, such as 5080, chlorite or oxy-chlorite are absent or very scarce. In other samples pale-green chlorite or reddish-brown oxy-chlorite can be seen replacing sodic amphibole or chloritoid (Fig. 3b), or grow along late crenulation cleavages. Therefore, they are inferred to be late minerals not in equilibrium with the high-pressure phases.

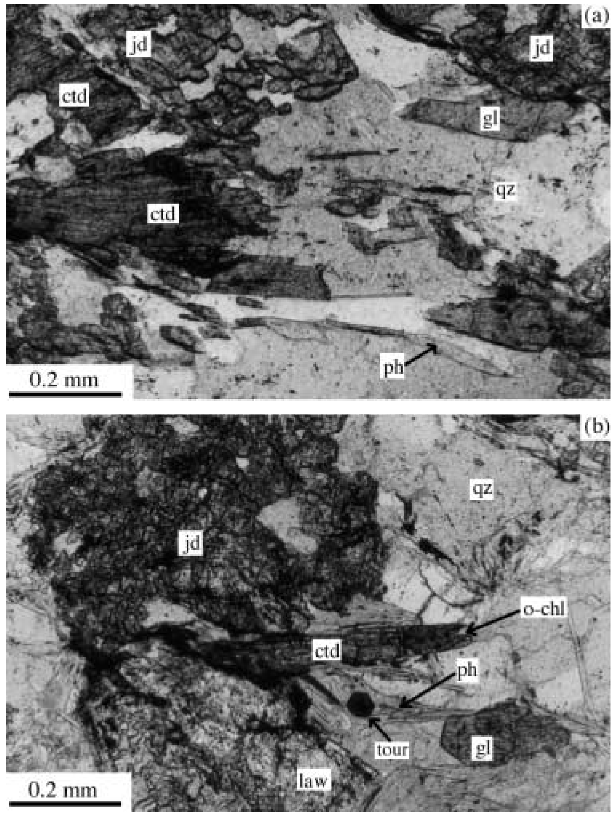

Fig. 3. Photomicrographs of jadeite-chloritoid paragenesis in the Orhaneli region, plane polarized light. (a) Greyschist (5080) with jadeite (jd), chloritoid (ctd), glaucophane (gl), phengite (ph) and quartz (qz). (b) Greyschist (4893B) with (jd) (ctd) (gl) (lw) (ph) (qz) and tourmaline (tour). Chloritoid is partially replaced by oxy-chlorite (o-chl).

Table 1. Estimated modal amounts of the analysed blueschist samples.

	Greyschist (metapelite)							Metadiorite	Metabasite		
	4892A	4892B	4893B	5038B	5040	5079	5080	5086	5366	104B	4291B
Quartz	19	47	49	38	49	41	43	33	34	1	12
White mica	$58_{ph,pa}$	15_{ph}	9_{ph}	23_{ph}	13_{ph}	18_{ph}	11_{ph}	21_{ph}	–	12_{ta}	–
Jadeite	–	14	23	19	18	15	21	–	41	tr_{cl}	–
Chloritoid	8	12	3	5	6	5	11	4	3	–	–
Na-amphibole	2	1	6	–	5	4	14	17	14	38	41
Lawsonite	3	5	6	–	2	3	–	15	3	42	45
Garnet	–	–	–	–	–	–	–	–	–	4	–
Rutile	–	tr	tr	1	tr	–	tr	–	tr	tr	–
Titanite	–	–	–	–	–	–	–	–	–	–	2
Opaque	–	tr	tr	tr	$tr_{py,ilm}$	–	tr	tr_{mag}	2	–	tr
Tourmaline	tr	tr	tr	–	tr	tr	tr	tr	–	tr	–
Apatite	tr	tr	–	tr	tr	–	–	–	–	tr	–
Graphite	1	tr	tr	tr	tr	2	tr	2	–	–	–
Chlorite	5	2	1	8	7	6	–	2	–	3	–
Oxy-chlorite	4	4	3	–	–	3	tr	6	–	–	–
Albite	tr	tr	tr	4	–	3	–	–	3	–	–
Ankerite	–	–	–	2	–	–	–	–	–	–	–

ph, phengite; pa, paragonite; ta, talc; py, pyrite; ilm, ilmenite; mag, magnetite; cl, chloromelanite. tr $<$ 0.5.

A very hard massive rock with a ghost magmatic texture forms a-few-hundred-metre long and *c.* 20 m wide elongate body in the greyschists southeast of the town of Orhaneli. It consists essentially of quartz and jadeite with minor amounts of glaucophane, chloritoid and lawsonite. The rock, probably a former dioritic dyke, is comparable to the jadeite-rocks described 25 km farther west from the Kocasu region (Okay & Kelley, 1994).

Metabasites around Deliballar consist mainly of lawsonite and sodic amphibole with minor sodic pyroxene, chlorite, white mica and titanite, and are petrographically similar to the blueschist metabasites described from north-east of Tavşanlı, 80 km farther east (Okay, 1980). Rarely, small pink garnet occurs in the blueschist metabasites coexisting with lawsonite and sodic amphibole.

Mineral chemistry

Eight greyschists, one metadiorite and two metabasite samples were studied with an electron microprobe. Samples 4892 A, B and 4893B were analysed in the Universite Paris 6 and the rest in the Open University using an SX-50 Cameca electron microprobe. The operating conditions for the microprobe were 15 kV accelerating voltage, 15 nA beam current and 10 μm beam size. Estimated modes of these samples are given in Table 1 and representative mineral compositions in Tables 2 and 3. The Fe^{3+} in sodic amphibole was estimated on the basis of structural formulae of 23 oxygen and 15 cations. Structural formulae of jadeite were calculated on the basis of four cations. The jadeite component is taken to be equal to Al^6; the aegerine component equals Na/(Na + Ca)-Al^6. The rest is assigned to the augite component.

Sodic pyroxene from the greyschists and the metadiorite is essentially endmember jadeite with the jadeite component ranging from 82 to 98 mol percent (Fig. 4, Table 2). Sodic amphibole from the metaclastic rocks is ferroglaucophane and glaucophane largely free of Fe^{3+}, as shown by the cation totals of <15 for a 23 oxygen formula. The zoning in sodic amphibole involves an increase in the Mg/(Fe^{2+} + Mg) ratio towards the rim (Fig. 5, Table 2). Sodic amphibole from the metabasites is glaucophane and crossite. Analysed lawsonite is very close to the ideal lawsonite composition. Chloritoid from the greyschists is iron-rich with a restricted Fe/(Fe + Mg) ratio of 0.83–0.92, whereas in the metadiorite it is slightly richer in magnesium. The Si per-formula-unit (p.f.u) in the analysed phengite ranges from 3.45 to 3.55 (Fig. 6). There is little variation in the K (0.86–0.93 p.f.u) and Na (0.013–0.037) contents of the analysed phengite. Only one sample (4892 A) contains stably coexisting paragonite and phengite. Paragonite is close to the endmember composition (Table 2). Oxy-chlorite contains higher SiO_2 and K_2O and lower Al_2O_3 contents than chlorite

Table 2. Representative mineral compositions from the greyschists.

	4892A						4893B					5080				
	ctd	law	gl	ph	pa	chl	ctd	jadeite	gl	ph	o-chl	ctd	jadeite	gl core	gl rim	ph
SiO_2	24.31	38.34	57.18	52.17	47.32	25.47	24.29	58.97	56.49	52.68	26.72	24.51	59.13	56.81	58.69	52.08
TiO_2	0.00	0.02	0.10	0.10	0.08	0.07	0.00	0.03	0.14	0.15	0.06	0.04	0.04	0.22	0.01	0.09
Al_2O_3	40.94	31.86	11.97	25.23	38.94	20.53	40.67	21.70	11.50	24.51	20.56	40.32	22.82	11.00	11.54	24.27
Cr_2O_3	0.02	0.03	0.04	0.05	0.00	0.00	0.01	0.00	0.02	0.09	0.08	n.d.	n.d.	n.d.	n.d.	n.d.
FeO	25.15	0.22	14.56	2.77	0.51	31.15	25.11	4.61	16.55	3.53	31.64	24.40	2.66	16.43	12.16	2.65
MgO	1.89	0.02	6.11	3.18	0.24	9.35	1.40	0.22	5.14	3.07	7.06	2.53	0.15	6.18	8.42	3.64
MnO	0.32	0.00	0.00	0.02	0.00	0.00	0.36	0.01	0.00	0.00	0.30	0.59	0.00	0.10	0.03	0.03
CaO	0.04	16.98	0.03	0.10	0.09	0.12	0.02	0.40	0.10	0.00	0.15	0.00	0.24	0.07	0.02	0.00
Na_2O	0.00	0.00	7.49	0.11	7.74	0.03	0.03	14.62	6.86	0.22	0.09	0.00	14.81	6.85	7.12	0.17
K_2O	0.04	0.01	0.05	10.35	0.74	0.10	0.00	0.00	0.07	10.05	0.74	0.00	0.04	0.01	0.00	10.32
Total	92.71	87.48	97.53	94.08	95.67	86.82	91.89	100.56	96.87	94.30	87.40	92.39	99.89	97.67	97.99	93.25
Oxygen	12	8	23	11	11	14	12	4 cat.	23	11	14	12	4 cat.	23	23	11
Si	2.01	2.02	7.99	3.52	3.02	2.77	2.02	2.02	8.03	3.55	2.90	2.03	2.01	8.01	8.06	3.55
Al^4	0.00	0.00	0.01	0.48	0.98	1.23	0.00	0.00	0.00	0.45	1.09	0.00	0.00	0.00	0.00	0.45
Al^6	3.99	1.98	1.96	1.53	1.95	1.44	4.00	0.87	1.93	1.50	1.58	3.93	0.92	1.83	1.87	1.50
Ti	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.02	0.00	0.01
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01					
Fe^{3+}	0.01	0.01	0.06	0.00	0.12	0.00	0.07	0.07	0.00	0.00						
Fe^{2+}	1.73	0.00	1.64	0.16	0.03	2.88	1.75	0.01	1.97	0.20	2.91	1.62	0.01	1.94	1.40	0.15
Mg	0.23	0.00	1.28	0.32	0.02	1.54	0.17	0.01	1.09	0.31	1.16	0.31	0.01	1.30	1.72	0.37
Mn	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.03	0.04	0.00	0.01	0.00	0.00
Ca	0.01	0.96	0.00	0.01	0.01	0.01	0.00	0.01	0.02	0.00	0.02	0.00	0.01	0.01	0.00	0.00
Na	0.00	0.00	2.03	0.01	0.96	0.01	0.00	0.96	1.89	0.03	0.02	0.00	0.97	1.87	1.90	0.02
K	0.00	0.00	0.01	0.89	0.06	0.01	0.00	0.00	0.01	0.86	0.10	0.00	0.00	0.00	0.00	0.90
Total	8.00	4.97	15.00	6.92	7.03	9.90	7.97	4.00	14.96	6.91	9.82	8.00	4.00	14.99	14.95	6.95
Activities at 24 kbar and 430 °C:																
	fct 0.88		gl 0.135	mu 0.35	pa 0.91		fct 0.90	jd 0.85	gl 0.089	mu 0.31	fct 0.83	jd 0.90	gl 0.09	gl 0.22	mu 0.32	
	mct 0.14		fgl 0.25	cel 0.17			mct 0.11		fgl 0.32	cel 0.16	mct 0.18		fgl 0.21	fgl 0.142	cel 0.20	

Table 3. Mineral compositions from the metadiorite and metabasites.

	5366				UL104B					4291B	
	ctd	jadeite	gl	law	gl	law	grt core	grt rim	talc	gl	law
SiO_2	24.64	58.56	58.38	37.64	56.96	38.16	36.58	36.84	59.85	56.40	38.31
TiO_2	0.00	0.00	0.14	0.00	0.00	0.03	0.00	0.00	0.00	0.18	0.13
Al_2O_3	42.26	22.28	12.20	32.47	5.02	30.95	20.17	20.43	0.10	8.66	31.42
Cr_2O_3	0.00	0.01	0.00	0.00	0.04	0.43	0.00	0.08	0.00	0.00	0.06
FeO	20.84	1.98	8.54	0.00	17.60	1.76	21.31	24.58	9.28	14.46	1.10
MgO	3.94	1.23	10.23	0.00	9.94	0.00	0.84	0.85	24.24	8.64	0.00
MnO	0.56	0.08	0.01	0.00	0.04	0.02	12.81	9.84	0.00	0.32	0.03
CaO	0.00	1.64	0.25	16.96	1.51	17.06	8.29	7.37	0.02	0.46	17.00
Na_2O	0.02	13.50	7.45	0.00	6.22	0.00	0.00	0.00	0.00	7.11	0.04
K_2O	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.07
Total	92.26	99.28	97.21	87.07	97.33	88.41	100.00	99.99	93.50	96.23	88.16
Oxygen	12	4 cat.	23	8	23	8	12	12	11	23	8
Si	2.00	2.01	7.96	1.99	8.05	2.02	2.95	2.98	4.02	7.96	2.02
Al^4	0.00	0.00	0.04	0.01	0.00	0.00	0.05	0.02	0.00	0.04	0.00
Al^6	4.04	0.90	1.92	2.02	0.84	1.93	1.87	1.92	0.01	1.40	1.95
Ti	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01
Cr	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
Fe^{3+}	0.00	0.04	0.05	0.00	0.78	0.05	0.13	0.08	0.53	0.04	
Fe^{2+}	1.42	0.02	0.93	0.02	1.30	0.03	1.31	1.58	0.52	1.18	0.01
Mg	0.48	0.06	2.08	0.00	2.10	0.00	0.10	0.10	2.43	1.82	0.00
Mn	0.04	0.00	0.00	0.00	0.01	0.00	0.88	0.67	0.00	0.04	0.00
Ca	0.00	0.06	0.04	0.96	0.22	0.97	0.72	0.64	0.00	0.07	0.96
Na	0.00	0.91	1.97	0.00	1.70	0.00	0.00	0.00	0.00	1.94	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	7.98	4.00	15.00	5.00	15.00	5.02	8.01	7.99	6.98	15.00	4.99
Activities at 24 kbar and 430 °C:											
	fct 0.75	jd 0.84	gl 0.33		gl 0.054		alm 0.073	alm 0.14	ta 0.55		
	mct 0.28		fgl 0.06		fgl 0.014		py 0.00016	py 0.00015	fta 0.0052		
							gr 0.011	gr 0.0085			

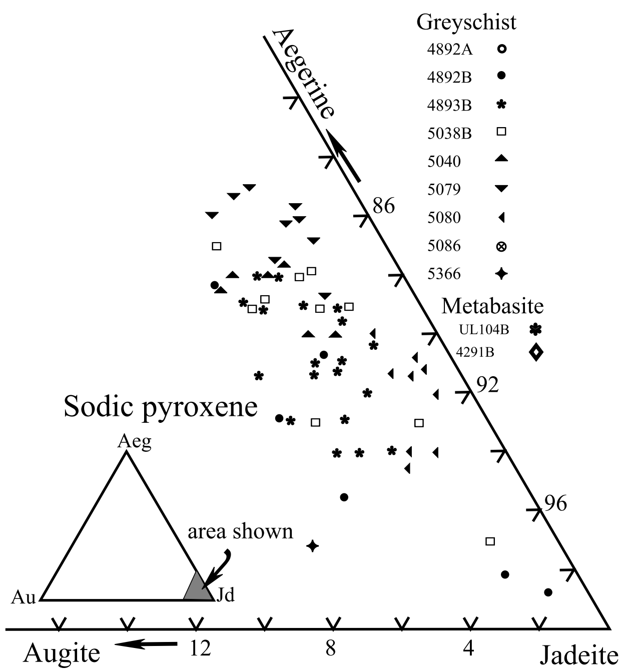

Fig. 4. Jadeite composition from the Orhaneli area plotted in the jadeite corner of the aegerine ($NaFeSi_2O_6$)-jadeite ($NaAlSi_2O_6$)-augite ($Ca(MgFe)Si_2O_6$) ternary diagram.

(Table 2) and is probable similar to the chlorite/biotite mixed layer silicate described as an alteration product of chlorite by Maresch *et al.* (1985). One of the analysed metabasite samples contains talc, which coexists with garnet, sodic amphibole and lawsonite. Garnet in this sample forms small subidioblastic grains, < 0.4 mm across, and is essentially an almandine-grossular-spessartine solid solution with minor pyrope

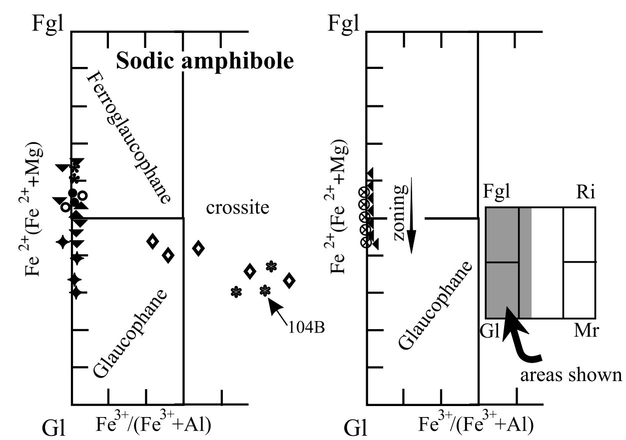

Fig. 5. Sodic amphibole compositions from the Orhaneli region plotted on part of the Miyashiro diagram. Arrows indicate core to rim compositions. Fg, ferro-glaucophane; Gl, glaucophane; Mr, magnesio-riebeckite; Ri, riebeckite. Other symbols as in Fig. 4.

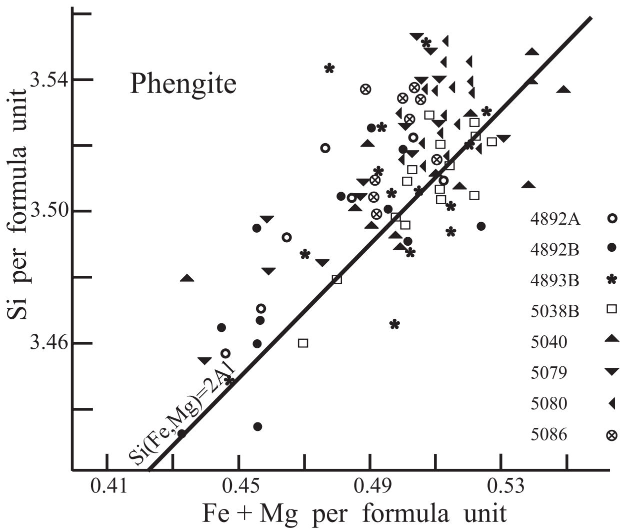

Fig. 6. Phengite compositions from the Orhaneli region shown in terms of Si and (Fe + Mg + Mn) per formula unit (p.f.u). The ideal celadonite-muscovite substitution line is also shown.

endmember (3–4 mol percentage). The garnet shows a growth zoning with an increase in Fe and Fe/Mg ratio and a decrease in Mn and Ca towards the rim with little variation in Mg (Table 3).

The regular Fe^{2} ± Mg partitioning among sodic amphibole, phengite and chloritoid in the greyschists, despite the restricted Fe/(Fe + Mg) range, suggests that the analysed compositions represent equilibrium or near-equilibrium assemblages (Fig. 7). The average Fe^{2+}/Mg partition coefficient K_D for chloritoid/sodic amphibole, chloritoid/phengite and sodic amphibole/phengite from nine samples are 5.6, 13.1 and 2.4, respectively. The Fe^{2}/Mg distribution coefficient K_D between sodic amphibole and chloritoid in the Orhaneli region is the lowest reported in the literature (*cf.* Theye & Seidel, 1991). This might reflect the high P/T ratio in the region, as incorporation of Mg into chloritoid will be favoured by increasing pressure (Chopin, 1981a).

PHASE RELATIONS AND *P–T* CONDITIONS

In the Orhaneli greyschists the low-variance blueschist facies mineral assemblage is sodic amphibole + chloritoid + jadeite + lawsonite + quartz + phengite + rutile ± paragonite. Phengite, lawsonite and rutile are the only major K-, Ca- and Ti-bearing phases, and sodic amphibole and chloritoid have very low Fe^{3+} contents, so that the sodic amphibole, chloritoid, jadeite and paragonite lie, to a first approximation, in the Na_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O system (NFMASH). High-pressure mineral equilibria in the NFMASH system have been investigated by Guiraud *et al.* (1990) and El-Shazly & Liou (1991). Both studies assign pressures of above 18 kbar, and temperatures of < 580 °C to the jadeite + chloritoid assemblage, regardless of the

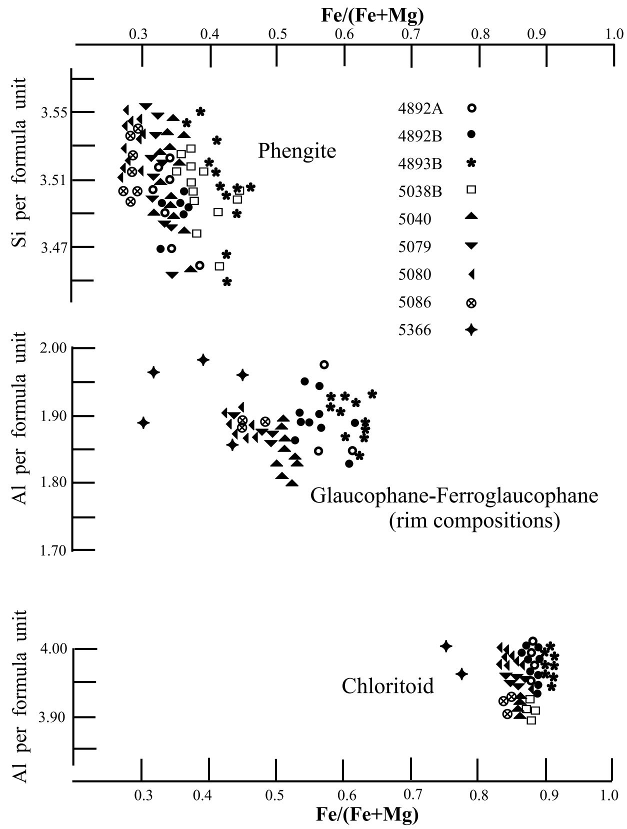

Fig. 7. Distribution of $Fe^{2+}/(Fe^{2+} + Mg)$ among chloritoid, sodic amphibole and phengite. Only rim compositions of sodic amphibole are shown.

composition of the chloritoid. In the 400–580 °C temperature range, the jadeite + chloritoid assemblage is limited at low pressures by the near isobaric reaction (Fig. 9):

$$\text{jadeite} + \text{chloritoid} + \text{quartz} + H_2O = \text{paragonite} + \text{sodic amphibole} \qquad (1)$$

Paragonite and sodic amphibole is a common assemblage in the high-pressure rocks in both pelitic and mafic rock compositions (*cf.* Mollini & Poli, 1997). It has been described among others from Cyclades, Greece (e.g. Schliestedt, 1986; Okrusch & Bröcker, 1990), Alps (e.g. Holland, 1979; Oberhänsli, 1986; Heinrich, 1986), Turkey (Okay, 1989; Okay & Kelley, 1994), Oman (e.g. El-Shazly & Liou, 1991), Himalaya (Guillot *et al.*, 1997), Alaska (Patrick & Evans, 1989) and Venezuela (Sisson *et al.*, 1997). In contrast, jadeite + chloritoid, the high pressure equivalent of paragonite + sodic amphibole, has only been described from inclusions in garnet in the Cyclades and in the Himalaya (Schliestedt & Okrusch, 1988; Guillot *et al.*, 1997).

The presence of lawsonite + jadeite + rutile, and absence of coesite designate a broad *P–T* field for the blueschists in the Orhaneli region on the basis of the reactions:

$$\text{jadeite} + \text{lawsonite} + \text{rutile} \\ = \text{paragonite} + \text{titanite} + H_2O \qquad (2)$$

$$\text{quartz} = \text{coesite} \qquad (3)$$

Low-variance mineral assemblages in the greyschists in the Orhaneli region have a potential of accurately constraining the *P–T* conditions of the blueschist metamorphism. Mineral equilibria in the analysed blueschists in the Orhaneli region were calculated using the THERMOCALC program (v. 2.75) of Powell & Holland (1988) with the thermodynamic data set of Holland & Powell (1998). The activities used in equilibria leading to the *P–T* estimation are shown in Tables 2 and 3. They were obtained using the AX program of T.J.B. Holland (www.esc.cam.ac.uk/astaff/holland). The program uses ideal site mixing for talc and sodic amphibole, two-site nonideal mixing for chloritoid ($W_{Fe,Mg} = 1.5$ kJ), two-site mixing with regular solution for jadeite ($W_{jd,di} = 24$ kJ, $W_{jd,ac} = 0$ kJ), nonideal mixing for phengite and paragonite and regular solution model for garnet ($W_{py,alm} = 2.5$ kJ, $W_{gr,py} = 33$ kJ).

The jadeite + chloritoid + sodic amphibole subassemblage without paragonite is found in several samples in the Orhaneli area (*cf.* Fig. 2). It allows an estimation of *minimum* metamorphic pressures from the near-isobaric reaction (1). This equilibrium was calculated for ferrous- and magnesian-endmembers using analysed mineral compositions from five samples (cf. Table 1), and a paragonite activity of 0.9. It indicates minimum pressures of *c.* 20 kbar for the temperature range of 400–500 °C (Fig. 8). Similar minimum pressures of *c.* 22 kbar are also obtained from the H_2O-free reaction:

$$\text{paragonite} + \text{glaucophane} + \text{muscovite} \\ = \text{Jadeite} + \text{magnesiochloritoid} + \text{quartz} \\ + \text{celadonite} \qquad (4)$$

The apparent absence of coesite places a maximum pressure of 27 kbar for the metamorphism in the Orhaneli region.

The metabasite sample 104B contains garnet + lawsonite + talc + quartz, which allows an estimation of the metamorphic temperature on the basis of the reaction:

$$\text{talc} + \text{lawsonite} = \text{garnet} + \text{quartz} + H_2O \qquad (5)$$

This reaction indicates a metamorphic temperature of 430 ± 20 °C at 24 kbar and at an activity of H_2O equal to one (Fig. 8). A lower activity of H_2O would indicate an even lower metamorphic temperature. A similar metamorphic temperature of 430 °C was

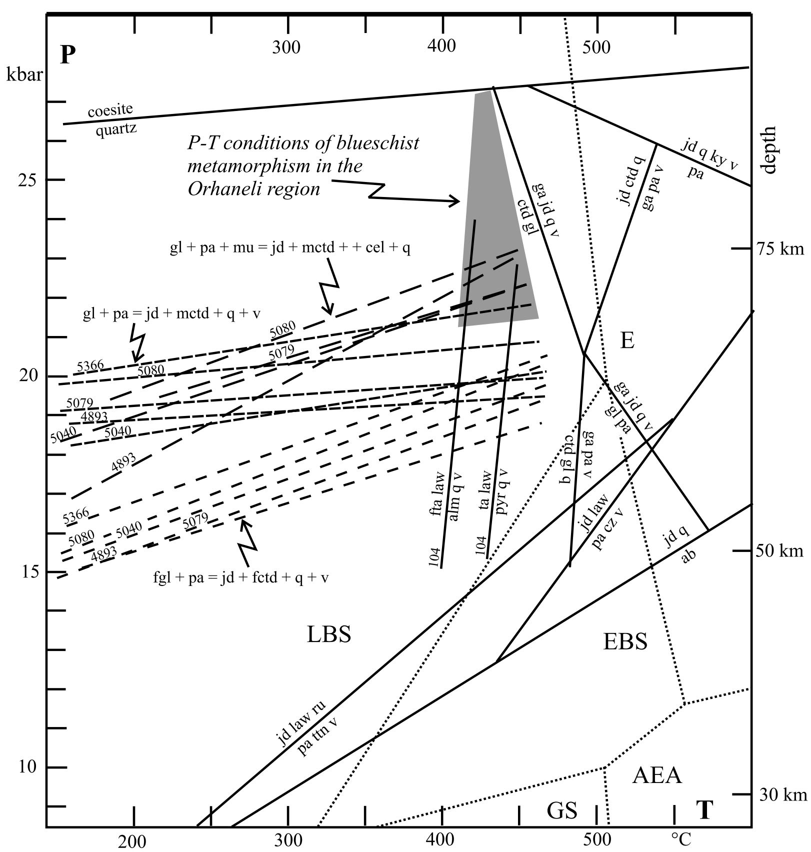

Fig. 8. Pressure-temperature diagram showing equilibria relevant to the estimation of the *P–T* conditions of the Orhaneli greyschists. Facies boundaries are after Evans (1990); LBS, lawsonite blueschist; EPS, epidote blueschist; E, eclogite; AEA, albite-epidote amphibolite; GS, greenschist facies. All reactions were calculated using THERMOCALC of Powell & Holland (1988) and Holland & Powell (1998). The garnet-forming equilibria represent an average of the ferrous and magnesian endmember reactions for almandine and pyrope activities of 0.26 and 0.00061, respectively, and the data from the sample 5080. As paragonite does not occur with jadeite-chloritoid-sodic amphibole subassemblage, the dashed reactions lines in the Figure involving these minerals provide minimum pressure estimates. Abbreviations: ab, albite; clin, clinochlore; coe, coesite; ctd, chloritoid; cz, clinozoisite; di, diopside; fctd, Fe-chloritoid; fgl, ferroglaucophane; fta, ferrotalc; ga, garnet; gl, glaucophane; jd, jadeite; ky, kyanite; law, lawsonite; mctd, Mg-chloritoid pa, paragonite; q, quartz; ru, rutile; sa, sodic amphibole; ttn, titanite; ta, talc; v, H_2O.

estimated in the blueschists from the Kocasu area, 25 km farther west using a different garnet-forming reaction in a calc-silicate blueschist (Okay & Kelley, 1994). The low metamorphic temperatures estimated in the Orhaneli region are also supported by petrological comparison with other blueschist and eclogite terranes, as discussed below.

In most high-pressure metamorphic terranes chloritoid in the metasediments is accompanied by garnet, and the associated metabasites contain sodic amphibole + garnet + epidote ± omphacite paragenesis (e.g. Alps: Chopin, 1981b; Spear & Franz, 1986; Vuichard & Ballevre, 1988; Oman: Goffé *et al*., 1988; El-Shazly & Liou, 1991; New Caledonia: Ghent *et al*., 1987; Alaska: Brown & Forbes, 1986). In the high-pressure metapelites garnet forms in the temperature interval 450–500 °C through continuous reactions involving chloritoid, sodic amphibole, jadeite:

$$\text{chloritoid} + \text{sodic amphibole} = \text{garnet} + \text{jadeite} + \text{quartz} + H_2O \quad (6)$$

$$\text{chloritoid} + \text{sodic amphibole} + \text{quartz} = \text{garnet} + \text{paragonite} + H_2O \quad (7)$$

$$\text{chloritoid} + \text{jadeite} + \text{quartz} = \text{garnet} + \text{paragonite} + H_2O \quad (8)$$

$$\text{chloritoid} + \text{chlorite} + \text{quartz} = \text{garnet} + H_2O \quad (9)$$

Schliestedt & Okrusch (1988), and Guillot *et al*. (1997) inferred reaction (8) in the sodic metapelites in the Cyclades and in the Himalaya, respectively, on the basis of chloritoid and jadeite inclusions in garnet. The metamorphic temperatures and pressures estimated for the chloritoid-garnet bearing metasediments are *c*. 450 °C, 17 kbar in Peloponnese (Theye & Seidel, 1991), *c*. 460 °C, 12 kbar in the Seward peninsula, Alaska (Forbes *et al*., 1984; Patrick & Evans, 1989), *c*. 470 °C, 15 kbar in the Cyclades (Schliestedt, 1986; Okrusch & Bröcker, 1990), *c*. 475 °C, 8 kbar in Oman (Goffé *et al*., 1988). In the Orhaneli area, the greyschists do not contain garnet and the associated metabasites are characterized by the sodic amphibole + lawsonite paragenesis, suggesting that the metamorphic temperatures were < 470 °C, which is compatible with the general observation that garnet starts to form in pelitic metasediments at *c*. 450 °C (Yardley, 1989; p. 86). At pressures > 16 kbar, the transition from lawsonite–blueschist to epidote–blueschist and eclogite facies is estimated to occur at between 450 and 500 °C (Fig. 8, Evans, 1990). Thus, various lines of evidence suggest that the metamorphic temperatures in the Orhaneli blueschists were below 450 °C, in accordance with the temperature estimate from reaction (5).

The temperature at which garnet would have formed in the sodic metapelites in the Orhaneli region is estimated by using an appropriate garnet composition that would have coexisted with chloritoid and sodic amphibole at higher temperatures. Sodic metapelites from the Peloponnese contain chloritoid + sodic amphibole + garnet + paragonite assemblages with chloritoid compositions similar to that in the Orhaneli area (Theye & Seidel, 1991). The estimated temperature in the Peloponnese is only slightly higher than that in the Orhaneli area (450 ± 30 °C) so that there will be little change in the K_D values $[(Fe/Mg)_{ctd}/(Fe/Mg_{ga})]$ between the two areas. Garnet-forming equilibria in the sample 5080 from the Orhaneli region were calculated using a garnet composition from the Peloponnese (sample P80/36) that coexists with chloritoid of similar composition as that in the sample 5080 (Fig. 8). The equilibria indicate that garnet would have formed in the metapelites of the Orhaneli region at around 450 °C through reaction (6).

The arguments above suggest a 24 ± 3 kbar pressure and 430 ± 30 °C temperature for the peak blueschist facies conditions in the Orhaneli area. The temperature and pressure estimates assume the presence of a free hydrous phase ($a_{H_2O} = 1$). The abundance of hydrous minerals (e.g. phengite, lawsonite, sodic amphibole, chloritoid), and textural and mineralogical equilibrium at these relatively low temperatures argue for the presence of a fluid phase. A high H_2O activity is also indicated by the reaction (4), which does not involve H_2O. The frequent presence of lawsonite in the greyschists indicates that the fluid consisted mainly of H_2O ($X_{CO_2} < 0.03$, Nitsch, 1972).

The blueschists from the western Tavşanlı Zone are characterised by prograde rather than retrograde textures and minerals (Okay, 1984). This is also true for the Orhaneli region, where the rimward increase in the glaucophane component in zoned sodic amphibole suggests increasing pressures and temperatures according to reaction (1). Similarly the zoning in garnet in the metabasite is a typical prograde feature. A greenschist overprint, e.g. barroisite rims around sodic amphibole or breakdown of lawsonite to clinozoisite, is absent in the western part of the Tavşanlı Zone. The estimated *P–T* conditions in the Orhaneli region are close to the formation temperatures of garnet. Therefore, it is remarkable that although the garnet-forming reaction (7) has a positive slope in the *P–T* field, garnet has not formed in the retrograde path of the Orhaneli blueschists. This suggests that temperature in the blueschists in the Orhaneli region did not increase during the exhumation. The late minerals in the blueschists are chlorite, which has formed at the expense of sodic amphibole and chloritoid, and minor albite. Both the prograde and retrograde paths of the blueschists must have stayed in the lawsonite–blueschist facies field.

CONCLUSIONS

Blueschists metaclastic rocks and marble form a thick coherent stratigraphic sequence in the Orhaneli area in northwest Turkey. The jadeite + chloritoid + glaucophane + lawsonite + quartz + phengite assemblage in the metasediments provides a *P–T* estimate of 24 ± 3 kbar and 430 ± 30 °C, giving a T/P ratio of 18 °C $kbar^{-1}$. The overburden on the blueschists probably consisted of metasediments, accretionary complex and oceanic lithosphere (Okay *et al.*, 1998). Taking an average density of 3.1 g cm^{-3} for the overburden, the 24-kbar pressure translates into 79 km depth. For a peak temperature of 430 °C, this would indicate a geotherm of 5.4 °C km^{-1}, one of the lowest geotherm recorded in the high-pressure rocks. It is important to stress that this geotherm is not for blocks in a melange but for a coherent blueschist terrane, several tens of square kilometres in size and at least one kilometre thick. Peak *P–T* estimates from selected blueschist and low-temperature eclogite terranes are shown in Fig. 9. Most H*P*/L*T* metamorphic regions appear to be characterized by geotherms of 8 to 14 °C km^{-1}. However, this could partly reflect the problems of estimating metamorphic pressures in blueschist terranes that lack metapelitic lithologies. It is significant that the lowest geotherms occur in regions, such as the Peloponnese (Theye & Seidel, 1991), where metapelitic mineral assemblages are used in the estimation of metamorphic pressures. The recent proliferation of coesite-bearing metamorphic terranes is probably another indication that very low geotherms in H*P*/L*T* metamorphic terranes are more common than realized.

The thermal structure of the subducting lithosphere is controlled by the shear and radioactive heating, geometry and rate of subduction and the thermal structure of the downgoing slab. Atlantic ocean-floor anomaly data indicate a convergence rate of *c*. 3 cm y^{-1} during the Cretaceous between Africa and Eurasia in the vicinity of northwest Turkey (Patriat *et al.*, 1982; Livermore & Smith, 1984). For this rate of convergence, and for a wide-range of other subduction zone parameters (*cf*. Peacock, 1992), the 5 °C km^{-1} geotherm suggests low shear stresses of *c*. 200 bar along the subduction interface.

Unstable minerals such as jadeite are preserved in the Orhaneli blueschists indicating that the rocks have stayed largely dry during their exhumation, presumably the fluid phase was expelled from the rocks at peak temperatures. However, even when fluids locally reached the blueschists during exhumation, only chlorite and sericitic white mica formed at the expense of glaucophane and chloritoid, rather than barroisite or epidote. In this aspect the western part of the Tavşanlı Zone is more typical of high-pressure belts

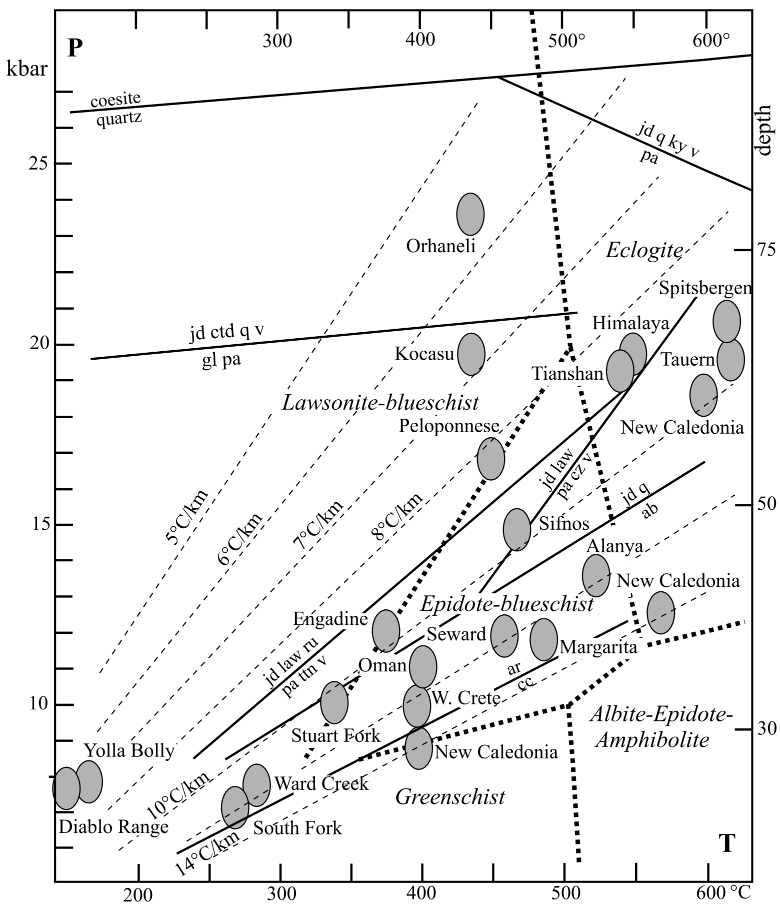

Fig. 9. Peak *P–T* conditions of blueschist and eclogite facies metamorphism for selected areas. Note that the *P–T* uncertanties are usually several times larger than that indicated by the ellipses. The dotted lines are the facies boundaries after Evans (1990). The data sources are: Franciscan Complex: Diablo Range (Ernst, 1993; Dalla Torre *et al.*, 1996), Ward Creek (Brown, 1977; Maruyama *et al.*, 1986), Yolla Bolly terrane (Jayko *et al.*, 1986); Stuart Fork terrane, California (Goodge, 1989), South Fork Mountain schist (Brown & Ghent, 1983); western Crete and Peloponnese, Greece (Theye & Seidel, 1991); Oman (Goffé *et al.*, 1988; El-Shazly & Liou, 1991); Seward Peninsula, Alaska (Forbes *et al.*, 1984; Patrick & Evans, 1989); Sifnos, Greece (Schliestedt, 1986); Alanya, Turkey (Okay, 1989); Margarita, Venezula (Maresch & Abraham, 1981); New Caledonia (Clarke *et al.*, 1997; Carson *et al.*, 1999); Tauern Window, Alps (Holland, 1979; Spear & Franz, 1986); Engadine Window (Bousquet *et al.*, 1998); Himalaya (Guillot *et al.*, 1997); Tianshan (Klemd *et al.*, 2002) Spitsbergen (Hirajima *et al.*, 1988); Tavşanlı Zone, Turkey**:** Kocasu (Okay & Kelley, 1994), Orhaneli (this study). For other symbols see Fig. 8.

produced during the steady-state subduction of the oceanic lithosphere, which commonly escape a high temperature overprint (e.g. Ernst, 1988). A fast overall exhumation rate was also not required for the preservation of the Orhaneli blueschists. Jadeite formed at *c*. 79 km depth during the Cretaceous (80 Ma) as still residing at 10 km depth during the Eocene (48 Ma), 30 million years later.

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