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U–Pb zircon geochronology of unusual eclogite-facies rocks from Syros and Tinos (Cyclades, Greece)

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Abstract – Low-temperature eclogite-facies rocks from Syros and Tinos (Cyclades, Greece) include meta-igneous blocks of unclear origin (meta-olistostrome or tectonic mélange) with very high trace element concentrations (e.g. Zr up to 4850 ppm; Y up to 475 ppm). The unusual geochemistry is considered to be the result of metasomatic alteration in a subduction-zone environment. Locally, metasomatic exchange with an ultramafic matrix further enhanced compositional anomalies. A concordant U–Pb zircon age of 78 ± 1 Ma recorded for an omphacitite from Syros is interpreted as the time of pre-Eocene high-pressure metamorphism in the Cyclades. Zircon dates of 61 and 63 Ma for a jadeitite from Tinos possibly indicate an additional discrete event (deformation?). These results are a first geochronological indication that high-pressure metamorphism in the Cyclades commenced significantly earlier than indicated by previous white mica chronology which provided ages between *c.* 50 and 40 Ma.

1. Introduction

The Attic–Cycladic Crystalline Belt forms a complex polymetamorphic terrane within the Alpidic orogenic belt of the Hellenides. Previous geochronological and petrological studies resulted in an apparently straightforward interpretation of a Tertiary polymetamorphic evolution. The tectono-thermal history includes a high-pressure/low-temperature event during the Eocene and a greenschist- to amphibolite-facies metamorphism in Oligocene to Miocene times (e.g. Dürr *et al.* 1978; Dürr, 1986; Schliestedt, Altherr & Matthews, 1987; Okrusch & Bröcker, 1990). Although the general framework of the metamorphic evolution is well constrained, some important aspects of the *P–T–t* deformation path still are poorly understood, such as the duration of high-pressure/low-temperature conditions and the protolith ages of eclogites and blueschists. It is unclear whether eclogite- to blueschist-facies rocks were developed during a single metamorphic cycle, or were related to multiple episodes, significantly separated in time.

White mica dating (K–Ar, ^{40}Ar–^{39}Ar and Rb–Sr) mostly provided ages between *c.* 50 and 40 Ma for the eclogites and blueschists (e.g. Altherr *et al.* 1979; Maluski, Bonneau & Kienast, 1987; Wijbrans, Schliestedt & York, 1990; Bröcker *et al.* 1993). Most authors agree that the Eocene white mica ages characterize a relatively late stage of metamorphism, indicating only a lower time limit for (polyphase?) subduction-related metamorphism (e.g. Altherr *et al.* 1979; Maluski, Bonneau & Kienast, 1987; Bröcker *et al.* 1993). In contrast to the Cyclades, where well-preserved high-pressure rocks yielded only one group of Tertiary ages (50–40 Ma), indications either for pre-Tertiary blueschist metamorphism, or for discrete Tertiary high-pressure stages were recognized on mainland Greece (Bavay *et al.* 1980; Maluski *et al.* 1981; Schermer, Lux & Burchfiel, 1990; Faupl *et al.* 1996; Lips, White & Wijbrans, 1997).

In this contribution, new geochronological results from the islands of Syros and Tinos (Fig. 1) are reported. The emphasis is on the question of whether timing of peak metamorphism in the Cycladic blueschist belt is broadly constrained by Eocene white mica ages, or whether any indications for earlier high-pressure metamorphism can be documented.

2. Geological setting

Syros and Tinos (Fig. 1) belong to the Attic–Cycladic Crystalline Belt which consists of two major structural groups of units, separated by low-angle faults (Dürr *et al.*, 1978; Schliestedt, Altherr & Matthews, 1987; Okrusch & Bröcker, 1990). The upper group is rarely exposed and mainly consists of a heterogeneous sequence of unmetamorphosed Permian to Mesozoic sediments, ophiolites and Late Cretaceous greenschist- to amphibolite-facies rocks. The lower group is the Cycladic blueschist unit which comprises a pre-Alpidic crystalline basement overlain by thrust sheets of a metamorphosed volcano-sedimentary sequence. The Cycladic blueschist unit has experienced two stages of Tertiary metamorphism. The first metamorphic event at eclogite- to blueschist-facies conditions ($T = c.$ 450–500 °C, $P = c.$ 15 ± 3 kbar; e.g. Okrusch,

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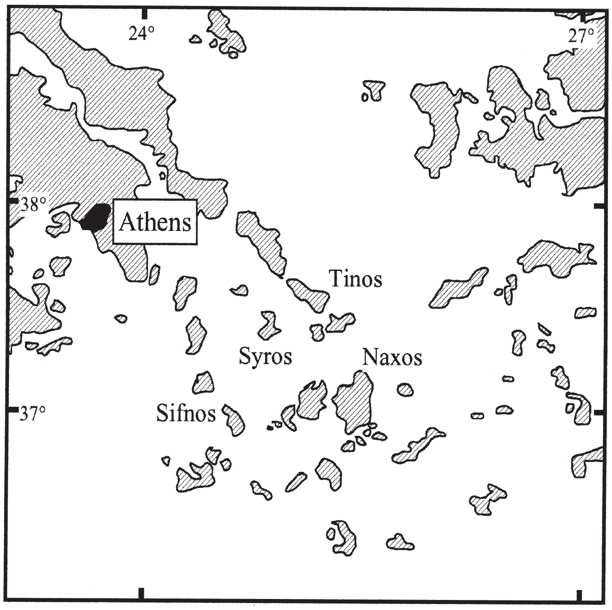

Figure 1. Geographical map of mainland Greece and the Cyclades archipelago.

Seidel & Davis, 1978; Matthews & Schliestedt, 1984; Bröcker *et al.* 1993) was caused by the subduction of the Apulian microplate beneath the Eurasian continent (Bonneau, 1984). The second greenschist- to amphibolite-facies metamorphism was interpreted to result either from nearly isothermal decompression during uplift (northern Cyclades), or from renewed prograde metamorphism (southern Cyclades), reaching conditions of migmatization (e.g. Okrusch & Bröcker, 1990; Avigad *et al.* 1992). High-pressure rocks were widely replaced by their lower pressure counterparts, but relicts of eclogites and blueschists still occur on many islands. Pressures attained during the main stages of overprint are estimated at 4–7 kbar (e.g. Avigad *et al.* 1992; Bröcker *et al.* 1993). K–Ar, ^{40}Ar–^{39}Ar and Rb–Sr dating of white mica from blueschists and eclogites yielded Eocene ages between 53 and 40 Ma; white mica of greenschist- and amphibolite-facies rocks provided ages between 25 and 18 Ma (e.g. Altherr *et al.* 1979, 1982; Wijbrans & McDougall, 1986, 1988; Maluski, Bonneau & Kienast, 1987; Wijbrans, Schliestedt & York, 1990; Bröcker *et al.* 1993). Detailed overviews of the geology and metamorphic evolution of the Cyclades are given by Dürr *et al.* (1978), Dürr (1986), Schliestedt, Altherr & Matthews (1987) and Okrusch & Bröcker (1990).

3. Sample description

On several locations on Syros, blocks of glaucophanites, metagabbros, eclogites, omphacitites, jadeitites and ultramafic rocks occur. These blocks are enclosed by either altered serpentinites and/or pelitic to tuffitic schists (e.g. Ridley & Dixon, 1984; Dixon & Ridley, 1987). It is controversially discussed whether the block–matrix association represents a meta-olistostrome (Dixon & Ridley, 1987), derived from a disrupted ophiolite, or a tectonic mélange (Altherr & Seidel, 1977). We dated an omphacitite (sample 1081) that was collected from a small block in the Kampos area (north Syros, Fig. 2). This occurrence was described in detail by Dixon & Ridley (1987), who noted that the lens-shaped to rounded tectonic blocks (metre to several decametre in size) and the matrix show evidence for eclogite- to-blueschist-facies metamorphism at identical *P–T* conditions. High-pressure metasomatic reaction zones and rinds are common at contacts between blocks and matrix (Dixon & Ridley, 1987).

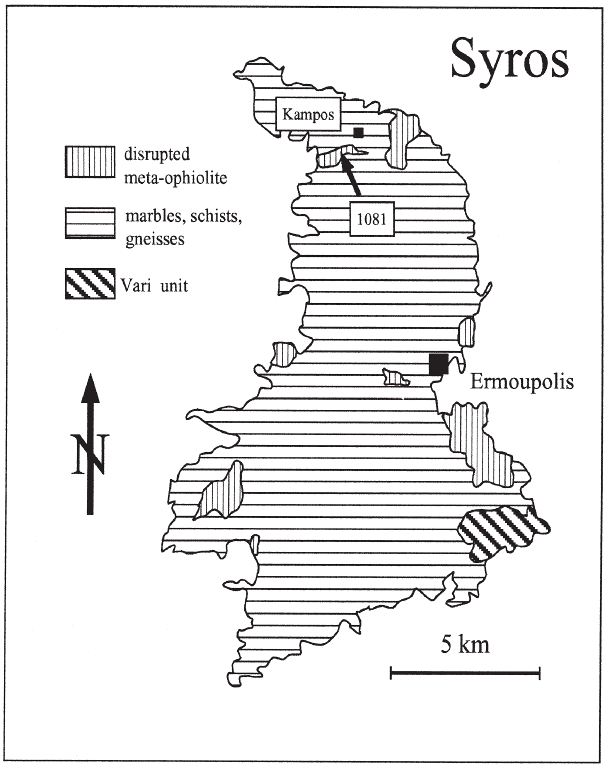

Figure 2. Simplified geological map of Syros (after Hecht, 1984) indicating the sample location discussed in the text.

The mineral assemblage of sample 1081 comprises omphacite (*c.* 70–80 vol. %; jadeite component 32–44 mol. %) and minor amounts of epidote, phengite, titanite, zircon and opaques. Subordinate quantities of chlorite and albite are related to the greenschist overprint. The nature of the protolith is unclear but most likely this sample represents a metasomatic reaction rim. In the course of this study, such omphacitite rinds were recognized around jadeitite blocks. Dixon & Ridley (1987) described disrupted omphacite–epidote slabs from the contact between ultramafic rocks and calcareous glaucophane schists, that formed by a decarbonation reaction of the general type glaucophane + quartz + calcite = omphacite + CO_2 + H_2O. Sample 1081 was not collected from an outcrop, but from a loose block. Nevertheless, judging from the

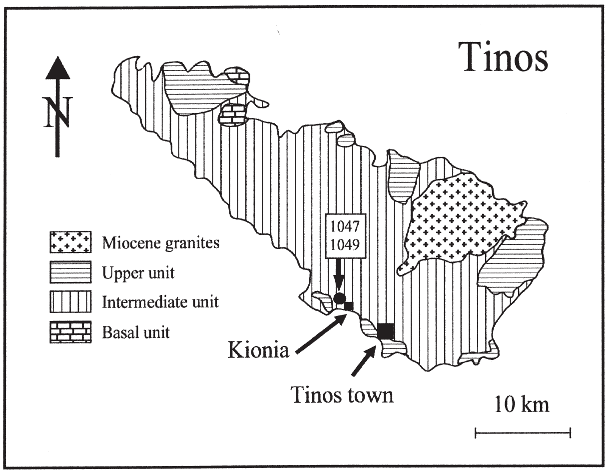

Figure 3. Simplified geological map of Tinos (after Melidonis, 1980 and Avigad & Garfunkel, 1989) indicating the sample locations discussed in the text.

general field relationships, sample 1081 is considered to be a representative constituent of the disrupted meta-ophiolite association.

On Tinos (Fig. 3), the Cycladic blueschist unit is represented by at least two subunits, which are designated as Intermediate unit and Basal unit (e.g. Bröcker & Franz, 1998; cf. Melidonis, 1980; Avigad & Garfunkel, 1989). Samples were collected from the Intermediate unit which consists of marbles, calcareous schists, siliciclastic metasediments, cherts and metavolcanic rocks. Greenschist-facies rock types dominate, but variably overprinted remnants of earlier eclogite- and blueschist-facies metamorphism were preserved in many places on the island (e.g. Melidonis, 1980; Bröcker, 1990; Bröcker & Franz, 1998). Two eclogites (1046, 1047) and a jadeitite (1049) were collected near Kionia, about 5 km northwest of the main village (Fig. 3). The studied samples were taken from a large jadeitite–eclogite block (several metres in diameter) with obscure contact relations to enclosing foliated country rocks and from loose boulders that are derived from this outcrop. The occurrence studied here and other types of blocks are interpreted as constitutents of a meta-olistostrome and not as a tectonic mélange (Bröcker & Enders, unpub. data).

The eclogites (1046, 1047) consist of garnet, omphacite (x_{jd} = 49–65; average x_{jd} = 58), an altered Ti-phase (titanite–hematite intergrowths) and zircon. Chlorite, albite, epidote and calcic amphiboles are typical secondary phases related to the greenschist-facies overprint. The jadeitite 1049 is mainly composed of sodic clinopyroxene (x_{jd} = 55–87; average x_{jd} = 70), garnet, allanite, phengite, titanite, zircon and opaques. Secondary epidote, chlorite and albite are present in variable modal proportions.

The eclogites (samples 1046, 1047) and the omphacitite 1081 have broadly basaltic compositions (SiO_2 44.9–51.8 wt. %), within the range reported for similar rocks from Syros (J. Kötz, unpub. doctoral thesis, Univ. Köln,1989; Seck *et al.* 1996). Trace element abundances are exceptionally high for metabasic rocks (Zr up to 4845 ppm; Y up to 476 ppm; Nb up to 87 ppm; Ce up to 207 ppm; Nd up to 163 ppm). The jadeitite is characterized by higher SiO_2 (54.9 wt. %) and extremely high Na_2O concentrations (10.7 wt. %). Bulk-rock compositions do not allow a direct identification of the protolith. Trace element characteristics are similar to those from the eclogites, but do not reach their unusual high elemental concentrations. The geochemistry will be discussed in detail in a forthcoming paper (Bröcker & Enders, unpub. data).

4. Results

Conventional U–Pb multi-grain dating was applied to non-abraded zircon grain size fractions from an omphacitite from Syros (sample 1081) and a jadeitite from Tinos (sample 1049). In both samples, zircon populations consist of clear, euhedral to subhedral, short- to medium-prismatic grains (Fig. 4) with few inclusions. Grains with smooth edges and surface pitting indicate minor metamorphic dissolution. Cathodoluminescence (CL) imaging of zircons from sample 1081 indicates internal structures with narrow zoning patterns and sector zoning. In contrast, internal structures of zircons from sample 1049 are highly complex. Similar patterns were also observed in zircons recovered from eclogites (Fig. 5). Electron-microprobe mapping indicates differences in Y and Hf concentrations between irregular-shaped patches and domains, whereas no significant variations in Ce, Fe, Al, Ti and Ca were detected. The U concentrations in zircons from sample 1049 are low (42–63 ppm), thus excluding recrystallization induced by metamictization. These structures may be related to solid-state recrystallization caused by the attempt to eliminate originally incorporated contaminants from the crystal lattice (Pidgeon, 1992). Although this recrystallization is not necessarily associated with Pb loss, it is obvious that U–Pb multi-grain or single-grain dates of zircons with such complex internal patterns are highly suspect, if not confirmed by other isotope systems. Despite this objection, we have also analysed this zircon type in order to investigate the effects of recrystallization on the age information.

In all fractions of both samples, U concentrations are low and range between 60–92 ppm and 42–63 ppm, respectively (Table 1). Measured $^{206}Pb/^{204}Pb$ vary between 715–1178 and 473–644, respectively. Four fractions of sample 1081 are essentially concordant and define an age of 78 Ma ± 1 Ma (Fig. 6a). The differences in $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages range between 0.1 and 0.4 Ma (Table 1). A weighted mean yields an average $^{206}Pb/^{238}U$ age of 77.86 ± 0.12 (95% confidence level). The cluster of matching ages clearly indicates a geologically significant event.

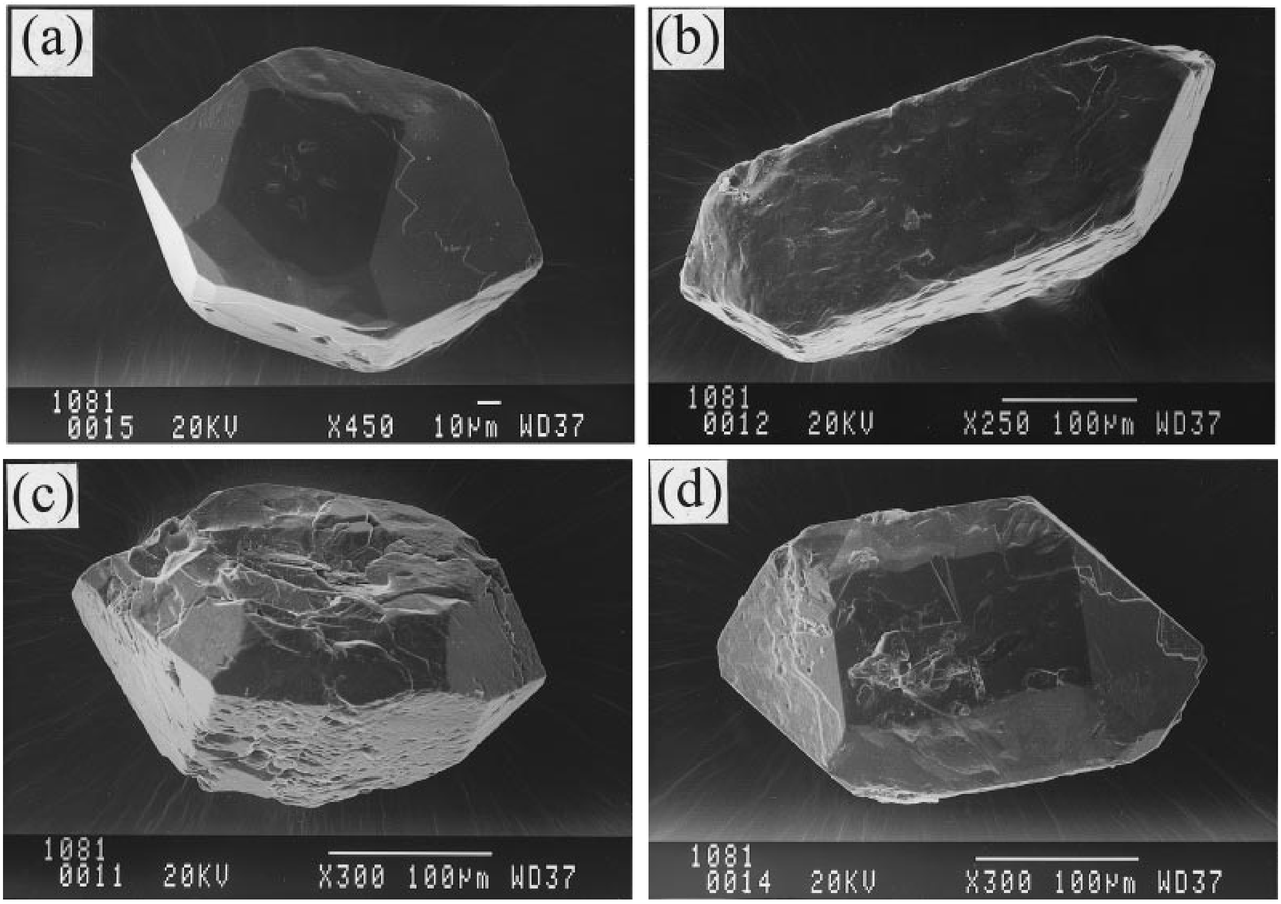

Figure 4. Scanning electron microscope images of gold-coated zircon showing the range of morphologies in bulk grain-size fractions of the omphacitite 1081 from Syros: (a) euhedral, short-prismatic; (b) subhedral, medium prismatic with smoothed etches; (c) subhedral, short-prismatic with surface pitting due to metamorphic dissolution; (d) subhedral, short-prismatic. Note that sample 1049 from Tinos shows the same zircon morphologies.

Zircons of sample 1049 cluster between 61 and 63 Ma (Fig. 6b). Interpretation is not straightforward. Three fractions overlap with the concordia curve at 62 Ma (fractions A and B, and at 61 Ma (fraction D), respectively. Two explanations may account for fraction D. Zircons were affected by minor Pb loss, which might be related to different processes of unknown importance (e.g. blueschist-facies disturbance, the greenschist-facies overprint, recent alteration). Alternatively, the smallest zircons are indeed slightly younger. Fraction C is weakly discordant, suggesting an inherited lead component.

Interpretation of the zircon data is hampered by the small curvature of the concordia for young samples, and a larger uncertainty in $^{207}Pb/^{235}U$ ratios compared to $^{206}Pb/^{238}U$ ratios. The most reasonable conclusion that can be drawn from sample 1049, is to suggest a geological significant event in the time span between 61 and 63 Ma. This event most likely characterizes a discrete stage during high-pressure metamorphism that caused (1) resetting of older zircons with corresponding shift of data points closely along the concordia curve, and (2) led to the formation of new zircon.

5. Discussion

5.a. Primary igneous compositions or metasomatic modification?

A remarkable characteristic of the studied rocks is unusually high modal proportions of zircon. In some metabasic samples about 50 to 80 zircon grains were already identified on thin-section scale. It is not understood whether this characteristic is a primary feature of the protoliths or resulted from metasomatic processes. However, for an understanding of the zircon ages this question is of utmost importance in order to assess the geological significance of the geochronological results.

Seck *et al.* (1996) interpreted the unusual compositions of similar blocks from the Syros mélange (e.g. eclogites with TiO_2 up to 10 wt. %; $Fe_2O_3^{total}$ up to 20.5 wt. %; J. Kötz, unpub. doctoral thesis, Univ. Köln, 1989) as original igneous characteristics of ferrogabbroic protoliths or strongly differentiated basalts. These authors explained the geochemical heterogeneity of Fe- and Ti-rich eclogites as indication for protolith evolution in discrete, small-scale magma

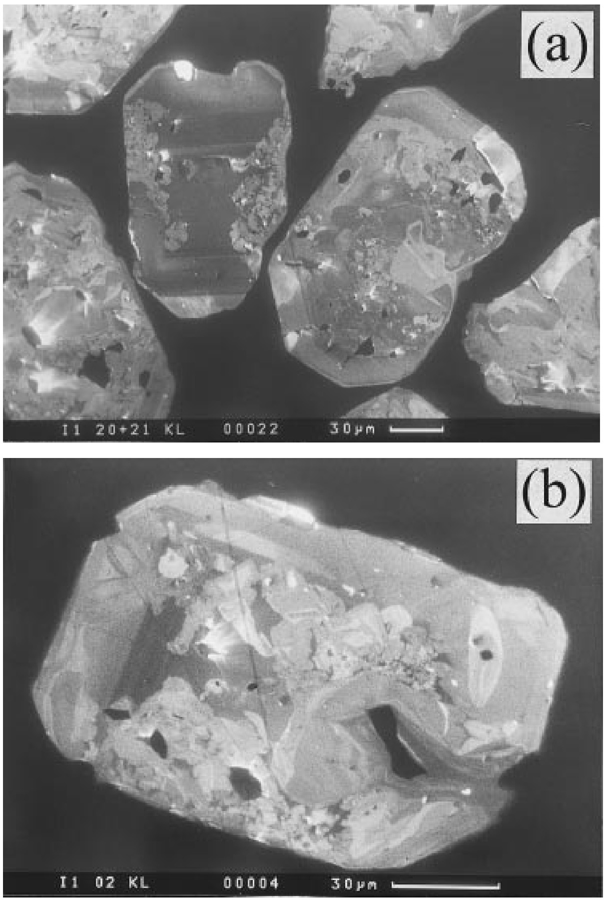

Figure 5. Cathodoluminescence photomicrographs of zircons from eclogite 1047. See text for explanation. Similar internal structures were recognized in the jadeitite 1049 from Tinos.

chambers. In contrast, Dixon & Ridley (1987) attributed the remarkably high concentrations of Ti, P and Na to mineral reactions at the boundary between blocks and enclosing ultramafic rocks. Some boulders show reaction rinds (almost monomineralic glaucophane, actinolite or sodic pyroxene) which clearly suggest fluid-enhanced metasomatic exhange processes (Dixon & Ridley, 1987).

We agree with Dixon & Ridley (1987) that the compositional features cannot merely be explained by a magmatic evolution, but require metasomatic contamination. It is suggested here that the compositional characteristics of the studied samples mainly reflect trace element enrichment during subduction-zone metamorphism (Bebout & Barton, 1993; Sorensen & Grossman, 1993). Additional compositional changes were locally superimposed by syn-metamorphic interaction with an ultramafic matrix during the high-pressure stage. A comprehensive discussion of this topic will be presented in a forthcoming paper (Bröcker & Enders, unpub. data).

As indicated by textural observations, the high modal abundances of zircon record the syn-metamorphic metasomatism. Zircon is found randomly distributed in the eclogite-facies groundmass and is apparently in textural equilibrium with high-pressure phases. In samples from Tinos, inclusions of omphacite, rutile and allanite in zircon clearly indicate zircon growth during or after high-pressure metamorphism. In samples from Syros, rutile was recognized as inclusion in zircon. Zircon formation related to redistribution of Zr released by retrograde breakdown of omphacite in neighbouring rock volumes can be ruled out. Zircon was found as inclusions in garnet, thus indicating early growth. Indication for zircon formation in greenschist-facies veins or domains of partially overprinted eclogites was not observed.

Millimetre-scale veins with late high-pressure assemblages (almost monomineralic omphacite or sphene) were observed in several samples from Tinos. This texture documents the presence of a network for infiltrating fluids under high-pressure conditions. In principle, a similar system of microfractures may have provided infiltration paths for trace-element-enriched fluids during earlier stages of high-pressure metamorphism. There is no indication for earlier high-temperature metamorphism. Estimates for peak temperature conditions range only between 450 and 550 °C (e.g. Ridley & Dixon 1984; Bröcker *et al.* 1993). Consequentely, zircon growth is related to metasomatic processes at relatively low temperatures. Although unexpected in the first instance, it should be noted that zircon crystallization is known from hydrothermal environments (e.g. Rubin, Henry & Price, 1989).

5.b. Implications of new geochronological results

The studied samples yield U–Pb ages which differ significantly from previous geochronological results obtained by the K–Ar, ^{40}Ar–^{39}Ar and Rb–Sr methods. White mica records maximum ages of 53.4 ± 1.6 Ma (K–Ar; A. Kohlmann, unpub. diploma thesis, Univ. Würzburg, 1978, quoted in Bröcker *et al.* 1993) and 53.5 ± 1.3 Ma (Ar–Ar; Maluski, Bonneau & Kienast, 1987), respectively, for blueschist-facies rocks from Tinos and Syros. In contrast, U–Pb zircon chronology of an omphacitite from Syros yielded a concordant age of 78 ± 1 Ma (Fig. 6a) and a jadeitite from Tinos provided U–Pb dates ranging between *c.* 60 and 63 Ma (Fig. 6b). In both cases, zircon is considered to be the product of metasomatic alteration during high-pressure metamorphism. The 78 ± 1 Ma age recorded for sample 1081 is interpreted as the time of a high-pressure stage in the metamorphic evolution of the Cyclades. The geological significance of U–Pb dates ranging between *c.* 60 and 63 Ma (sample 1049) remains ambiguous, because of highly complex internal zircon structures. However, it appears reasonable to suggest that this time span also indicates a distinct episode during high-pressure metamorphism.

Currently only white mica ages of high-pressure rocks collected from structurally coherent sequences are available. These rocks have experienced pervasive

Table 1. U–Pb analytical results for zircon of eclogite-facies rocks from Syros and Tinos[1]

Sample	Size (µm)	Weight (mg)	Concentration			Measured ratios		Corrected ratios[2]			corr. coef.	Apparent ages (Ma)		
			U (ppm)	Pb^{total} (ppm)	^{206}Pb* (ppm)	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$		$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
1081:	250–200	5.175	59.7	0.767	0.624	0.14971	715	0.012154 (38)	0.07928 (69)	0.04731 (37)	0.44	77.9	77.5	65 ± 18
	200–160	3.568	76.9	0.980	0.804	0.14441	762	0.012143 (40)	0.07953 (71)	0.04750 (38)	0.43	77.8	77.7	74 ± 19
	160–125	4.755	92.1	1.169	0.959	0.13655	742	0.012118 (40)	0.07914 (69)	0.04737 (37)	0.45	77.7	77.3	68 ± 18
	125–100	3.705	83.2	1.026	0.871	0.11688	1178	0.012174 (38)	0.07970 (113)	0.04749 (66)	0.23	78.0	77.9	73 ± 32
1049:	160–125	5.307	42.1	0.443	0.351	0.18722	552	0.009694 (30)	0.06349 (69)	0.04750 (48)	0.39	62.2	62.5	75 ± 24
	125–100	3.870	60.1	0.625	0.499	0.17812	644	0.009666 (30)	0.06283 (70)	0.04715 (49)	0.36	62.0	61.9	56 ± 25
	100–80	3.636	59.7	0.633	0.501	0.19727	473	0.009785 (32)	0.06486 (94)	0.04807 (66)	0.33	62.8	63.8	103 ± 32
	63–40	4.557	63.1	0.658	0.516	0.18202	515	0.009506 (30)	0.06227 (83)	0.04751 (60)	0.34	61.0	61.3	75 ± 29

[1]Isotope analyses were carried out at the Zentrallaboratorium für Geochronologie, Münster, using a VG Sector 54 multicollector machine equipped with a Daly detector. Laboratory methods and details of data evaluation are described in Bröcker *et al.* (1998).
[2] Corrected for fractionation, spike, blank and initial common lead. Numbers in parentheses indicate uncertainties in ratios quoted at the 2 sigma level.
* Radiogenic ^{206}Pb only.

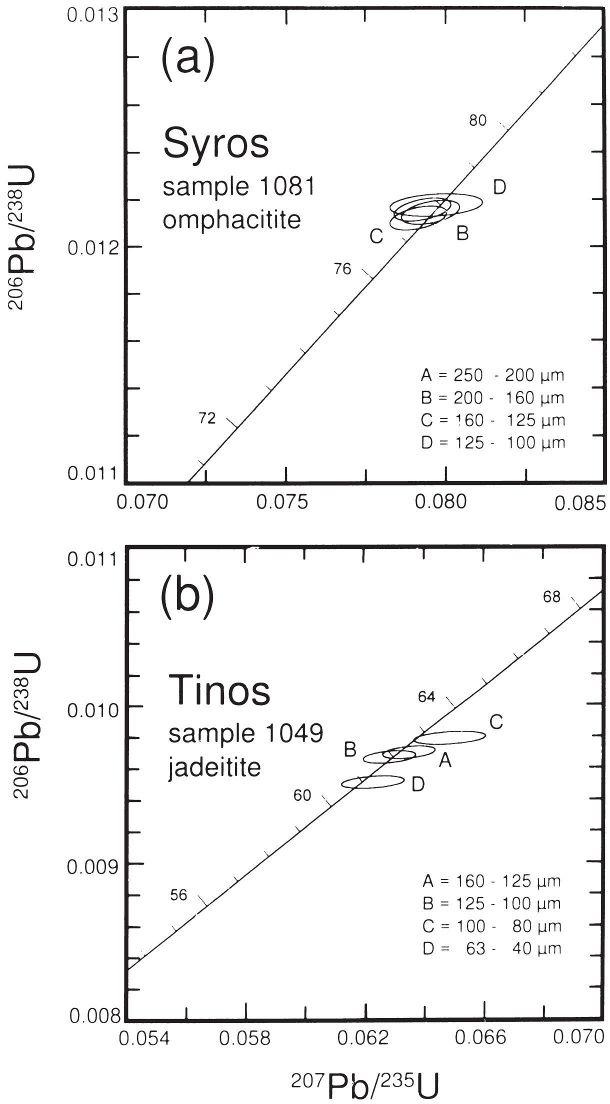

Figure 6. Concordia diagram for zircons of (a) sample 1081 and (b) for sample 1049. Error ellipses after Ludwig (1994) are at the 95% confidence level. In (a), error ellipse of grain-size fraction A is hidden behind B, C and D and not labelled.

syn-metamorphic deformation. The considerably younger white mica ages may indicate that the ^{40}Ar–^{39}Ar and Rb–Sr isotopic systems were continuously resetted as a result of deformation-related recrystallization which did not affect the U–Pb systems of the zircons. The difference between U–Pb zircon and ^{40}Ar–^{39}Ar white mica ages may also be explained by resubduction of older high-pressure fragments, with records of earlier stages almost completely erased by subsequent blueschist-facies overprints.

Although the interpretation favoured here is a syn-metamorphic, metasomatic origin, zircon crystallization from a melt cannot be ruled out. Due to the fact that the morphological criteria of the studied zircons are consistent with a magmatic origin (Fig. 4), it could be argued that small amounts of unusual melts intruded into an accretionary complex during high-pressure metamorphism. In this case, the interpretation that zircon is a monitor for syn-metamorphic, metasomatic processes would be erroneous. Nevertheless, the 78 Ma still would indicate a minimum age for the eclogite-facies metamorphism, as indicated by inclusions of high-pressure phases in zircon.

6. Conclusion

The new geochronological results challenge the widely held view that high-pressure metamorphism in the Cyclades is restricted to the Tertiary and suggest a more complex collisional history. The Cycladic blueschist belt did not develop in a relatively short time span during the Tertiary, as suggested by previous geochronology, but formed over an extended period from Late Cretaceous to Tertiary time.

In order to obtain a better understanding of the metamorphic evolution and a correct geodynamic interpretation, additional geochronological work is needed. This hopefully will clarify whether the Late Cretaceous ages are confined to rocks with unusual geochemistry and obscure origin (meta-olistostrome or tectonic mélange) or are also characteristic of high-pressure rocks collected from structurally coherent sequences.

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References

ALTHERR, R., KREUZER, H., WENDT, I., LENZ, H., WAGNER, G. A., KELLER, J., HARRE, W., & HÖHNDORF, A. 1982. A Late Oligocene/Early Miocene high temperature belt in the Attic–Cycladic Crystalline Complex (SE Pelagonia, Greece). *Geologisches Jahrbuch* **E23,** 97–164.

ALTHERR, R., SCHLIESTEDT, M., OKRUSCH, M., SEIDEL, E., KREUZER, H., HARRE, W., LENZ, H., WENDT, I. & WAGNER, G. A. 1979. Geochronology of high-pressure rocks on Sifnos (Cyclades, Greece). *Contributions to Mineralogy and Petrology* **70,** 245–55.

ALTHERR R. & SEIDEL, E. 1977. Speculations on the geodynamic evolution of the Attic–cycladic crystalline complex during alpidic times. *Proceedings of the VI. Colloquium on the Geology of the Aegean Region, Athens*, **1**, 347–52.

AVIGAD, D. & GARFUNKEL, Z. 1989. Low angle faults underneath and above a blueschist belt – Tinos Island, Cyclades, Greece. *Terra Nova* **1**, 182–7.

AVIGAD, D., MATTHEWS, A., EVANS, B. W. & GARFUNKEL, Z. 1992. Cooling during the exhumation of a blueschist terrane; Sifnos (Cyclades), Greece. *European Journal of Mineralogy* **4**, 619–34.

BAVAY, D., BAVAY, P., MALUSKI, H., VERGELY, P. & KATSIKATSOS, G. 1980. Datations par la méthode $^{40}Ar/^{39}Ar$ des minéraux de métamorphismes de haute pression en Eubée du Sud (Grèce). Corrélations avec les événements tectono-métamorphiques des Héllenides internes. *Comptes Rendues de l'Academie des Sciences, Paris*, Serie D **290,** 1051–4.

BEBOUT, G. E. & BARTON, M. D. 1993. Metasomatism during subduction: products and possible paths in the Catalina Schist, California. *Chemical Geology* **108,** 61–92.

BONNEAU, M. 1984. Correlation of the Hellenide nappes in the South-East Aegean and their tectonic reconstruction. *In* The geological evolution of the eastern Mediterranean (eds J. E. Dixon and A. H. F. Robertson), pp. 517–27. Geological Society Special Publication no. 17. Oxford: Blackwell.

BRÖCKER, M. 1990. Die Blauschiefer-Grünschiefer-Assoziation der Insel Tinos (Kykladen, Griechenland) und ihre kontaktmetamorphe Überprägung. *Geotektonische Forschungen* **74,** 1–107.

BRÖCKER, M. & FRANZ, L. 1998. Rb–Sr isotope studies on Tinos Island (Cyclades, Greece): additional time constraints for metamorphism, extent of infiltration-controlled overprinting and deformational activity. *Geological Magazine* **135**, 369–82.

BRÖCKER, M., KREUZER, H., MATTHEWS, A. & OKRUSCH, M. 1993. $^{40}Ar/^{39}Ar$ and oxygen isotope studies of polymetamorphism from Tinos Island, Cycladic blueschist belt. *Journal of Metamorphic Geology* **11,** 223–40.

BRÖCKER, M., ZELAZNIEWICZ, A. & ENDERS, M. 1998. Rb–Sr and U–Pb geochronology of migmatitic gneisses from the Góry Sowie (West Sudetes, Poland): the importance of Mid–Late Devonian metamorphism. *Journal of the Geological Society London* **155,** 1025–36.

DIXON, J. E. & RIDLEY, J. R. 1987. Syros. In *Chemical transport in metasomatic processes* (ed. H. C. Helgeson), pp. 489–501. Dordrecht: Reidel.

DÜRR, S. 1986. Das Attisch-kykladische Kristallin. In *Geologie von Griechenland* (ed. V. Jacobshagen), pp.116–48. Berlin, Stuttgart: Borntraeger.

DÜRR, S., ALTHERR, R., KELLER, J., OKRUSCH, M. & SEIDEL, E. 1978. The Median Aegean Crystalline Belt: Stratigraphy, structure, metamorphism, magmatism. In *Alps, Apennines, Hellenides* (eds H. Closs, D. H. Roeder and K. Schmidt), pp. 455–77. IUGS report no.38. Stuttgart: Schweizerbart.

FAUPL, P., PAVLOPOULOS, A., WAGREICH, M. & MIGIROS, G. 1996. Pre-Tertiary blueschist terrains in the Hellenides: evidence from detrital minerals of flysch successions. *Terra Nova* **8,** 186–90.

HECHT, J. 1984. *Geological map of Greece 1 : 50 000, Syros Island.* Athens: Institute of Geology and Mineral Exploration.

LIPS, A.L., WHITE, S. H. & WIJBRANS, J. R. 1997. Dating discrete deformational and kinematic events in blueschist facies rocks: an example from the Pelagonian Zone in Greece. *Terra Nova* **9, Supplement 1,** 487.

LUDWIG, K. R. 1994. *Isoplot: a plotting and regression program for radiogenic-isotope data, version 2.75.* United States Geological Survey Open-File Report.

MALUSKI, H., BONNEAU, M. & KIENAST, J. R. 1987. Dating the metamorphic events in the Cycladic area: $^{39}Ar/^{40}Ar$ data from metamorphic rocks of the island of Syros (Greece). *Bulletin de la Société géologique de France* **(8) t.III, no 5,** 833–42.

MALUSKI, H., VERGELY, P., BAVAY, P. & KATSIKATSOS, G. 1981. $^{39}Ar/^{40}Ar$ dating of glaucophanes and phengites in southern Euboa (Greece), geodynamic implications.

Bulletin de la Société géologique de France **(7) 23,** 469–76.

MATTHEWS, A. & SCHLIESTEDT, M. 1984. Evolution of the blueschist and greenschist facies rocks of Sifnos, Cyclades, Greece. *Contributions to Mineralogy and Petrology* **88,** 150–63.

MELIDONIS, N. G. 1980. The geological structure and mineral deposits of Tinos island (Cyclades, Greece). *The Geology of Greece* **13,** 1–80.

OKRUSCH, M. & BRÖCKER, M. 1990. Eclogite facies rocks in the Cycladic blueschist belt, Greece: A review. *European Journal of Mineralogy* **2,** 451–78.

OKRUSCH, M, SEIDEL, E & DAVIS, E. N. 1978. The assemblage jadeite–quartz in the glaucophane rocks of Sifnos (Cyclades Archipelago, Greece). *Neues Jahrbuch für Mineralogie. Abhandlungen* **132**, 284–308.

PIDGEON, R. T. 1992. Recrystallization of oscillatory zoned zircon: some geochronological and petrological implications. *Contribution to Mineralogy and Petrology* **110,** 463–72.

RIDLEY, J. R. & DIXON, J. 1984. Reaction pathways during the progressive deformation of a blueschist metabasite: the role of chemical disequilibrium and restricted range equilibrium. *Journal of Metamorphic Geology* **2,** 115–28.

RUBIN, J. N., HENRY, C. D. & PRICE, J. G. 1989. Hydrothermal zircons and zircon overgrowths, Sierra Blanca Peaks, Texas. *American Mineralogist* **74,** 865–9.

SCHERMER, E. R., LUX, D. R. & BURCHFIEL, B. C. 1990. Temperature–time history of subducted continental crust, Mount Olympos Region, Greece. *Tectonics* **9**, 1165–95.

SCHLIESTEDT, M., ALTHERR, R. & MATTHEWS, A. 1987. Evolution of the Cycladic crystalline complex: Petrology, isotope geochemistry and geochronology. In *Chemical Transport in Metasomatic Processes*, (ed. H. C. Helgeson), pp. 389–428. NATO ASI series. Reidel Publishing Company.

SECK, H. A., KÖTZ, J., OKRUSCH, M., SEIDEL, E. & STOSCH, H. G. 1996. Geochemistry of a meta-ophiolite suite: an association of meta-gabbros, eclogites and glaucophanites on the island of Syros, Greece. *European Journal of Mineralogy* **8,** 607–23.

SORENSEN, S. S. & GROSSMAN, J. N. 1993. Accessory minerals and subduction zone metasomatism: a geochemical comparison of two mélanges (Washington and California, U.S.A.). *Chemical Geology* **110,** 269–97.

WIJBRANS, J. R. & MCDOUGALL, I. 1986. ^{40}Ar/^{39}Ar dating of white micas from an Alpine high-pressure metamorphic belt on Naxos (Greece): resetting of the argon isotopic system. *Contributions to Mineralogy and Petrology* **93,** 187–94.

WIJBRANS, J. R. & MCDOUGALL, I. 1988. Metamorphic evolution of the Attic Cycladic Metamorphic Belt on Naxos (Cyclades, Greece) utilizing ^{40}Ar/^{39}Ar age spectrum measurements. *Journal of Metamorphic Geology* **6,** 571–94.

WIJBRANS, J. R., SCHLIESTEDT, M. & YORK, D. 1990. Single grain argon laser probe dating of phengites from the blueschist to greenschist transition on Sifnos (Cyclades, Greece). *Contributions to Mineralogy and Petrology* **104,** 582–93.