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The age of blueschist metamorphism in the Mesozoic cover series of the Menderes Massif

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Abstract

On the Dilek Peninsula, western part of the Menderes Massif, relics of HP metamorphism under epidote-blueschist facies conditions were recognised in metavolcanic and marly interlayers of the Mesozoic cover series. $^{40}Ar/^{39}Ar$ determinations of phengites revealed Tertiary ages (40 Ma) for the subduction-related high-pressure metamorphism (470 °C, min. 10 kbar). Lithostratigraphic correlation allows to suggest a similar age for the HP metamorphism on Samos.

Keywords: blueschist, age determination, $^{40}Ar/^{39}Ar$, Menderes Massif, W Anatolia.

Introduction

In western Anatolia, the Menderes Massif consists of a large crystalline nappe complex conformably overlain by Mesozoic to Cenozoic marbles (DÜRR, 1975). Within the crystalline complex, relic eclogites related to high-pressure metamorphism were recorded in the Precambrian "core series" (CANDAN et al., 1994, OBERHÄNSLI et al., 1995). These HP relics occur in close association to granulite-grade assemblages. Both events have been dated as Panafrican (OELSNER et al., 1997; MEZGER, pers. com.). Additionally, evidence for high-pressure metamorphism, most probably not related to the HP event in the "core series", has been detected in the "cover series" (CANDAN et al., 1997) of the Dilek Peninsula. The platform carbonates of the "cover series", which contain metabauxite horizons are considered to be paraautochthonous. The prograde transition from diaspore to corundum (corundum-in isograd; see Fig. 1) within the metabauxites of the marble cover defines a bowl-shaped surface throughout the crystalline massif and demonstrates a post HP upper greenschist facies overprint. The shape if this isograd is often interpreted as to demonstrate, that the entire massif could be a metamorphic core complex.

The Menderes Massif is bordered to the south by the Lycian nappes of the Taurides and to the north and north-west by the Izmir-Ankara Zone. To the north and north-east, the blueschist belt of the Anatolides is exposed. The age of this blueschist event is poorly constrained, but K/Ar and $^{40}Ar/^{39}Ar$ dating of phengites from blueschists reveals Late Cretaceous ages in the range 88–65 Ma (ÇOGULU and KRUMMENACHER, 1967; OKAY and KELLEY, 1994). Additionally, blueschist detritus is reported from Cenomanian flysch of the Haymana basin (BATMAN, 1978).

The Menderes Massif is considered to be linked to the west to the Cycladic Crystalline Complex of the Central Aegean Sea, as a part of the Median Crystalline Belt (DÜRR, 1986). Due to subduction zone roll-back, two HP events are known in the Aegean realm; an Eocene (40–45 Ma) one in the Attic-Cycladic belt and an Oligocene (ca. 25 Ma) one documented in Crete and the Pelponnesus. The structural relation of these stacked tectonic complexes to

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the simple picture of the autochthonous cover of the Menderes crystalline complex is not yet clear.

The aim of this paper is to document the age of the blueschist metamorphism recorded in the Mesozoic cover series of the Menderes Massif and to discuss tectonic implications.

Geological frame

As reported earlier (CANDAN et al., 1997), relics of a high-pressure metamorphism were recognised in the areas of Selçuk, Kusadasi and the Dilek Peninsula (Fig. 1). In the studied areas, two clearly different tectonic settings containing high-pressure relics can be identified. On one hand, blueschist relics are observed in mafic metavolcanic and metapelitic layers occurring as intercalations in the carbonaceous cover series (Kayaalti formation of GÜNGÖR, 1995) of the Menderes Massif. This sequence of platform rocks is considered to be parautochthonous and to rim the entire crystalline complex (DÜRR, 1975). On the other hand, eclogitic material and blueschists are present in an olistostromal unit, exposed as a klippe

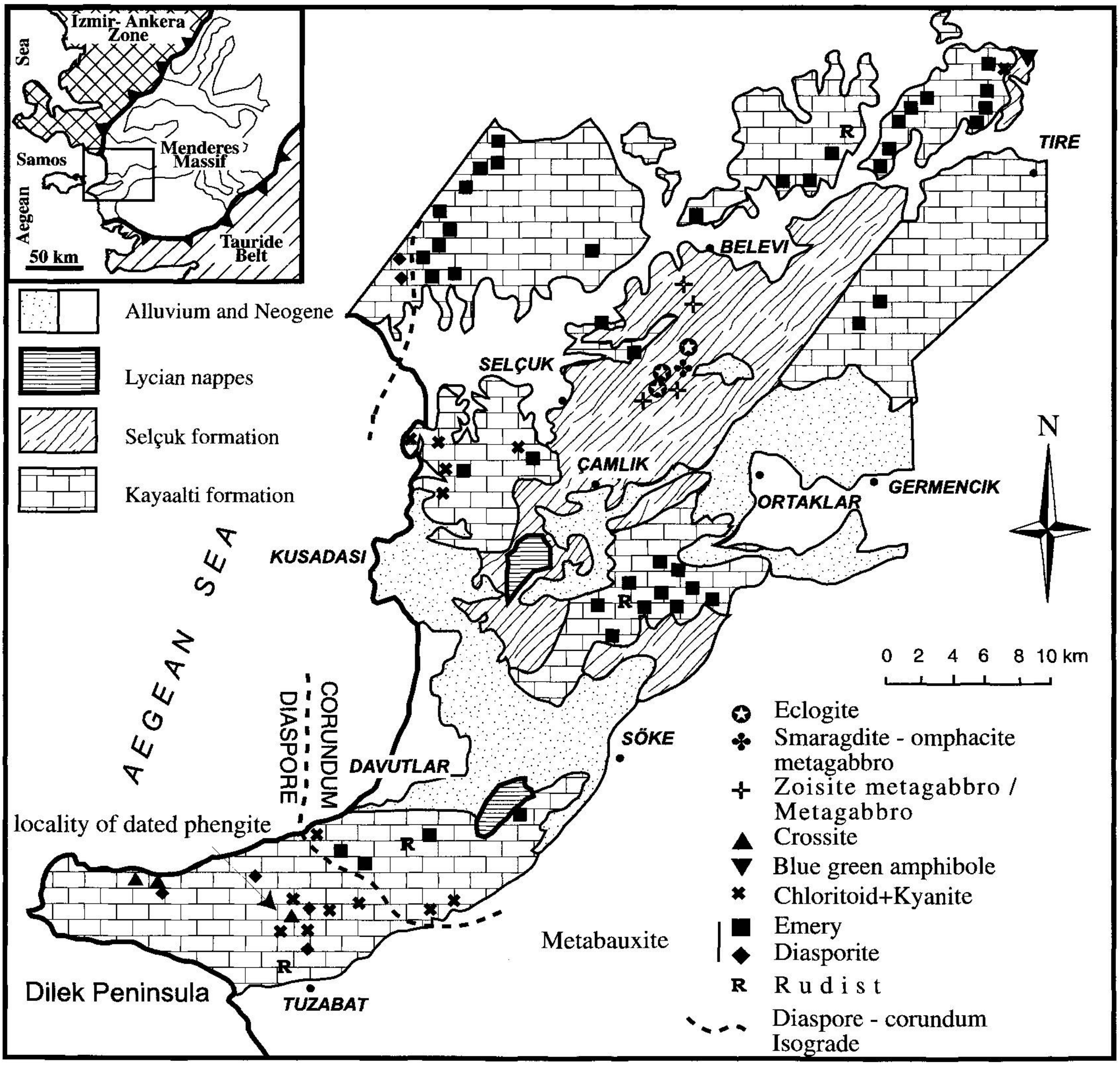


Fig. 1 Geological map of the Mesozoic units of the western part of Menderes Massif showing the rudist as well as the metabasite and metapelite bearing platform sediments and the olistostromal Selçuk unit. The diaspore-corundum isograd as well as occurrences of metamorphic minerals are indicated. Localities of metabauxites after ÖNAY (1949) and rudists after ÖZER (1993). Lycian nappe after GÜNGÖR (1995).

between Selçuk and Tire (Selçuk formation of GÜNGÖR, 1995).

KAYAALTI FORMATION

On the Dilek Peninsula, the Permo-Mesozoic sediments consist of two tectono-stratigraphic units considered to compose the Kayaalti formation. The structurally higher unit is characterised by meta-bauxite-bearing Cretaceous marbles with rudist fossils, while the lower unit comprises a Triassic to Jurassic (GÜNGÖR, 1995) carbonaceous sequence of marbles and micaschists with minor metabasic intercalations. Both units are separated by a S-dipping tectonic contact. The structurally lower unit has been correlated to the Vourliotis unit in Samos by CANDAN et al. (1997), although serpentinite lenses as occurring on Samos, have not been reported so far. On Samos (THEODOROPOULOS, 1979) the Vourliotis unit consists of an alternance of marbles and schists with metabauxites and metavolcanic intercalations. The Ampelos unit contains more clastic material: Ultramafic rocks are largely restricted to the contact between the two units and occur within the latter (A. FEENSTRA, pers. com.).

Both units of the Dilek Peninsula predominantly contain greenschist facies assemblages. In the footwall, three localities with well-preserved blue amphiboles within thin epidote-crossite-rich layers and lens-shaped bodies were found in metabasites. These layers are interpreted to represent mafic volcanic tuffs. Rectangular-shaped calcite epidote-albite aggregates are thought to represent pseudomorphs after lawsonite. Mg-rich layers containing dolomite + talc occur associated with the metabasites. Furthermore, metapelites rich in carbonate, most probably mixed with volcanic material, contain blue amphibole porphyroblasts up to 2 cm in length. The crossitic blue amphiboles are rimmed by barroisitic green amphiboles which are altered to actinolite and chlorite. Phyllitic metapelites, interbedded with marbles, contain the typical greenschist facies assemblage chlorite + albite + chloritoid + white mica + quartz. The blueschist facies mineral assemblages contain crossite + epidote + albite + quartz ± phengite in metabasites and crossite + calcite + epidote + phengite + quartz ± albite in metapelites.

SELÇUK FORMATION

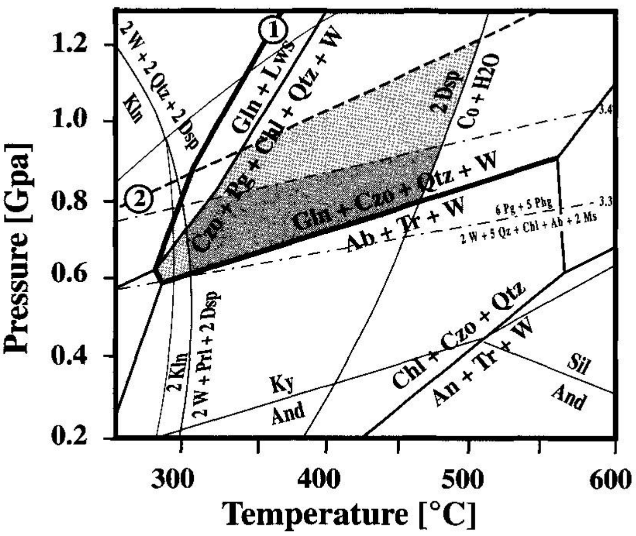
Blocks occurring in a metamorphosed olistostrome unit (Fig. 1) near Selçuk are mainly composed of eclogite, smaragdite-omphacite metagabbro and flaser metagabbro. The well-preserved high-pressure relics are mostly associated with strongly foliated metaserpentinites. Fresh eclogites with zoisite/clinozoisite-omphacite-rich layers, form lenses and schlieren and are characterised by the assemblage omphacite + garnet + rutile + zoisite ± epidote. Most of the eclogites display retrograde alteration to garnet amphibolites. The olistostrome matrix is schistose and contains chlorite + calcite + actinolite + albite + quartz. This meta-olistostrome could be correlated with similar units found on Syros Island in the Cyclades (SECK et al., 1996; CANDAN et al., 1997) or with the Izmir Ankara zone (SENGÖR et al., 1984), where similar assemblages have been reported.

In the area NW of Tire, small outcrops characterised by serpentinites, metabasites and calc-micaschists occur. They have been interpreted to belong to the Selçuk formation by GÜNGÖR (1995). This foliated and isoclinally folded sequence overlies the platform sediments containing corundum bearing metabauxites. The contact between the marbles and the calc-micaschists is strongly tectonised and sharp. The calc-micaschists contain quartz + calcite + muscovite + garnet ± chlorite, the metabasites show actinolite + epidote + crossite? + rutile. Thus, a distinctly higher degree of medium-P metamorphic overprint compared to the blueschist layers from the Dilek Peninsula or from the olistostrome matrix near Selçuk is obvious.

This raises the question whether these rocks can be considered as the continuation of the sediments of Dilek and Vourliotis as well as Ampelos nappes of Samos or if this locality has to be considered as part of the olistostromal unit. GÜNGÖR (1995) is strongly in favour of the last hypothesis. This then would imply a metamorphic gradient within the olistostromal matrix schist increasing from SW to NW. It is noteworthy that the lithostratigraphic as well as the contact relations are not comparable in the Söke Selçuk area (SW) as compared to the Belevi-Tire (NW) region.

PT estimates of the Dilek blueschist

Sodic and sodic-calcic amphiboles are partly to completely altered to green amphibole and chlorite. They can be classified as crossites, winchites and barroisitic amphiboles respectively (CANDAN et al., 1997). As mentioned there, the distribution of crossite in the blueschist relics coincides roughly with the diaspore zone in the metabauxites of the Dilek Peninsula. The crossite composition allows to use grid number 5 of EVANS (1990) for the observed blueschist assemblage (Fig. 2) The stability field for assemblages containing epidote and sodic amphibole is delimited by heavy lines. In figure 2, the reactions kaolinite <=> pyrophyllite + diaspore + water, pyrophyllite <=> diaspore + quartz as well as the diaspore <=> corundum + water reactions were calculated with GEO-CALC (BROWN et al., 1988) and the databank of BERMANN (1988). As for the epidote blueschist grid a water activity $a_{H_2O} = 0.9$ has been used. Diaspore and quartz are stable at low temperatures and elevated pressures. The absence of this paragenesis in the metabauxites sets an upper pressure limit, whereas the absence of corundum limits the P,T conditions with respect to temperature. The occurrence of kyanite + quartz instead of pyrophyllite again sets a lower T limit of ~ 400 °C. The reaction albite <=> jadeite + quartz (hatched line) also constrains the upper pressure limit experienced by these rocks. A further pressure constraint can be gained by the Si content (3.3–3.4 atoms p.f.u.) of phengite (Tab. 1). Again using GEO-CALC in combination with the databank of BERMAN (1988) and phengite mixing models of MASSONNE (1995), phengites associated with albite record pressures between 0.6 and 0.8 GPa in the field of blueschists. In conclusion, the first PT estimates by CANDAN et al. (1997) are now better constrained to pressures in the order of 0.7 GPa for temperatures in the range 350 to 420 °C, indicating a clear subduction related geotherm of ca. 17 °C/km. The observation of pseudomorphs after lawsonite is an indication for an even lower geotherm during the prograde evolution of the Dilek blueschists.



① Lws + Jd + Di ⇌ Gln + Czo + Qtz + H2O

② Ab ⇌ Jd + Qtz

Fig. 2 P-T diagram relevant for the Dilek blueschist relics based on grids of EVANS (1990). Additional equilibria are discussed in the text.

Tab. 1 Representative microprobe analyses of phengites from Dilek blueschist facies rocks.

	pheng	pheng	pheng
SiO_2	49.48	48.78	48.37
TiO_2	0.19	0.22	0.28
Al_2O_3	25.06	25.34	25.19
FeO	6.00	5.79	6.81
MnO	0.02	0.04	0.07
MgO	3.04	3.81	3.49
CaO	0.02	0.01	0.01
Na_2O	0.22	0.25	0.65
K_2O	10.15	9.65	9.38
Total	94.18	93.89	94.25
number of ions on the basis of 22 O			
Si	6.810	6.721	6.681
Ti	0.019	0.022	0.029
Al	4.066	4.115	4.101
Fe	0.690	0.667	0.786
Mn	0.002	0.004	0.008
Mg	0.623	0.782	0.718
Ca	0.002	0.001	0.001
Na	0.058	0.066	0.174
K	1.782	1.696	1.652
Fe/(Fe + Mg)	0.525	0.460	0.522

These conditions are slightly lower in P and T than the ones proposed by CHEN et al. (1995) for the three units on Samos. However both studies result in very similar geotherms.

$^{40}Ar/^{39}Ar$ geochronology of blueschists

Phengites from a well-preserved blueschist assemblage from the Dilek Peninsula were dated by the laser probe $^{40}Ar/^{39}Ar$ method. A small amount of pure phengite with a grain size in the range 50–100 microns has been hand-picked under a binocular and carefully washed by ultrasonic treatment in aceton, ethanol and distilled water. The samples were irradiated in the Canadian McMaster nuclear reactor together with several age monitors, including the MMHb-1 amphibole (520.4 ± 1.7 Ma, SAMSON and ALEXANDER, 1987) and LP-6 biotite (128.9 ± 1.4 Ma, INGAMELLS and ENGELS, 1976). After irradiation, they were placed on a drilled copper plate and loaded into a stainless sample chamber with a pyrex window connected to a small volume gas cleaning inlet system. The system was baked for two days to reduce the atmospheric argon contamination to a very low level. Mean blank values during this experiment for ^{40}Ar, ^{39}Ar, ^{38}Ar, ^{37}Ar and ^{36}Ar were 3.5,

Tab. 2 $^{40}Ar/^{39}Ar$ results.

N°	$^{40}Ar^{*}/^{39}Ar$	$^{36}Ar/^{40}Ar \times 1000$	$^{39}Ar/^{40}Ar$	$^{37}Ar/^{39}Ar$	% Atm.	^{39}Ar 10^{-16} mole	Age ± 1sd
Phengite step-heating			J = 0.017986				
1	3.322	2.628	0.0672	2.505	77.67	1.61	104.7 ± 9.5
2	1.240	0.794	0.6166	0.144	23.48	31.24	39.8 ± 0.3
3	1.261	0.661	0.6377	0.054	19.55	77.46	40.5 ± 0.3
4	1.248	0.252	0.7413	0.012	7.45	96.08	40.1 ± 0.3
5	1.223	0.278	0.7501	0.013	8.22	46.47	39.3 ± 0.3
6	1.232	0.428	0.7084	0.022	12.66	98.01	39.6 ± 0.5
7	1.248	0.294	0.7310	0.067	8.69	36.72	40.1 ± 0.5
8	1.252	0.405	0.7026	0.050	11.98	44.71	40.2 ± 0.4
9	1.266	0.198	0.7432	0.035	5.86	84.30	40.6 ± 0.3
10	1.264	0.218	0.7395	0.028	6.46	22.41	40.6 ± 0.6
11	1.240	0.161	0.7674	0.013	4.77	26.06	39.8 ± 0.7
12	1.305	0.060	0.7523	0.015	1.79	10.27	41.9 ± 1.4
13	1.254	0.213	0.7469	0.027	6.32	57.24	40.2 ± 0.2
						mean age =	40.2 ± 0.4
Phengite single grain fusions							
1	1.208	1.108	0.5564	0.029	32.76	44.32	38.8 ± 0.4
2	1.262	0.761	0.6139	0.023	22.49	25.28	40.5 ± 0.4
3	1.206	0.885	0.6118	0.011	26.16	32.64	38.7 ± 0.5
4	1.268	0.377	0.7000	0.006	11.17	41.77	40.7 ± 0.4
5	1.231	0.326	0.7335	0.003	9.64	28.88	39.5 ± 0.5
6	1.245	0.676	0.6422	0.013	20.00	30.11	40.0 ± 0.6
7	1.256	0.709	0.6290	0.002	20.96	11.41	40.3 ± 0.1
8	1.207	0.475	0.7121	0.016	14.04	28.76	38.7 ± 0.4
9	1.218	0.313	0.7445	0.023	9.26	24.05	39.1 ± 0.5
10	1.203	0.235	0.7731	0.014	6.96	32.45	38.6 ± 0.3
11	1.215	0.669	0.6596	0.023	19.79	57.01	39.0 ± 0.3
						mean age =	39.3 ± 0.4

0.04, 0.04, 0.13 and 0.06 $\times 10^{-12}$ cm^3 STP respectively. They were carried out at room temperature and were measured every three experiments. During analysis, they typically increase by a factor of 20%. Argon was extracted from the samples using a 6W continuous argon laser and isotopes were measured into a MAP 215-50 mass spectrometer. In a first experiment, an age spectrum was produced from the simultaneous degassing of five grouped grains using a very defocused laser beam. The homogeneous heating of the grains was optically controlled through the CCD camera placed above the sample chamber. A second set of experiments was performed by focusing the laser beam on individual mica flakes, thus allowing the isotopic homogeneity of the phengite population to be checked. Data have been corrected for blanks, mass discrimination, ^{37}Ar and ^{39}Ar decay and irradiation-induced mass interferences. They have been fitted on $^{36}Ar/^{40}Ar$ vs $^{39}Ar/^{40}Ar$ isochron plots following the regression technique reported by YORK (1969). The mean square of weighted deviates (MSWD) is used to test the goodness of fit. MSWD values greater than 1+2 σ would indicate scatter of results along the regression line.

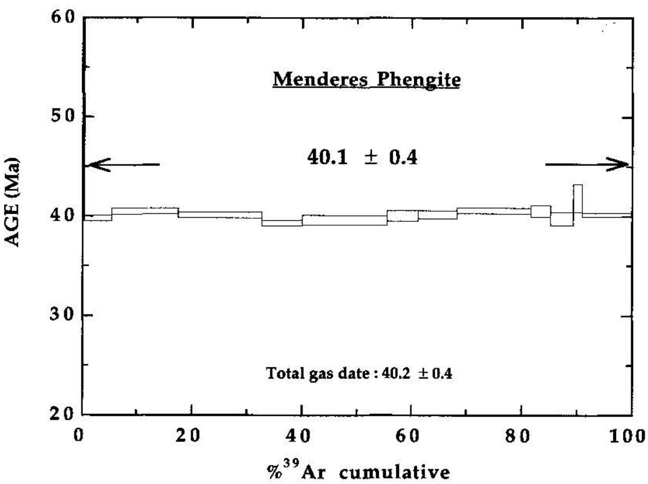


Fig. 3 Age spectrum of phengite grains using a strongly defocused laser beam.

$^{40}Ar/^{39}Ar$ results are listed in table 2, with age errors quoted at the 1σ level.

The age spectrum of phengite is presented in figure 3. With the exception of the first heating step that is severely contaminated by atmospheric argon and probably represents argon released from the mica surface, twelve gas fractions yielded concordant apparent ages which define a plateau date of 40.1 ± 0.4 Ma. The isochron age (Fig. 4) is exactly similar to the plateau date with a $^{40}Ar/^{36}Ar$ intercept value of 293.3 ± 11.9 (MSWD = 1.85 ± 0.45). Eleven phengites were successively melted with a focused laser beam. Individual ages range from 38.6 ± 0.3 Ma to 40.7 ± 0.4 Ma, with an integrated mean value of 39.3 ± 0.4 Ma. The isochron plot (Fig. 5) yielded an intercept age of 39.1 ± 0.4 Ma, a $^{40}Ar/^{36}Ar$ initial value of 302.8 ± 16.5 and a MSWD of 3.68 ± 0.47. This fit parameter indicates that the data do not strictly define a straight line, suggesting that the isotopic composition of argon slightly deviates from one grain to another, as observed from individual apparent ages.

The interpretation of $^{40}Ar/^{39}Ar$ phengite ages in high-pressure rocks is frequently complicated by the occurrence of excess argon, mainly for rocks subjected to high and very high-pressure metamorphic conditions (e.g. LI et al., 1994; ARNAUD and KELLEY, 1995; RUFFET et al., 1995). However, several arguments suggest that excess argon has probably not been incorporated in the blueschist-facies phengites of the Dilek Peninsula: (i) individual total fusion ages do not scatter considerably, as could be expected for minerals contaminated by excess argon. The scattering (~ 2 Ma) most likely records the influence of the late greenschist grade metamorphic event; (ii) the isochron plots do not reveal abnormal initial $^{40}Ar/^{36}Ar$ ratios; (iii) the K-poor nature of the protolith, the relatively low peak metamorphic pressure and the penetrative deformation of the sample are not suitable conditions for incorporation of excess argon; (iv) an Eocene age for blueschist facies metamorphism is compatible with geological constraints reported from the Cyclades; (v) the obtained age of ~ 40 Ma is in agreement with the range of Rb–Sr muscovite ages (43–63 Ma) reported in the underlying medium-pressure metamorphic series of the Menderes crystalline massif (SATIR and FRIEDRICHSEN, 1986); (vi) there is also agreement with the age of HP/LT metamorphism in the neighbouring Cyclades at 40–50 Ma (e.g. MALUSKI et al., 1987; WIJBRANS et al., 1990; BRÖCKER et al., 1993; CHEN et al., 1995).

Despite the poor knowledge of the blocking temperature for Ar diffusion in phengite (most probably in the range 350–450 °C; ANDRIESSEN, 1991), and given the relative low temperature peak conditions (T: 350–420 °C), we interpret the 40 Ma $^{40}Ar/^{39}Ar$ age of phengite to reflect an early stage of cooling close to the crystallisation age of the mica.

Discussion

The Tertiary age of the blueschist facies metamorphism recorded on the Dilek Peninsula as well as their lithological character provide strong support for correlation of the metasediments of the Menderes Massif cover sequence with rocks in the Attic-Cycladic crystalline complex in the central Aegean Sea, which is characterised by spectacular outcrops of eclogites and blueschists. This complex underwent high-pressure metamorphism at a grade corresponding to the transition between eclogite and epidote-blueschist facies metamorphism in Late Eocene – Early Oligocene

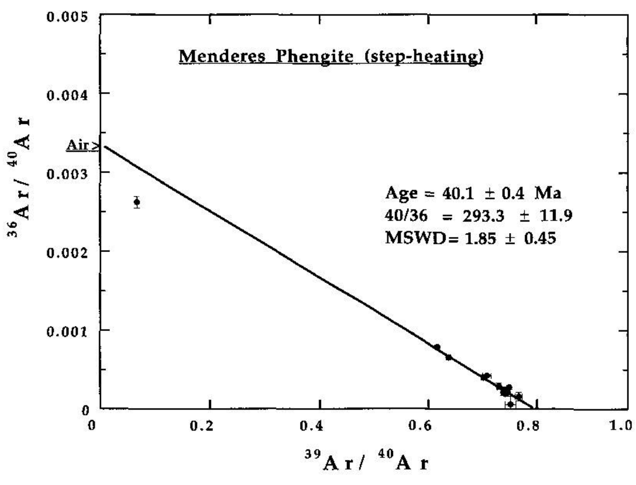


Fig. 4 Isochron diagram for laser step heating experiments.

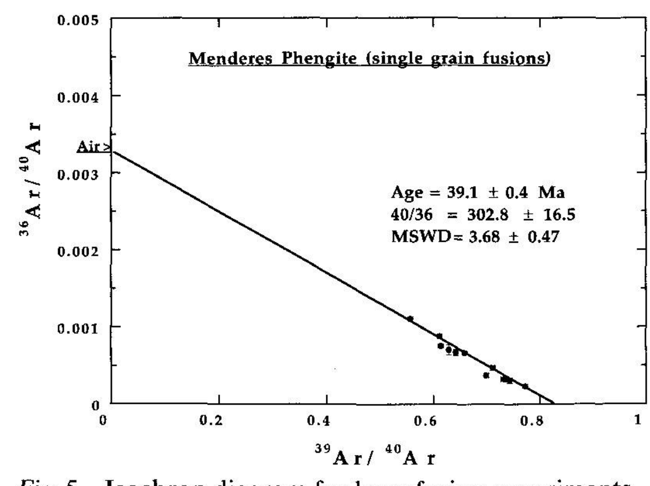


Fig. 5 Isochron diagram for laser fusion experiments.

time, and was subsequently overprinted by a medium-pressure Barrovian-type metamorphism under greenschist to amphibolite facies conditions at the Oligocene/Miocene boundary (ALTHERR et al., 1979; OKRUSCH and BRÖCKER, 1990).

On the Island of Samos (situated 2 km NW of the Dilek Peninsula), widespread blueschist relics, glaucophane bearing metagabbros, glaucophanites and one omphacitic rock (+ czo/zo ± chl) occur (MPOSKOS and PERDIKATSIS, 1984; OKRUSCH et al., 1984; CHEN, 1992). The Vourliotis unit, exposed in the eastern part of Samos, consists of interbedded marbles and metapelites with minor mafic intercalations (OKRUSCH et al., 1984). This isoclinally folded succession with widespread blueschist relics is typified by quartzitic phyllites (Ky + Chd), metabauxites (Dsp + Chd; FEENSTRA, 1997) and rudist (Hippurites s.l.) bearing Upper Cretaceous marbles (PAPANIKOLAOU, 1979). In the Central northern part of the island, the Ampelos unit comprises garnet bearing blueschists (OKRUSCH et al., 1984). However, the area where these rocks occur is characterised by slightly higher M1 P-T conditions than elsewhere on Samos and therefore it is a matter of debate, whether these rocks really belong to the Ampelos unit (FEENSTRA, pers. com.).

The Tertiary blueschists in the western cover sequence of the Menderes Massif are garnet free in the Dilek area and comprise garnet in the Tire region. Based on their lithostratigraphic aspects, their metamorphic overprint and age, these localities can be correlated with the Vourliotis (+ Ampelos) nappe of the Cycladic complex in Samos. The rocks exposed on Dilek Peninsula (Kayaalti FM) are a continuation of the Vourliotis unit, while the rocks occurring NW of Tire (Selçuk FM) might correlate with the Ampelos unit (RING, pers. com.). As a consequence, the north-western cover sequence of the Menderes Massif must be considered as the continuation of the Cycladic complex. Thus, these marble sequences cannot be considered as stratigraphic cover of the Menderes Massif crystalline complex in the sense of DÜRR (1975). They compose an allochthonous, internally imbricated exhumed sequence.

Rocks containing ample relics of blueschists are trending SW–NE along the thrust of the Izmir-Ankara zone, as indicated by GÜNGÖR (1995). They tentatively might be further correlated with the HP/LT belt of the Anatolides as defined by OKAY (1984) in the NE of the Menderes Massif. However such a correlation is incompatible with metamorphic ages. As shown above, we have strong arguments for a Tertiary HP/LT overprint on Dilek. Contrarily to this, available age information up to now indicate a Late Cretaceous metamorphism for the Anatolides. ÇOGULU and KRUMMENACHER (1967) published K/Ar ages of phengites in blueschists from Mihalliçcik ranging from 82–65 Ma, while KULAKZIS and PHILLIPS (1984) obtained ages scattering from 126 to 115 Ma for glaucophanes and phengites from Sivrihisar. OKAY and KELLEY (1994) reported laser probe $^{40}Ar/^{39}Ar$ phengite ages of 88 Ma from jadeite schists of the Kocasu region. Thus, it seems unlikely that a genetic relation exists between this blueschist terrain and the HP rocks described in this paper.

Acknowledgements

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