Miocene high-pressure metamorphism in the Cyclades and Crete, Aegean Sea, Greece: Evidence for large-magnitude displacement on the Cretan detachment

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ABSTRACT

The Cyclades in the backarc region of the present Hellenic subduction zone are known for widespread Late Cretaceous to Eocene high-pressure metamorphism in the Cycladic blueschist unit. We report $^{40}Ar/^{39}Ar$ and Rb/Sr phengite ages of 24–21 Ma for high-pressure metamorphism (8–10 kbar, 350–400 °C) in the lowest tectonic unit in the Cyclades, the Basal unit, which structurally underlies the Cycladic blueschist unit. The Basal unit is correlated with the Tripolitza unit of the External Hellenides in the forearc region of the Hellenic subduction zone. The Tripolitza unit is unmetamorphosed on Crete, where it is separated from the underlying high-pressure (8–10 kbar, 300–400 °C) Plattenkalk and Phyllite-Quartzite units by the extensional Cretan detachment. The age for high-pressure metamorphism in the latter units is similar to our age for the Basal unit in the Cyclades. Because pressure-temperature conditions in the Plattenkalk and Phyllite-Quartzite units on Crete and the Basal unit in the Cyclades are also similar, they must have been in close proximity in the early Miocene Hellenic subduction zone. A palinspastic reconstruction suggests a subsequent displacement of >100 km on the Cretan detachment. This is one of the greatest displacement magnitudes ever reported from detachment faults. Because of this large offset, the Cretan detachment was an efficient agent for exhuming high-pressure rocks.

Keywords: detachment fault, displacement, exhumation, high-pressure metamorphism, geochronology, Aegean, Greece.

INTRODUCTION

The exhumation of high-pressure rocks is widely attributed to normal faulting (Platt, 1986). Shallowly dipping extensional detachments can only make a significant contribution to exhumation if displacement on them is large (Ring et al., 1999a). However, a common problem is that the displacement on faults is difficult to quantify.

High-pressure metamorphism in the Aegean occurs in two coherent belts: a Late Cretaceous to Eocene belt (the Cycladic blueschist unit) in the backarc area of the Cyclades, and a Miocene external belt on Crete and the Peleponnesus in the forearc region of the present Hellenic subduction zone (Fig. 1). How these two high-pressure belts are structurally connected is unknown. This is in part due to severe subsequent extension, which attenuated the crust by ≥50% (McKenzie, 1978; Makris and Stobbe, 1984). The exhumation of the Aegean high-pressure rocks has widely been attributed to extensional faulting in a backarc setting (Lister et al., 1984; Avigad et al., 1997).

We report early Miocene ages (24–21 Ma) for high-pressure metamorphism (8–10 kbar, 350–400 °C) of the Basal unit, which is structurally below the Late Cretaceous to Eocene Cycladic blueschist unit in the Cyclades. The age and pressure-temperature conditions of the Basal unit indicate that its metamorphism occurred in a forearc setting in close proximity to the Miocene high-pressure rocks of the external belt on Crete. Subsequently the external high-pressure belt and the Basal unit were separated by the Cretan detachment and now occur in two different settings. Thomson et al. (1999) showed fast exhumation (>4 km/m.y.) by normal faulting of the Cretan high-pressure rocks, which demands a huge displacement on the Cretan detachment. On the basis of age dating and correlation of metamorphism and geology, we suggest that the Cretan detachment is a shallowly dipping detachment fault with >100 km of displacement.

SETTING

Previous detailed research has led to the widely accepted view that the Hellenides are composed of northwest-striking tectonic units, which are distinguished by stratigraphy, depositional facies, and precollisional paleogeography (Dürr et al., 1978; Jacobshagen, 1986). The Cycladic zone is fringed to the north by the oceanic Vardar-Izmir-Ankara suture zone, the Lycian nappes, and the Pelagonian zone (Fig. 1). The dominant tectonic unit of the Cycladic zone is the Cycladic blueschist unit, which comprises, in descending order, three composite nappe units: (1) a melange-like unit of ophiolitic rocks underlain by (2) a nappe containing a post-Carboniferous shelf sequence, and (3) a Carboniferous basement unit (Ring et al., 1999b). In some windows in the Cycladic zone, the metasediments of the Basal unit crop out below the Cycladic blueschist unit. The Basal unit is considered to be part of the External Hellenides (Avigad et al., 1997). The External Hellenides are made up of the Pindos and Tripolitza units, below which the Plattenkalk and Phyllite-Quartzite units occur. The Pindos and Plattenkalk carbonates have intercalated chert layers and represent a deep-water facies, whereas metabauxites and reef-building fossils indicate that the carbonates of the Tripolitza unit were deposited on a carbonate platform that was periodically emergent. Eocene and Oligocene flysch is another characteristic of the Pindos and Tripolitza units (Jacobshagen, 1986).

On Crete, the Plattenkalk and Phyllite-Quartzite units have a high-pressure overprint and are separated from the overlying unmetamorphosed Tripolitza unit by the early Miocene Cretan detachment (Fassoulas et al., 1994). The detachment is a ~0.5–10-m-thick fault plane, which parallels Oligocene–early Miocene thrust surfaces (Jolivet et al., 1996). Thomson et al. (1999) showed that movement on the Cretan detachment commenced in the early Miocene and was completed by ca. 17 Ma. Stöckhert et al. (1999) pointed out that the rocks in the hanging wall and footwall of the Cretan detachment are remarkably undeformed, indicating that the detachment was very weak.

The metamorphic evolution of the Cycladic blueschist unit includes a prolonged Late Cretaceous to Eocene high-pressure event (ca. 78–50 Ma) followed by a greenschist to amphibolite facies overprint ca. 23–16 Ma (Altherr et al., 1982; Wijbrans et al., 1990; Bröcker and Enders, 1999). High-pressure metamorphism in the Plattenkalk and Phyllite-Quartzite units of

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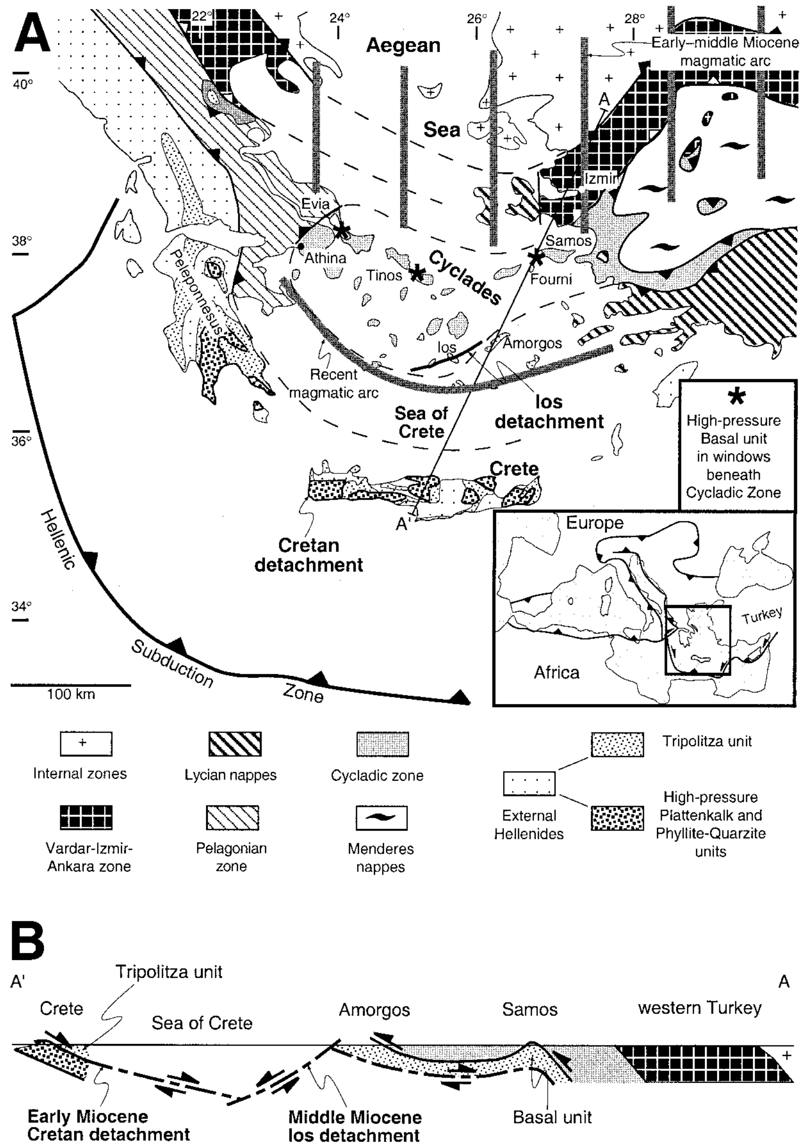

Figure 1. A: Generalized tectonic map of Aegean (modified from Jacobshagen, 1986). Asteriks indicate windows of Basal unit below Cycladic blueschist unit in Cyclades; early-middle Miocene and recent volcanic arcs (Fytikas et al., 1984) are shown. Inset shows location of main map. B: Northeast-southwest cross section showing nappe pile and probable position of Cretan detachment with high-pressure metamorphic Basal unit in Cyclades and unmetamorphosed Tripolitza unit on Crete in hanging wall. Cretan detachment is crosscut by younger Ios detachment (Forster and Lister, 1999), which brings Cretan detachment into relatively high position in Cyclades.

the External Hellenides is dated as ca. 24–20 Ma (Seidel et al., 1982; Thomson et al., 1999).

BASAL UNIT

In the Cycladic zone, the Basal unit is exposed in the Almyropotamus and Panormos windows on Evia and Tinos Islands and as the Kerketas nappe on Samos and Fourni Islands (Fig. 1; Table 1). Oligocene–early Miocene thrusting of the Cycladic blueschist unit onto the Kerketas nappe caused high-pressure metamorphism (8–10 kbar, 350–400 °C; Table 1) in the nappe, which was followed by a greenschist facies overprint (Ring et al., 1999b). Vestiges of the high-pressure metamorphic assemblage are phengite, chlorite, quartz, and talc in calcschist. A metabauxite deposit contains a diaspore + kyanite paragenesis, which can also be related to the high-pressure event (E. Mposkos, 1998, written commun.).

In the Almyropotamos window on Evia Island, thrusting of the Cycladic blueschist unit caused high-pressure metamorphism in the Basal unit similar to that in the Kerketas nappe (Shaked et al., 2000). Bröcker and Franz (1998) reported a Rb/Sr phengite age of 22 Ma from the Basal unit in the Parnormos window on Tinos Island. The dated phengite has a composition similar to those from the Basal unit on Evia and Samos. Previous research has shown that the silica content in phengite increases with increasing pressure and that phengite with a silica content of $>\sim 3.3$ per formula unit does not form during greenschist facies metamorphism (Velde, 1967; Massone and Schreyer, 1987).

This summary suggests that the Basal unit in the Cycladic zone underwent high-pressure metamorphism. Reef-building fossils and metabauxite horizons indicate shallow-water conditions and periodic emergence (Table 1). Hence, we follow Avigad et al. (1997), and correlate the Basal unit with the Tripolitza unit of the External Hellenides. The latter is unmetamorphosed on Crete. On Amorgos Island to the north of Crete (Fig. 1), carpholite in metabauxite suggests mild high-pressure conditions. Therefore, metamorphism of the Tripolitza Basal unit increases northward.

GEOCHRONOLOGY

We performed $^{40}Ar/^{39}Ar$ single-crystal step-heating analyses at the University of Alaska in Fairbanks, and Rb/Sr analysis at the Max-Planck-Institut für Geochemie in Mainz, Germany[1]. The silica content of the dated phengites varies from 3.29 to 3.48 per formula unit. Detailed microscopy and microprobe mapping revealed no compositional zoning, except for phengite of sample Sa97–85B, which has an additional Ca-bearing phase. X-ray diffraction analysis indicates that the phengites are 3T polymorphs. This work indicates that the phengites were not affected by greenschist facies recrystallization.

The $^{40}Ar/^{39}Ar$ single-crystal dating on phengite from samples Sa97-85, Sa97-85F, and Sa97-113 yielded consistent plateau ages of 23.9–22.8 Ma (Fig. 2). The Ca/K ratios associated with heating steps showed little variation, consistent with degassing of a monomineralic phase. Isochron calculations suggest that the Ar is not contaminated by an excess component. The age of sample Sa97-85B is slightly more difficult to interpret. This mineral is contaminated with excess Ar. We regard the isochron age of 25.2 ± 3.2 Ma, which is within error similar to the other ages, as the best estimate. A Rb/Sr phengite–whole-rock isochron from sample Sa97-85 yielded an age of 20.8 Ma (Fig. 3).

The usually assumed closure temperature for Rb/Sr in phengite (500 ± 50 °C) is above the maximum metamorphic temperature in the

[1]GSA Data Repository item 2001043, Analytical procedures, chemical data, element distributions maps, and geochronologic data, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, and at www.geosociety.org/pubs/ft2001.htm.

TABLE 1. LITHOLOGY AND METAMORPHISM OF BASAL UNIT IN CYCLADES

Window and/or island with Basal unit*	Lithology	High-pressure conditions	Age of metamorphism
Almyropotamos[1]	~2000 m Mesozoic to Eocene platform carbonates (including rudists); ~1500 m Eocene to Oligocene(?) metaflysch	~10 kbar, ~350 °C	?
Panormos[2]	Dolomitic marble (including corals, algae and echinoids), quarzite, calcschist, phyllite	?	22 Ma (Rb/Sr on phengite with Si content of 3.3–3.4 per formula unit)
Kerketas[3]	>1000 m dolomitic marble (including metabauxite), calcschist	8–10 kbar, 350–400 °C	24–21 Ma ($^{40}Ar/^{39}Ar$ and Rb/Sr on phengite with Si content of 3.3–3.5 per formula unit)
Amorgos[4]	>1000 m Mesozoic to Eocene marble (including metabauxite, rudists, corals, megalodonts, and in situ carbonate breccias), Eocene to Oligocene metaflysch	5–8 kbar, <350 °C	?

*Data sources: [1]Shaked et al. (2000); [2]Avigad and Garfunkel (1989), Bröcker and Franz (1998); [3]Ring et al. (1999b, this study); [4]Jacobshagen (1986). ? is unknown.

Kerketas nappe. Villa (1998) showed that phengite retains most or all of its Ar below 550–580 °C in the absence of subsequent greenschist facies recrystallization. Therefore, the determined ages are not cooling ages. Consequently, we interpret the ages of 24–21 Ma as phengite crystallization ages during high-pressure metamorphism in the Kerketas nappe.

DISCUSSION

The $^{40}Ar/^{39}Ar$ and Rb/Sr phengite ages of 24–21 Ma from the Kerketas nappe on Samos are similar to the Rb/Sr phengite age of 22 Ma from the Parnormos window on Tinos (Bröcker and Franz, 1998). We interpret this early Miocene date as the time of high-pressure metamorphism in the Basal unit in the Cycladic zone. The proposed correlative Tripolitza unit is unmetamorphosed on Crete, where it is separated from the high-pressure Plattenkalk and Phyllite-Quartzite units by the Cretan detachment. We note that the age of 24–20 Ma for high-pressure metamorphism in the Plattenkalk and Phyllite-Quartzite units and pressure-temperature conditions of 8–10 kbar and 300–400 °C (Seidel et al., 1982) are similar to the age and pressure-temperature conditions for high-pressure metamorphism in the Basal unit of the Cyclades (Table 1). Therefore, both units were metamorphosed in close proximity to each other in the early Miocene Hellenic subduction zone, which provides a critical piercing point for palinspastic reconstructions.

We propose a simple geometric model that links the pressure-temperature gradient in the Tripolitza unit from Crete across Amorgos into the Cycladic zone with high-pressure metamorphism in the Plattenkalk and Phyllite-Quartzite units for approximating the displacement on the Cretan detachment (Fig. 4). The present distance between Crete and the Cyclades of ~250 km is in part controlled by pronounced middle Miocene extension, which caused the opening of the Sea of Crete. The present crustal thickness beneath the Sea of Crete is ~16–20 km (Makris and Stobbe, 1984). Widespread blueschist facies metamorphism around the Sea of Crete (Seidel et al., 1982; Forster and Lister, 1999) suggests a preextension crustal thickness of ~40 km, which yields a vertical stretch (final length/initial length) of 0.4–0.5. Assuming plane-strain isochoric deformation gives a horizontal stretch of 2–2.5. McKenzie (1978) estimated a horizontal stretch of 1.5–2 for the entire Aegean. A value of 2 results in an early Miocene distance between Crete and the Cyclades of ~125 km. The vertical separation between the high-pressure and unmetamorphosed Tripolitza unit is ~22–33 km (Fig. 4). These crude estimates yield a displacement on the Cretan detachment of ~128 km and imply a dip of 10°–15° for the Cretan detachment. These dip angles are close to the present subduction angle of 14° of the Hellenic slab (Giunchi et al., 1996). Hence, is seems likely that the Cretan detachment was a former subduction-related thrust. As the Hellenic subduction zone retreated to the south, subduction-related thrusting also moved southward and the extensional Cretan detachment may have formed along a reactivated thrust plane.

The present crustal thickness of ~40–50 km underneath Crete (Knapmeyer and Harjes, 2000) is not fundamentally different from the minimum early Miocene crustal thickness of ~35 km as deduced from the high-pressure rocks. This implies that crustal extension across the Cretan detachment must have been associated with sustained underplating, which compensated crustal thinning in Crete.

CONCLUSIONS

The Basal unit in the Cyclades was metamorphosed under high-pressure conditions in the early Miocene. This age is considerably younger than the age of high-pressure metamorphism in the overlying Cycladic blueschist unit. We propose that the Basal unit of the Cyclades was in close proximity to the Cretan high-pressure rocks during early Miocene subduction. Both high-pressure units were subsequently displaced by >100 km along the Cretan detachment. Such a displacement magnitude is among the greatest ever reported from detachment faults. Because of large-

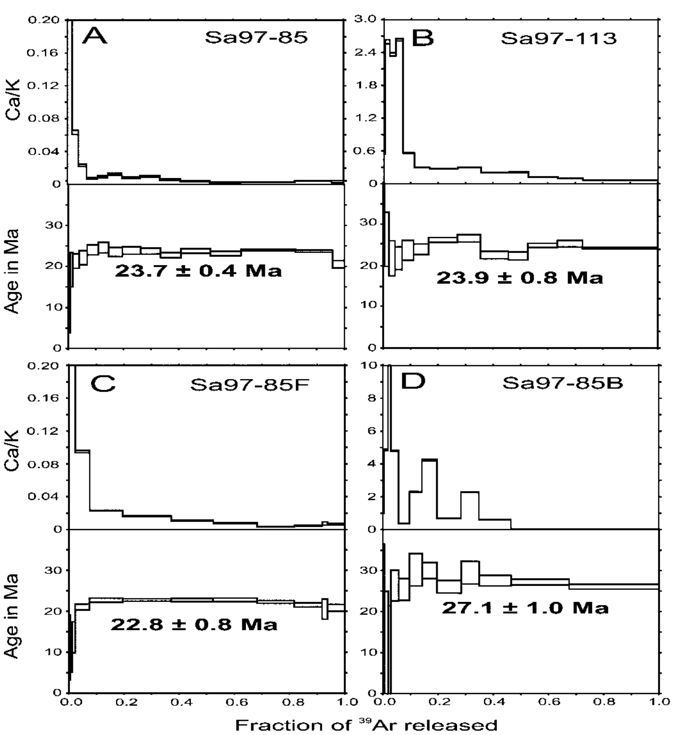

Figure 2. Ca/K ratios and $^{40}Ar/^{39}Ar$ apparent age spectra for phengites from Kerketas nappe; errors are quoted to 2 σ level. Ca/K ratio of sample SA97-85B suggests that mixture of phengite and Ca-bearing phase degassed within this temperature range; initial $^{40}Ar/^{36}Ar$ ratio of 565 ± 249 suggests excess Ar, which is apparently carried by Ca-bearing phase. We regard isochron age of 25.2 ± 3.2 Ma (see text footnote 1) as best age estimate.

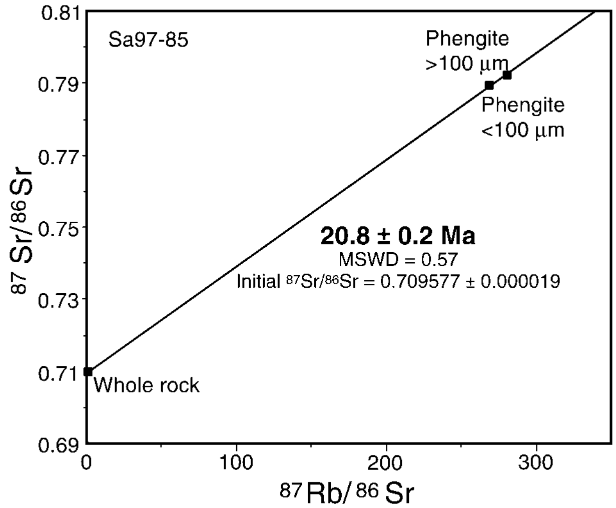

Figure 3. Rb/Sr isochron diagram for two phengite size fractions and whole rock from sample Sa97-85; due to high Rb/Sr ratios of phengite, age of 20.8 ± 0.2 Ma is well defined. Isochrons for phengite and corresponding leachates yielded ages of 20.9 ± 0.3 Ma for >100 µm fraction and 21.1 ± 0.3 Ma for <100 µm fraction (see text footnote 1). These ages are within error identical to phengite–whole-rock age, suggesting that Sr system was not disturbed, which is consistent with absence of post-high-pressure recrystallization of dated samples. MSWD is mean square of weighted deviations.

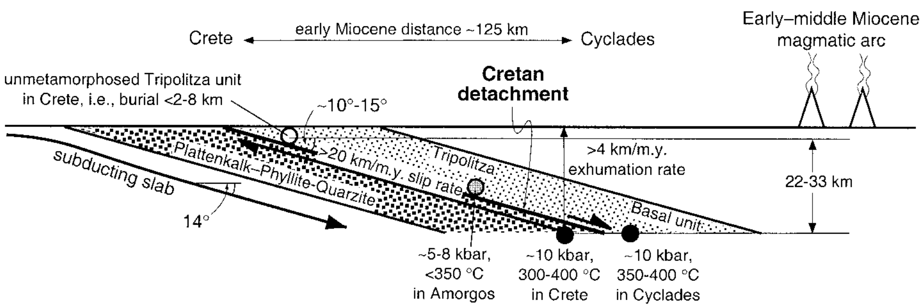

Figure 4. Geometric approximation of displacement on Cretan detachment. Pressure-temperature conditions and age of metamorphism in Plattenkalk and Phyllite-Quarzite units on Crete and Basal unit in Cyclades are similar, suggesting that they were in close proximity in early Miocene. Present distance between Crete and Cyclades of ~250 km has been restored using horizontal stretch of 2. Pressure was converted to depth assuming average rock density of 2800 kg/m³, which results in vertical separation between high-pressure and unmetamorphosed Tripolitza and Basal unit of 22–33 km. These values combined with early Miocene distance of 125 km yield displacement of ~128 km and dip angles of 10°–15° for Cretan detachment. Also shown is exhumation rate for Plattenkalk and Phyllite-Quartzite units (Thomson et al., 1999) and estimated slip rate on Cretan detachment. Extension is resolved on one single detachment, which is compatible with geology on Crete. Early-middle Miocene magmatic arc north of Cyclades (Fytikas et al., 1984) indicates that large-scale extension on Cretan detachment occurred in forearc region.

magnitude extension, low-angle detachment faulting was an efficient process for exhuming the Cretan high-pressure rocks.

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