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Protolith Ages of Meta-igneous and Metatuffaceous Rocks from the Cycladic Blueschist Unit, Greece: Results of a Reconnaissance U-Pb Zircon Study

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ABSTRACT

The Cycladic blueschist unit (CBU) in the central Aegean Sea comprises a pre-Alpidic crystalline basement that is overlain by thrust sheets of a metamorphosed volcanosedimentary sequence. Mélanges are widespread and enclose a wide variety of meta-igneous rock fragments in a serpentinitic and/or metasedimentary matrix. Previous geochronology has documented the general temporal framework for the Alpidic metamorphic history but did not produce well-constrained protolith ages for the main volcanosedimentary succession and for mélange blocks. This issue is addressed here in an ion probe U-Pb zircon study focusing on the islands of Andros, Sifnos, and Ios. The new results indicate a consistent regional pattern of Triassic ages (ca. 237–245 Ma) for the magmatic precursors of metatuffaceous and metavolcanic rocks, which occur as intercalations within metasediments. This narrow range of igneous crystallization ages records an important period of volcanic activity in the larger study area. On Andros, such ages were also determined for a disrupted tabular body of meta-acidic gneisses (several hundred meters in length) that has been considered an olistolith within a meta-olistostrome. Field observations are compatible with the interpretation that this fragment represents a layer of the main succession that has been disrupted by large-scale boudinage. A metagabbro and a meta-acidic gneiss from a high-pressure mélange on Andros yielded Jurassic $^{206}Pb/^{238}U$ ages of 156.2 ± 2.3 and 160.0 ± 2.0 Ma, respectively, that correspond very well to ages reported for ophiolites from mainland Greece, the Balkan region, and Crete. The new results and literature data document that remnants of both Jurassic and Cretaceous meta-ophiolites are included in the mélanges of the CBU. It is currently not known whether both age groups occur within the same mélange or at different lithostratigraphic and/or tectonic levels.

Online enhancement: table.

Introduction

The Cycladic blueschist unit (CBU) in the central Aegean Sea (fig. 1) records a polyphase *PT* evolution that includes Cretaceous to Eocene high-pressure/low-temperature (HP/LT) metamorphism and a greenschist- to amphibolite-facies overprint in Oligocene/Miocene times (e.g., Dürr et al. 1978; Altherr et al. 1979; Okrusch and Bröcker 1990; Dürr 1986; Bröcker et al. 1993). Previous research has documented the main characteristics of its complex structural, petrological, and geochronological evolution and has established the CBU as one of the most intensively studied HP/LT occurrences in the world. However, whereas structural, petrological, and geochronological aspects of the metamorphic history are well documented, key information concerning the premetamorphic evolution is poorly constrained. Our main aim in this study was to investigate this issue by unravelling protolith ages recorded in volcanosedimentary sequences and by exploring the age diversity and provenance of mélange blocks. We also aim to take the initiative in building a geochronological database that can serve as a framework for a more detailed stratigraphic subdivision of the CBU and as a tool for unravelling the litho- and/or tectonostratigraphic relationships across the larger study area. For these purposes, we have applied ion probe (SHRIMP, a sensitive high-resolution ion microprobe) U-Pb zircon dating to

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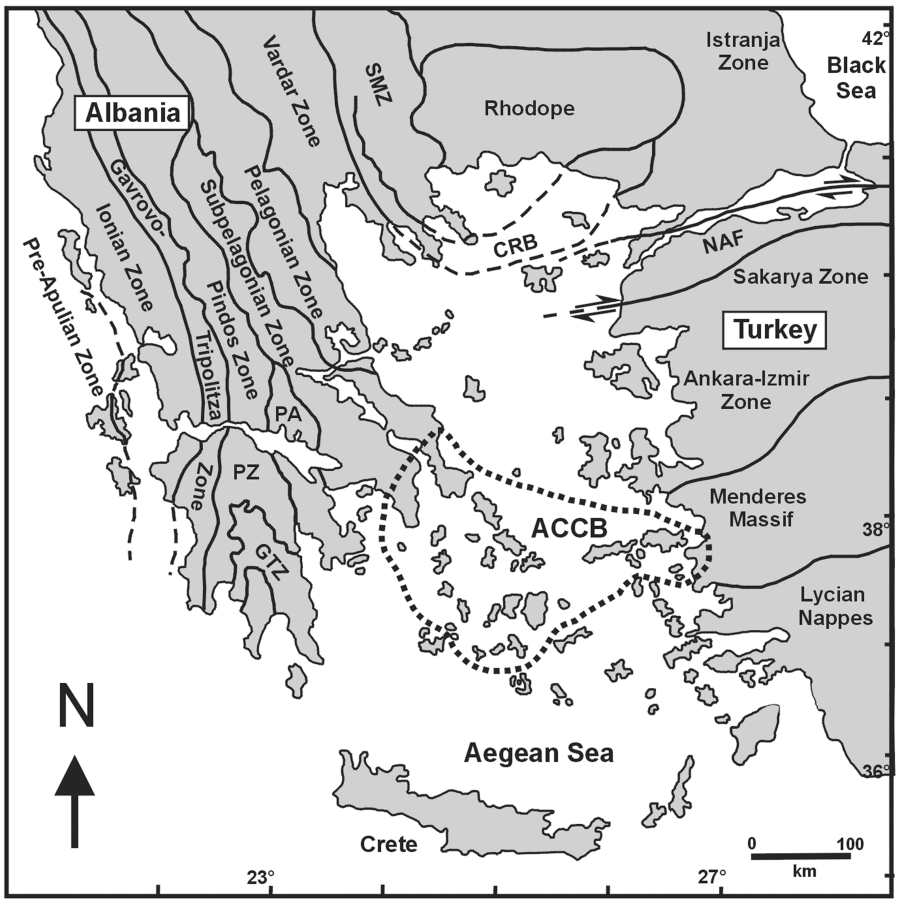


Figure 1. Major tectonostratigraphic units of the Aegean region and the position of the Attic-Cycladic crystalline belt (*ACCB*), modified after Jacobshagen (1986) and Barr et al. (1999). *PA* = Parnassos; *GTZ* = Gavrovo-Tripolitza Zone; *PZ* = Pindos Zone; *CRB* = Circum-Rhodope belt; *SMZ* = Serbo-Macedonian Zone; *NAF* = North Anatolian Fault Zone.

samples collected on the islands of Andros, Sifnos, and Ios (fig. 2). These sample locations cover a wide area of the CBU and thus are ideally suited as starting points for a reconnaissance study.

Geological Setting and Previous Geochronology

The Attic-Cycladic crystalline belt (ACCB) represents an important crustal fragment of the Hellenide orogen in the eastern Mediterranean region (fig. 1). It consists of two major structural groups that are separated by low-angle normal faults (e.g., Dürr et al. 1978; Dürr 1986; Okrusch and Bröcker 1990; Avigad et al. 1997; Jolivet and Patriat 1999; Jolivet et al. 2003). The upper group is exposed only in small areas and comprises a heterogeneous sequence of unmetamorphosed Permian to Mesozoic sediments, ophiolites, and greenschist-facies rocks of Cretaceous to Tertiary age, as well as Late Cretaceous medium-pressure/high-temperature rocks and granitoids (e.g., Reinecke et al. 1982; Patzak et al. 1994; Bröcker and Franz 1998, 2006; Zeffren et al. 2005). Available geochronological data are compatible with the interpretation that at least parts of the upper units experienced two distinct episodes of Cretaceous metamorphism (ca. 100–90 and ca. 80–70 Ma) and a Miocene event (ca. 24–21 Ma; e.g., Bröcker and Franz 1998, 2006; Zeffren et al. 2005). The lower group (hereafter referred to as the CBU) comprises a pre-Alpidic crystalline basement that is tectonically overlain by a metamorphosed volcanosedimentary sequence consisting mainly of clastic metasediments, calcschists, marbles, and meta-igneous rocks of basic and acidic bulk-rock composition (e.g., Dürr et al. 1978; Schliestedt et al. 1987; Okrusch and Bröcker 1990). The cover also

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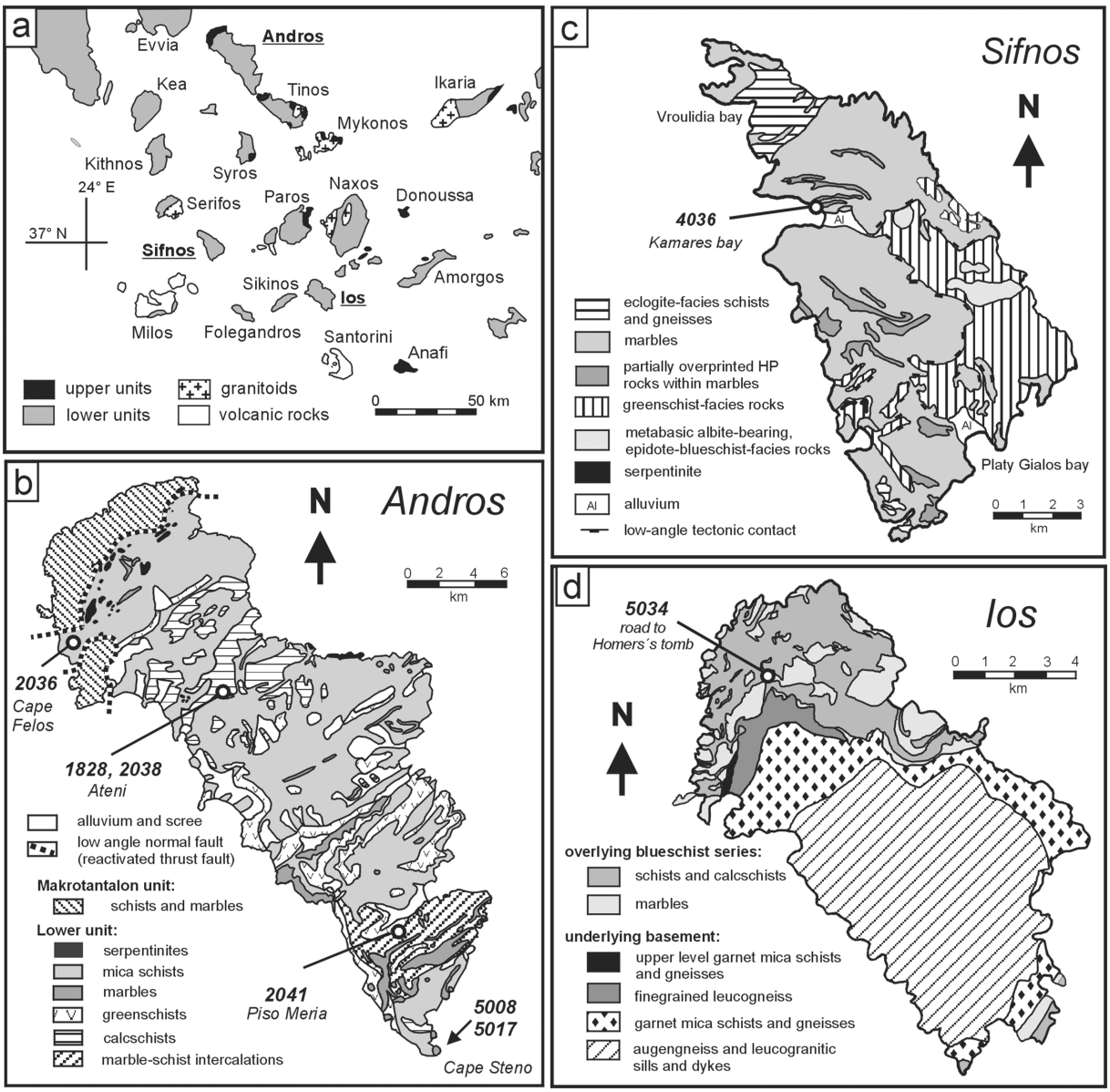


Figure 2. Simplified geological maps of the study areas with sample locations. *a*, Regional overview modified after Matthews and Schliestedt (1984); *b*, Andros, modified after Papanikolaou (1978) and Mukhin (1996); *c*, Sifnos, modified after Avigad (1993); *d*, Ios, modified after Vandenberg and Lister (1996).

includes mélanges with meta-igneous blocks and tectonic slabs (<1 m to several hundred meters long) that are enclosed in an ultramafic or metasedimentary matrix (e.g., Okrusch et al. 1984; Dixon and Ridley 1987; Mukhin 1996; Bröcker and Enders 1999, 2001; Katzir et al. 2000). Both basement and cover have experienced at least two stages of Tertiary metamorphism. During the first stage, which is related to subduction of the Apulian microplate beneath the Eurasian continent, eclogite- to epidote-blueschist–facies conditions were attained ($T_{max} \sim 450°–550°C$, $P_{max} \sim 12–20$ kbar; e.g., Matthews and Schliestedt 1984; Avigad et al. 1992; Bröcker et al. 1993; Trotet et al. 2001*b*). The subsequent greenschist- to amphibolite-facies overprint occurred during extension-related exhumation, which was caused by the southward retreat of the Hellenic subduction zone and/or the westward extrusion of the Anatolian plate due to collision between Arabia and Eurasia (e.g., Gautier et al. 1999 and references therein). In the northern and central CBU, overprinted rocks record greenschist-

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facies metamorphism ($T \sim 450°–550°C$, $P \sim 4–9$ kbar; e.g., Bröcker et al. 1993; Parra et al. 2002). In the southern Cyclades (e.g., Naxos), partially migmatized sequences are exposed in high-T metamorphic core complexes (e.g., Jansen and Schuiling 1976; Buick and Holland 1989). Regional metamorphism was followed by widespread intrusion of granitoids (e.g., Altherr et al. 1982). White mica geochronology (K-Ar, ^{40}Ar-^{39}Ar, Rb-Sr) of HP rocks yielded Eocene ages (ca. 55–40 Ma); greenschist- and amphibolite-facies rocks provided mostly Oligocene/Miocene dates (ca. 25–16 Ma; e.g., Altherr et al. 1979, 1982; Wijbrans and McDougall 1986, 1988; Maluski et al. 1987; Wijbrans et al. 1990; Bröcker et al. 1993, 2004; Baldwin 1996; Baldwin and Lister 1998; Bröcker and Franz 1998, 2006). Eocene ages for the HP stage were also determined by means of SHRIMP U-Pb dating of zircon overgrowths (Tomaschek et al. 2003) and Lu-Hf garnet chronology (Lagos et al. 2005). On the other hand, Bröcker and Enders (1999, 2001) and Bröcker and Keasling (2006) have emphasized the importance of pre-Eocene subduction and have interpreted Cretaceous U-Pb zircon ages (ca. 80 Ma) as evidence for a more complex HP history.

Earlier geochronological studies focused on the age of the major metamorphic events (e.g., Altherr et al. 1979, 1982; Wijbrans and McDougall 1986, 1988; Maluski et al. 1987; Wijbrans et al. 1990; Bröcker et al. 1993, 2004; Baldwin 1996; Baldwin and Lister 1998; Bröcker and Franz 1998, 2000, 2006) and the time of subsequent granitoid intrusions (e.g., Altherr et al. 1982; Keay et al. 2001). Less effort was devoted to documenting the protolith ages of the major rocks types. Sporadic findings of fossils (e.g., Dürr et al. 1978; Dürr and Flügel 1979; Melidonis 1980) and SHRIMP U-Pb ages of detrital zircons (Keay 1998) broadly constrain Triassic to Cretaceous depositional ages for metasediments and intercalated metavolcanic rocks. Some authors have even suggested a Lower Carboniferous (Schumacher et al. 2001) or Permo-Carboniferous origin (Ring and Layer 2003) for parts of the metamorphic succession, but convincing evidence for such formational ages has not yet been presented. Also unknown is the full range of protolith ages recorded in the mélanges that are a widespread but volumetrically subordinate feature of the CBU (e.g., Okrusch et al. 1984; Dixon and Ridley 1987; Mukhin 1996; Bröcker and Enders 1999, 2001; Katzir et al. 2000). Reliable ages are available only from the island of Syros, where Triassic and Cretaceous protoliths have been documented (Keay 1998; Tomaschek et al. 2003; Bröcker and Keasling 2006). However, taking into account the areal extent of the CBU (ca. 300 × 180 km) and the unknown relationship between different occurrences, the picture might be much more complex than implied by the available data set.

Local Geology. On Andros (fig. 2*a*, 2*b*), the metamorphic succession can be subdivided into two tectonic units, the Makrotantalon unit and the lower unit of central and southern Andros. Judging from structural and geochronological constraints, the Makrotantalon unit belongs to the upper group of units of the ACCB (e.g., Avigad et al. 1997; Bröcker and Franz 2006). The lower unit (up to 1200 m in thickness), which can be correlated with the Cycladic blueschist sequences, consists mainly of a volcanosedimentary sequence that comprises marbles, carbonate-rich schists, clastic metasediments, and metavolcanites (Papanikolaou 1978). Disrupted bodies of meta-ultramafic, metagabbroic, and meta-acidic rocks (up to several hundred meters in length) were recognized at various lithostratigraphic levels (Papanikolaou 1978; Buzaglo-Yoresh et al. 1995; Mukhin 1996). Mineral assemblages document severe greenschist-facies metamorphism, but relic HP rocks can still be found at many places. The *PT* conditions during the HP stage are considered to be not significantly different from those attained on the neighboring islands (Buzaglo-Yoresh et al. 1995). For details of the local geology, see Papanikolaou (1978) and Bröcker and Franz (2006).

On Sifnos (fig. 2*a*, 2*c*), the metamorphic succession (ca. 2500 m thick) belongs entirely to the CBU and can further be subdivided into an upper eclogite-blueschist unit and a basal greenschist unit (Avigad et al. 1992; Trotet et al. 2001*a*, 2001*b*). The eclogite-blueschist unit comprises well-preserved HP rocks intercalated between marble sequences (e.g., Altherr et al. 1979; Schliestedt 1986; Avigad et al. 1992; Trotet et al. 2001*a*, 2001*b*). Block-matrix associations like those found on other Cycladic islands (e.g., Syros, Tinos, and Andros) have not been described, but sporadic findings of eclogitic lenses (<1 m) within greenschists (Schliestedt and Matthews 1987) are most likely of comparable origin and do not simply represent relict domains that escaped retrogression. The greenschist unit (ca. 1000 m thick) is separated by a low-angle normal fault from the overlying sequences and consists mainly of strongly overprinted clastic metasediments, metabasic rocks, and marbles (e.g., Altherr et al. 1979; Avigad et al. 1992). High-pressure relicts are widespread. The higher degree of overprinting was related to a different cooling history (Avigad 1993). The thickness of the inferred crustal interval removed from between both units is controversial

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(Wijbrans et al. 1990; Avigad 1993). Details of the local tectonometamorphic history are given in Schmädicke and Will (2003) and references therein.

On Ios (fig. 2*a*, 2*d*), two tectonostratigraphic units can be distinguished: a pre-Alpidic basement and a volcanosedimentary series that has experienced Alpine polymetamorphism (e.g., Henjes-Kunst and Kreuzer 1982; van der Maar and Jansen 1983). The basement consists of an augen-gneiss core that is mantled by garnet mica schists and granitic gneisses. These rocks have experienced Hercynian amphibolite-facies metamorphism (ca. 295–305 Ma) and at least two metamorphic overprints in Tertiary times, related to an HP episode and subsequent overprinting at lower pressures (Henjes-Kunst and Kreuzer 1982; van der Maar and Jansen 1983; Andriessen et al. 1987). The importance of pre-Hercynian Rb-Sr whole-rock dates (ca. 500 Ma), interpreted to constrain the protolith age of the granitoids (Henjes-Kunst and Kreuzer 1982), cannot be substantiated at present. More recent work suggests that ages of ca. 300 Ma indicate the time of magmatic activity (Engel and Reischmann 2001), shortly after a high-temperature metamorphic event (Perraki and Mposkos 2001). The protolith ages of the metamorphic country rocks are unknown (Henjes-Kunst and Kreuzer 1982). The overlying cover, which consists of a variegated sequence of marbles, calcschists, clastic metasediments, and metabasic rocks, records only a Tertiary metamorphic history. Variably overprinted HP assemblages are often preserved, but greenschist-facies mineralogies predominate. Mineral assemblages and ages (e.g., Andriessen et al. 1987; Baldwin and Lister 1998) conform with the well-documented tectonometamorphic history of other Cycladic islands. The original contact between basement and cover is considered to represent a thrust fault (e.g., van der Maar and Jansen 1983), but its exact location is controversial (Vandenberg and Lister 1996 and references therein). Exhumation was accomplished by several generations of detachment faults that developed subparallel to the basement cover contact (Forster and Lister 1999).

Analytical Methods

Mineral separation, preparation of zircon mounts, and cathodoluminescence (CL) imaging were carried out at the Mineralogisches Institut, Universität Münster. Zircon was separated and enriched from fresh rock material (ca. 8–12 kg) by standard routines (jawbreaker, disk mill, Wilfley table, Frantz magnetic separator, heavy liquids). About 40–80 handpicked zircons were mounted in 25-mm epoxy disks, together with pieces of the CZ3 standard (Pidgeon et al. 1994; 564 Ma; $^{206}Pb/^{238}U$ = 0.0914, U = 551 ppm), and polished to expose the grain interior. Then, CL imaging (JEOL JSM-840A; 20 kV, ca. 15 nA, ca. 18–20 mm working distance) was applied to reveal the internal zircon structures and to guide spot placement for ion probe analysis. U-Pb dating was carried out in several sessions by use of a SHRIMP II at Curtin University of Technology, Perth. Analytical procedures followed standard operating routines and were similar to those reported by Compston et al. (1992). Instrumental characteristics have been described by De Laeter and Kennedy (1998). Cleaned zircon mounts were gold-coated and analyzed for U-Th-Pb isotopes using a spot diameter of ca. 20–40 μm. Before analysis, the primary beam was rastered over the target area for ca. 2–3 min. The data were collected in sets of seven scans through ZrO, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{238}U, ^{248}ThO, ^{254}UO, and a background mass near ^{204}Pb. The standard was analyzed after every three or four unknowns. Most analyses contain little common Pb and thus are insensitive to the choice of initial isotopic composition. Common Pb corrections were performed using the relevant Pb compositions after Stacey and Kramers (1975) and measured ^{207}Pb (Compston et al. 1984). The data were reduced using the SQUID Excel macro of Ludwig (2000). Uncertainties given for individual analyses (ratios and ages) are reported and plotted at the 1σ level; uncertainties of weighted mean ages are given at the 95% confidence level. Individual ages are quoted as $^{206}Pb/^{238}U$ ages. The uncorrected data for all samples are presented in Tera-Wasserburg (T-W) diagrams. The T-W plots, regressions, and weighted mean age calculations were carried out using Isoplot/Ex (Ludwig 2001).

Sample Description and Results

A major problem in this study was the difficulty in finding suitable samples. It was not unexpected that zircon is rare or absent in the metabasic rocks (blueschists and greenschists). However, in many cases, it was also difficult to find zircon in the meta-acidic rocks, which are considered to represent dacitic to rhyolitic precursors (e.g., Schliestedt and Okrusch 1988; Bröcker 1990; Mocek 2001). For example, with one exception, all samples from Tinos and Sifnos, which have been screened for the presence of zircon by means of thin-section studies and test processing of 10–15-kg samples, turned out to be useless for U-Pb geochronology. These rocks either did not contain zircons at all or contained

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only zircons too small for reasonable ion probe analysis that tries to avoid beam overlap on neighboring growth zones or the enclosing epoxy resin. Besides general compositional characteristics of the magmatic precursors, the scarcity of zircon in felsic rocks might indicate that such layers are composed of airfall ash derived from distal sources, whereas samples with more abundant and larger igneous zircons might correspond to pyroclastic material derived from more proximal eruption centers. In any case, although our sampling strategy aimed to document a more detailed age pattern on individual islands and across the region, only a few suitable samples were found. The general picture remains patchy, and the database needs to be enlarged by future studies. Sample locations are indicated in figure 2 and listed in table 1.

Andros. Six samples were collected from the lower unit, which records HP metamorphism and a greenschist-facies overprint. In the central part of Andros (Ateni; fig. 2*b*), a block-matrix association is exposed that was previously interpreted as a meta-olistostrome (Mukhin 1996). A prominent constituent is a disrupted tabular body of meta-acidic gneisses (several hundred meters in length) within clastic metasediments. Samples 1828 and 2038 were collected from this slab; a similar rock type was sampled in southern Andros (Piso Meria, sample 2041; fig. 2*b*). The mineral assemblages consist of albite, quartz, epidote/clinozoisite, and white mica (± chlorite, titanite, apatite, zircon, and opaques). At both localities, the field relationships are ambiguous, and it remains unclear whether these occurrences represent tectonic or sedimentary mélanges at all or instead are related to large-scale boudinage processes within the volcano-sedimentary succession.

The internal structure of most zircons is characterized by oscillatory or sector zoning (fig. 3*a*–3*f*). Broad and relatively homogeneous growth zones with faint oscillatory zoning also are common. Some grains have relatively dark (U-rich?) grain centers that show variable degrees of incipient recrystallization. Zircons of sample 1828 cluster at 241.3 ± 1.9 Ma (2σ, MSWD = 1.43, n = 13; fig. 4*a*; table A1, available in the online edition or from the *Journal of Geology* office). Thirteen grains from sample 2038 define an intercept at 249.4 ± 2.0 Ma (2σ, MSWD = 3.4; fig. 4*b*). One spot of this sample yielded a considerably younger age of 212.8 ± 2.1 Ma (1σ; table A1). Sample 2041 provided a weighted mean $^{206}Pb/^{238}U$ age of 240.0 ± 1.4 Ma (MSWD = 1.46; n = 11; fig. 4*c*; table A1). Two spots that yielded ages of 260.5 ± 4.3 and 224.7 ± 5.9 Ma (1σ for both) were excluded from this calculation (table A1). The Triassic ages for samples 1828, 2038, and 2041 are interpreted to indicate the time of igneous crystallization.

Table 1. Localities of Samples Selected for SHRIMP U-Pb Dating

Sample	Location	Latitude	Longitude
1828	Andros, Ateni	37°52.518′N	24°48.636′E
2038	Andros, Ateni	37°52.733′N	24°48.736′E
2041	Andros, Piso Meria	37°44.905′N	24°55.824′E
2036	Andros, Cape Felos	37°54.245′N	24°42.488′E
5017	Andros, Cape Steno	37°41.055′N	24°57.754′E
5008	Andros, Cape Steno	37°41.107′N	24°57.544′E
4036	Sifnos, Kamares	36°59.773′N	24°40.207′E
5034	Ios, roadcut Homer's tomb	36°45.687′N	25°17.140′E

From the Cape Felos region in northwestern Andros (fig. 2*b*), Mukhin (1996) described a block-matrix association of sedimentary origin that includes plagiogranitic fragments. Our field studies in this area yielded no indications of a chaotically mixed mélange. We have studied a disrupted felsic layer (sample 2036) most likely representing a boudinaged metagraywacke. The detrital zircon population of this sample comprises grains with variable internal patterns, including regular oscillatory zoning, convolute zoning, and relatively homogeneous structures. Many grains have inherited cores and distinct weakly banded or oscillatory overgrowths (fig. 3*j*–3*l*). In order to evaluate the importance of Alpidic metamorphic events, we have targeted mainly the zircon rims, most of which have both moderate to high U concentrations and relatively low Th contents (table A1). The Th/U ratio is variable but is often <0.1. Thirteen analyses of overgrowths show a spread in $^{206}Pb/^{238}U$ ages from ca. 315 to 372 Ma (fig. 4*d*; table A1), testifying to Variscan orogenic processes in the source area. In two cases, rims yielded $^{206}Pb/^{238}U$ ages of ca. 563 and ca. 569 Ma. Indications of metamorphic overgrowths related to the younger metamorphic history have not been recognized. Only one core was analyzed that yielded a $^{206}Pb/^{238}U$ age of ca. 1742 Ma (table A1).

An HP mélange at the southern tip of the island (Cape Steno; fig. 2*b*) comprises nondeformed to variably sheared metagabbros, metabasalts, metaplagiogranites(?), meta-acidic gneisses, and ultramafic rocks (Buzaglo-Yoresh et al. 1995; Mukhin 1996). A plagiogranitic rock from this location carries clinopyroxene with an up to 95 mol% jadeite component; closely associated metasediments contain glaucophane and garnet (Buzaglo-Yoresh 1995). This oc-

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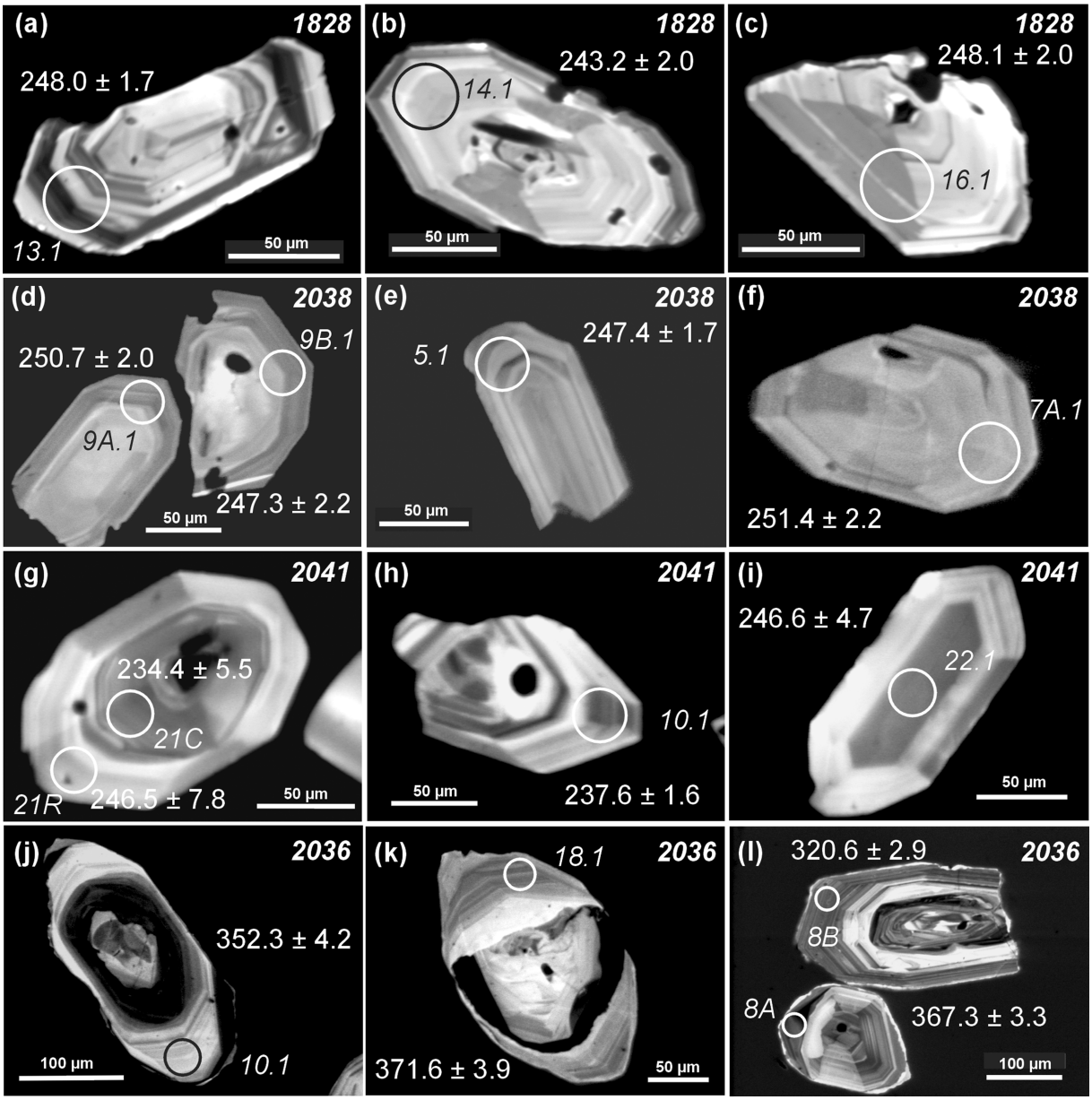


Figure 3. Cathodoluminescence images of representative zircons from samples 1828, 2038, 2041, and 2036. Numbers in italics, close to the circles, denote the spot identification number. SHRIMP spot ages (Ma) are reported with 1σ uncertainty. See table 1 for details.

currence is considered to represent a litho- or tectonostratigraphic equivalent to the succession exposed in northwestern Tinos, where mafic and ultramafic nodules and blocks are found sporadically within calcareous metasediments (Buzaglo-Yoresh 1995). We have studied a metagabbro (sample 5017), consisting mostly of brown and green amphibole, plagioclase, epidote/clinozoisite (±opaques, titanite, zircon), and a metagranitoid (sample 5008) with the mineral assemblage albite, quartz, white mica, chlorite, and epidote/clinozoisite (±opaques, titanite, apatite, and zircon). Zircons of sample 5017 often are fractured and comprise two types (fig. 5*a*–5*c*). The dominant group is characterized by relatively broad light- and dark-colored CL domains or bands that may show sector or faint oscillatory zoning. In some cases, two growth stages can be distinguished. The second group comprises zircons with dark grain centers that are surrounded by relatively broad CL bands. Such grains often display early

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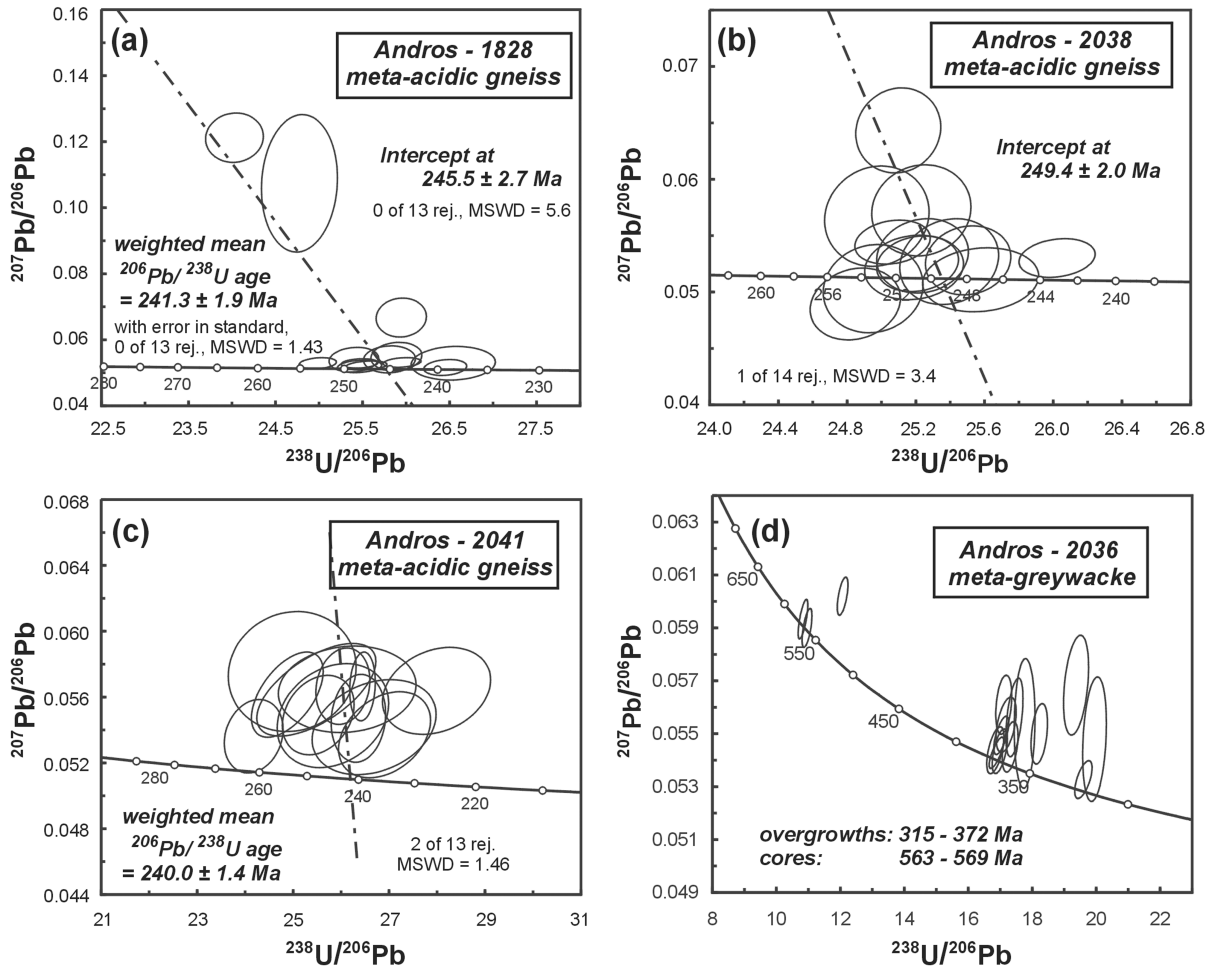


Figure 4. Tera-Wasserburg concordia diagrams for samples 1828, 2038, 2041, and 2036. Data point error ellipses are shown at the 1σ confidence level (c.l.). Error of the weighted mean is given at the 95% c.l. Dash-dotted line indicates mixing trend with common lead of Broken Hill composition.

stages of recrystallization. All zircons have Th/U ratios between 0.46 and 0.83. U and Th concentrations reach 1000 ppm or more, but are mostly 87–346 and 42–250 ppm, respectively (table A1). The SHRIMP analyses define an intercept at 156.2 ± 2.3 Ma (2σ; one spot dated at 137.9 ± 2.3 Ma is not included). However, the studied zircon population most likely comprises two distinct $^{206}Pb/^{238}U$ age groups that cluster at 153.8 ± 2.5 Ma (2σ; MSWD = 1.72, n = 11) and ca. 162 Ma (fig. 6*a*; table A1). Most zircons of sample 5008 show a patchy pattern of relatively broad CL domains, occasionally with weak oscillatory zoning (fig. 5*d*–5*f*). Grains with narrow oscillatory zoning are also common. Some zircons show distinct overgrowths (oscillatorily zoned or with relatively broad growth zones) around inherited cores. Twelve spot analyses of different grains define a dominant $^{206}Pb/^{238}U$ age cluster at 160.0 ± 2.0 Ma (MSWD = 0.54, n = 10; fig. 6*b*) that is interpreted as indicating the time of magmatic crystallization. Two grains yielded somewhat younger ages of ca. 150–153 Ma (table A1), possibly also recording magmatic processes. Two grains with a pronounced core-overgrowth relationship yielded Neo- to Mesoproterozoic $^{206}Pb/^{238}U$ ages for the grain centers (ca. 1126 and ca. 1421 Ma) and Permian $^{206}Pb/^{238}U$ ages (ca. 273 and ca. 281 Ma) for the rims (table A1). These grains are interpreted to represent xenocrysts caught up during melt extraction from the source rocks.

Sifnos and Ios. On Sifnos, we studied a bimodal sequence of interlayered greenschists and meta-acidic gneisses from the basal part of the eclogite-blueschist unit. Sample 4036 was collected from a felsic layer that belongs to a ca. 50-m-thick sequence of silicate rocks within marbles exposed

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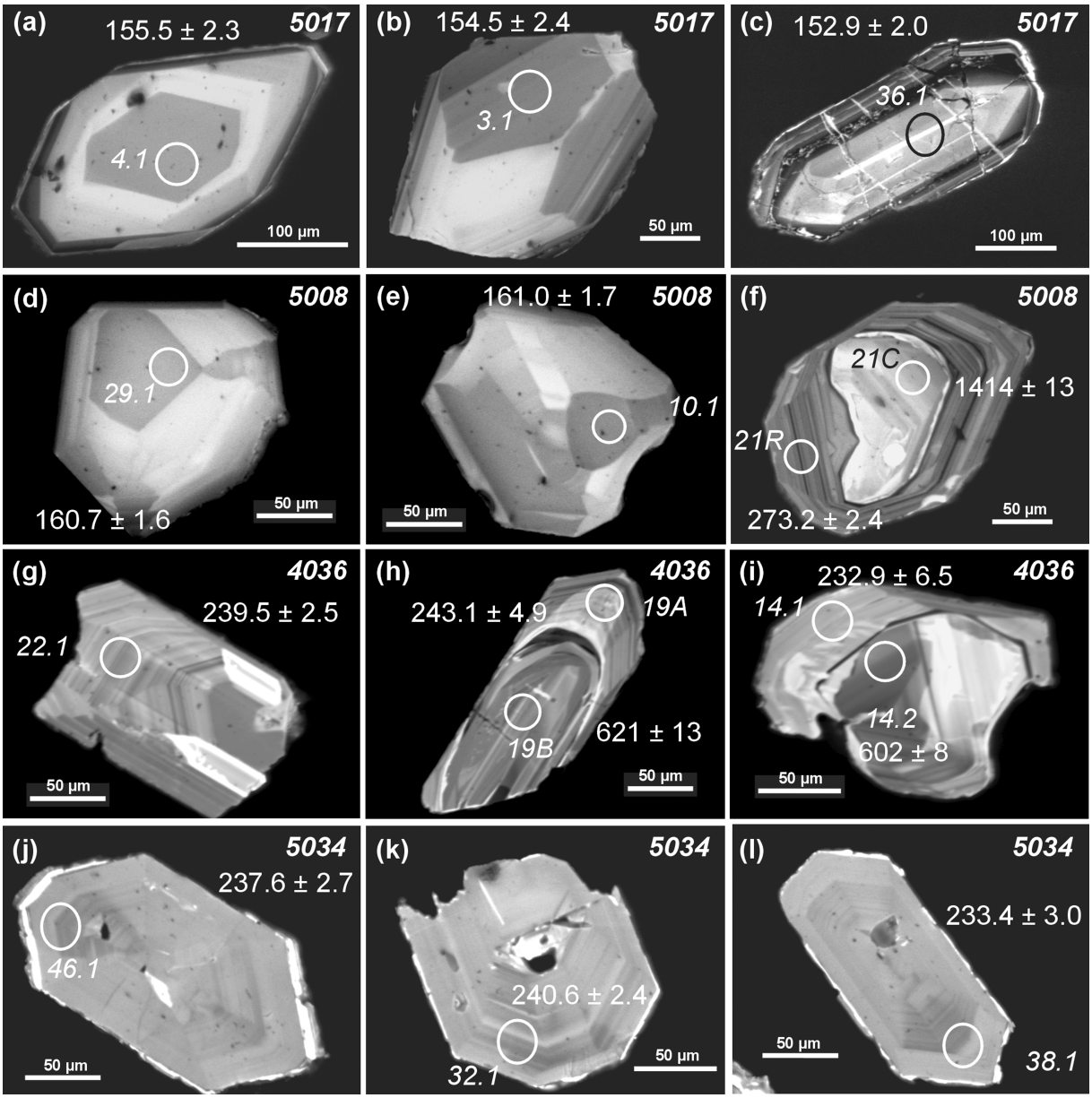


Figure 5. Cathodoluminescence images of representative zircons from samples 5017, 5008, 4017, and 5034. Numbers in italics, close to the circles, denote the spot identification number. SHRIMP spot ages (Ma) are reported with 1σ uncertainty. See table 1 for details.

close to the chapel Agios Ekaterini near Kamares (fig. 2*c*; Schliestedt and Matthews 1987). The mineral assemblage consists of albite, quartz, white mica, epidote/clinozoisite, and chlorite (± opaques, titanite, and zircon). Most of the zircons of this sample show variably developed oscillatory zonation (fig. 5*g*–5*i*). Some grains are characterized by distinct core-rim structures. Fifteen SHRIMP analyses of different grains (table A1) documented two Triassic age groups of 226.6 ± 2.0 Ma (2σ; MSWD = 0.58, n = 7) and 240.4 ± 2.1 Ma (2σ; MSWD = 0.15, n = 4). One spot analysis of an overgrowth yielded a $^{206}Pb/^{238}U$ age of ca. 307 Ma. Two zircon cores provided $^{206}Pb/^{238}U$ ages of ca. 602 and 621 Ma (table A1). This rock type is considered to be of metatuffaceous origin, and the zircon population most likely also comprises grains of detrital origin.

From Ios, we investigated a metatuffaceous rock (sample 5034) collected along the roadcut between

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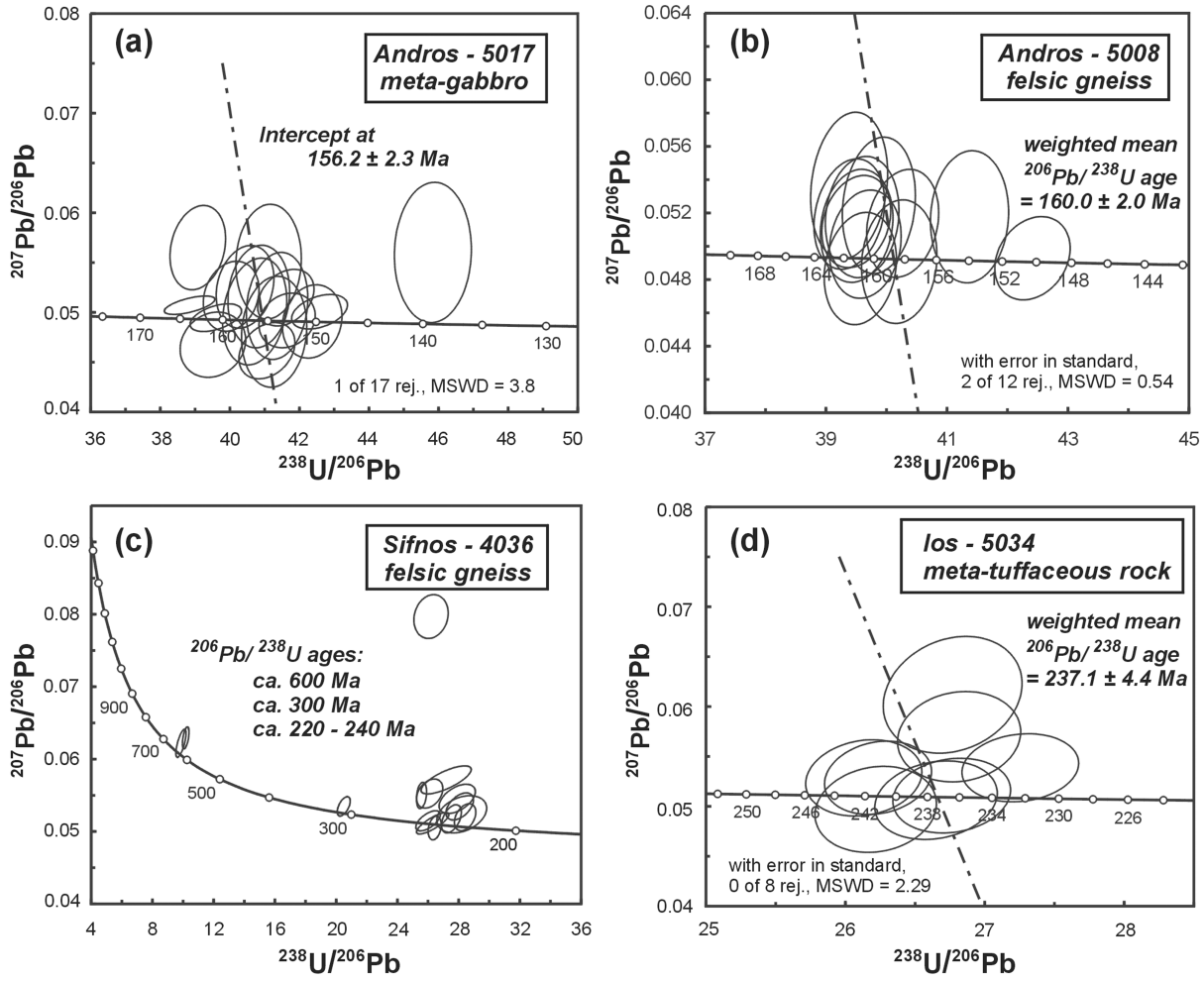


Figure 6. Tera-Wasserburg concordia diagrams for samples 5017, 5008, 4017, and 5034 using uncorrected data. Data point error ellipses are shown at the 1σ confidence level (c.l.). Error of the weighted mean is given at the 95% c.l. Dash-dotted line indicates mixing trend with common lead of Broken Hill composition.

Pano Kambos and Homer's tomb (fig. 2*d*). The rock consists mostly of albite, quartz, epidote/clinozoisite, chlorite, and white mica (± opaques, titanite, and zircon). The euhedral and normal prismatic zircons of this sample form a homogeneous group of grains with blurred oscillatory zoning that generally lack inherited cores (fig. 5*j*–5*l*). Thin metamorphic overgrowths (<10 μm) occasionally were recognized but could not be dated. All zircons have low to moderate U and Th concentrations (53–153 and 17–126 ppm, respectively) and Th/U ratios of 0.33–0.68. Eight spot analyses gave a weighted mean $^{206}Pb/^{238}U$ age of 237.1 ± 4.4 Ma (2σ; MSWD = 2.29; fig. 6*d*), which is interpreted as the time of zircon crystallization from a melt.

Discussion

Protolith Ages of the Volcanosedimentary Sequences. The new SHRIMP ages are surprisingly consistent on a regional scale and fall within a narrow range of Triassic crystallization ages (ca. 245–237 Ma; figs. 4, 6; table A1). Similar SHRIMP $^{206}Pb/^{238}U$ zircon ages have also been reported for a bimodal metatuffaceous sequence that occurs within the main schist-marble sequence in southern Syros (243 ± 2 Ma; cited in Tomaschek et al. 2003) and for a tectonic slab within the Syros mélange that consists of a meta-acidic gneiss-glaucophanite sequence (240.1 ± 4.1 and 245.3 ± 4.9 Ma; Bröcker and Keasling 2006). Basic, intermediate, and acidic volcanic rocks of Triassic age are widespread within

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the Hellenides (for a regional distribution map, see Pe-Piper 1998 and Pe-Piper and Piper 2002). The compilation of the relevant literature by these authors lists radiometric ages for only two occurrences (Crete and Othris; ca. 237–250 Ma, based on K-Ar and Ar-Ar hornblende dating). In other cases, the time of formation is constrained by biostratigraphic considerations. The Triassic metavolcanic rocks are widely considered to document rifting associated with the creation of two Neotethyan oceanic basins, the Pindos and Vardar oceans (e.g., Pe-Piper 1998; Pe-Piper and Piper 2002 and references therein). The importance of subduction- and back-arc-related volcanism is controversial (Pe-Piper and Piper 2002). For the CBU, several studies have suggested a back-arc setting with a nearby island arc to explain the geochemical characteristics of the meta-igneous rocks (Bröcker 1991; Seck et al. 1996; Mocek 2001), but the exact geotectonic is not yet clear. It is worth noting that Triassic protolith ages (ca. 244–240 Ma) also were reported for metagranitoids from the Hellenides, for example, from Naxos (Reischmann 1998) and Syros (Keay 1998; Tomaschek et al. 2001).

The Early to Middle Triassic age cluster for metavolcanic rocks of the CBU documents a regionally important period of magmatic activity (see also Keay 1998) but certainly does not bracket the full duration of sedimentation recorded by the metamorphosed succession. Fossil findings (e.g., Dürr 1975; Dürr and Flügel 1979; Melidonis 1980) and SHRIMP U-Pb ages of detrital zircons (Keay 1998) suggest that, at least locally, deposition continued through Late Triassic to Jurassic time and may have persisted into the Cretaceous. Keay (1998) focused mainly on the southern Cyclades, with Naxos as the main center of interest, but also studied samples from Sifnos, Sikinos, Folegandros, Ios, and Syros. This data set, presented in parts by Keay and Lister (2002), documented for the CBU a mixed provenance including detritus from different Precambrian, Paleozoic, and Mesozoic terrains. The Mesozoic sources yielded a dominant age cluster at 250–220 Ma, embracing the newly determined protolith ages of interbedded metatuffaceous and metavolcanic rocks. This indicates that detrital zircon populations most likely comprise contributions from both recycling of preexisting rocks and more or less synsedimentary volcanism. In this context, it is worth noting that Keay (1998) described two samples with a single age cluster at ca. 220 Ma, which she related to reworking of a proximal volcanic source.

Protolith Ages of Ophiolitic Mélange Blocks: The Example of Andros. The ophiolite occurrences of the eastern Mediterranean can be subdivided into a western region (Albania, the former Yugoslavia, mainland Greece, and Crete) and an eastern region (Turkey, the southern Aegean islands, Cyprus, and Syria) with different protolith ages, clustering in the Middle–Late Jurassic (ca. 157–180 Ma) and the Late Cretaceous (mostly 70–95 Ma), respectively (Parlak and Delaloye 1999 and references therein; Koepke et al. 2002; Robertson 2002). These ophiolites are related to the formation of one or more oceanic basins that formed during breakup of microcontinental fragments at the northern margin of Gondwana (for overviews, see Pe-Piper and Piper 2002, Robertson 2002, and references therein). In the western region, two subparallel, NNW-trending belts with different geochemical characteristics can be distinguished, lending support to models suggesting the existence of one or two major oceanic basins (Vardar and Pindos) enclosing parts of present-day Greece and surrounding areas (Pe-Piper and Piper 2002; Robertson 2002).

Dating of ophiolites is generally difficult, because of the lack of suitable mineral phases and/or severe overprinting of the primary mineral assemblages. Protolith ages for the meta-ophiolites in the eastern Mediterranean were deduced mostly from geochronological results for amphibolite-facies metamorphic soles, which are considered to approximate the age of the overlying ophiolite, and from paleontological data of closely associated sediments (e.g., Robertson 2002 and references therein). Only for a few ophiolite occurrences (Vourinos, Pindos, and Othrys) are ion probe U-Pb zircon ages available that directly constrain the time of magmatic crystallization (Liati et al. 2004). In the HP mélanges of the CBU, remnants of metamorphic soles are not preserved or have been unnoticed until now. However, at least some meta-ophiolitic fragments contain highly resistant zircon, which would allow the determination of protolith ages.

The status of meta-ophiolitic fragments from the CBU within the overall eastern Mediterranean pattern is unclear. Radiometric data, available for only one occurrence on Syros, indicate Cretaceous protolith ages (Keay 1998; Tomaschek et al. 2003; Bröcker and Keasling 2006). The newly dated block-matrix association from Andros yielded protolith ages of ca. 156–160 Ma for a metagabbro and a felsic gneiss, in good agreement with radiometric data (K-Ar, Ar-Ar, U-Pb) reported for metamorphic soles from the Balkan peninsula and Crete (Parlak and Delaloye 1999; Koepke et al. 2002; Liati et al. 2004). Such ages were also described for felsic rocks (granites, gneisses, and volcanic rocks) from the eastern Vardar zone (fig. 1), Greece, where the close spatial association of granitic and ophiolitic rocks was interpreted to indicate a volcanic arc setting at an

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active continental margin that formed during eastward subduction of the Vardar Ocean (e.g., Brown and Robertson 2003, 2004; Anders et al. 2005). The Vardar zone is considered to represent an important Mesozoic–Early Tertiary suture zone, comprising remnants of oceanic lithosphere, sediments, arc-related magmatism, and basement rocks (e.g., Brown and Robertson 2003, 2004 and references therein). After Permo-Triassic rifting and subsequent ocean floor formation, the Vardar Ocean experienced a first phase of eastward-directed subduction in Jurassic time, associated with the formation of a volcanic arc. Remnants of the Vardar Ocean or related back-arc basins outlasted the main Jurassic closure phase and persisted locally into Late Cretaceous to Tertiary times (e.g., Pamić et al. 2002; Robertson 2002; Brown and Robertson 2004).

The new and published results indicate that both Jurassic and Cretaceous meta-ophiolites occur in the HP mélanges of the CBU. However, it is not known whether both age groups occur within the same mélange or at different lithostratigraphic and/or tectonic levels. Until now, an unambiguous correlation of block-matrix associations between different Cycladic islands has been impossible. It is tempting to propose a Vardar Ocean–related origin for both age groups. However, an alternative explanation is to suggest that the Cretaceous meta-ophiolites on Syros belong to the E-W-trending ophiolite belt of the Taurides (Turkey, southern Aegean islands, Cyprus, and Syria; Parlak and Delaloye 1999), which might stretch into the Cyclades. In this scenario, the Jurassic meta-ophiolites on Andros could be linked to either the Vardar Ocean or a different coeval oceanic basin (Robertson 2002). Further geochronological and geochemical studies may help resolve the relationship between the mélanges on Andros and Syros and to establish correlations on a broader regional scale within the eastern Mediterranean.

Conclusions

The CBU is widely known as an important study area for HP/LT metamorphism and the exhumation of related rocks. Structural, petrological, and geochronological aspects of the metamorphic history are well documented, but key information concerning the premetamorphic evolution is only poorly constrained. The aim of this study was to shed some light on this issue by unravelling protolith ages recorded in volcanosedimentary sequences and by exploring the age diversity and provenance of mélange blocks. The new results indicate a consistent regional pattern of Triassic ages (ca. 237–245 Ma) for the magmatic precursors of metatuffaceous and metavolcanic rocks that occur as intercalations within metasediments. This narrow range of igneous crystallization ages records an important period of volcanic activity in the larger study area but does not cover the full time span of sedimentation. The sampling pattern has many gaps, and complete sections are yet not dated. Field relationships and sample characteristics indicate that only a multimethod approach can resolve the full range of depositional ages. U-Pb zircon dating of metavolcanic layers that occur interbedded with the metasediments is the most promising tool for establishing well-constrained protolith ages. However, in the study area, zircon-bearing metavolcanites generally are rare and do not occur at all lithostratigraphic levels. In these cases, Sr isotope stratigraphy applied to calcitic marbles (e.g., Melezhik et al. 2001; Thomas et al. 2004) and U-Pb dating of detrital zircons from clastic metasediments might help to unravel further details of the sedimentation history.

The new data set bears an interesting implication for a better understanding of the tectonic evolution of the CBU. On Andros, the blueschist-facies sequences of the lower unit are tectonically overlain by the Makrotantalon unit, which contains marbles with well-preserved Permian fossils (Papanikolaou 1978). This indicates an inverted tectonostratigraphy—rocks at the top of the succession are older than the structurally lower sequences—implying that the contact between both units originally represented a thrust fault (Papanikolaou 1978). Because of large-scale regional extension, this contact was possibly later reactivated as a low-angle normal fault (e.g., Avigad et al. 1997).

This study has documented for the first time the occurrence of Jurassic meta-ophiolites and metagranitoids in HP mélanges of the CBU. Remnants of both Jurassic and Cretaceous oceanic lithosphere were recognized in close proximity to each other, possibly within directly correlated block-matrix associations. The geological background is not yet fully explored, but the picture emerging from an increasing number of dated mélange blocks (e.g., Keay 1998; Bröcker and Enders 1999, 2001; Tomaschek et al. 2003; Bröcker and Keasling 2006; this study) indicates rock associations of mixed provenance with different protolith ages and not a homogeneous group with a single formation age.

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