Rb–Sr isotope studies on Tinos Island (Cyclades, Greece): additional time constraints for metamorphism, extent of infiltration-controlled overprinting and deformational activity

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Abstract – This study presents new Rb–Sr age data concerning the metamorphic evolution of the Attic-Cycladic Crystalline Belt which represents a complex polymetamorphic terrane within the Alpidic orogenic belt of the Hellenides. Two major groups of tectonic units can be distinguished. Metamorphism in parts of the upper units is commonly considered as a Cretaceous event. In contrast, the group of lower units experienced Tertiary high-pressure metamorphism which was followed by a medium-pressure overprint. We focus on the island of Tinos where a representative spectrum of the rock units found in the Cyclades is exposed in three tectonic units: the Upper Unit, the Intermediate Unit and the Basal Unit. The complete range of tectono-metamorphic and magmatic events affecting the Attic-Cycladic Crystalline Belt is documented by numerous petrological and tectonic studies. Phyllites and phyllonites from the ophiolitic Upper Unit yielded Rb–Sr apparent ages (phengite–whole-rock) between c. 92 and 21 Ma. The older age differs from the Cretaceous dates reported for upper unit rocks elsewhere in the Cyclades. It is suggested that the sequence studied belongs to the Jurassic ophiolites of the Hellenides rather than to Cretaceous occurrences. The spread to younger ages is related to non-pervasive rejuvenation and resetting of the Rb–Sr system during tectonic juxtaposition of the Upper Unit over the Intermediate Unit. The youngest age obtained so far for a sample from the Upper Unit (21 Ma) is believed to approximate the timing of tectonic juxtaposition which probably occurred during a regional greenschist-facies episode producing a pervasive overprint in the structurally lower tectonic unit. The major phylrite/meta-gabbro/serpentinite sequence of the Upper Unit is interpreted as an emplacement-related ductile shear zone which experienced reworking under brittle conditions. In the Intermediate Unit, a gradient in Rb–Sr ages from top (c. 40 Ma) to the bottom (c. 22 Ma) was recognized, which is interpreted to represent greater effects of fluid infiltration and overprinting in the lower parts of this unit, possibly controlled by variable intensity of deformation which might be related to tectonic juxtaposition onto the Basal Unit. We suggest that synmetamorphic stacking of all three tectonic units took place during an Oligocene–Miocene greenschist event. Extensional deformation continued after tectonic stacking and after intrusion of the main granite, as is indicated by a Rb–Sr whole-rock isochron (15.1 ± 0.6 Ma) for a ductilely deformed garnet-bearing leucogranite from the marginal parts of the main undeformed pluton. Application of the Rb–Sr dating technique provided no unequivocal evidence that previously published Eocene K–Ar and 40Ar/39Ar dates for high-pressure phengites from the lower units are significantly contaminated with excess argon.

1. Introduction

In the Cyclades, two main groups of tectonic units with contrasting metamorphic histories can be distinguished (for overviews and references see Dürr et al. 1978a; Dürr, 1986; Schliestedt, Altherr & Matthews, 1987; Okrusch & Bröcker, 1990). The lower group of units was affected by at least two metamorphic events: (1) a period of regional eclogite to blueschist metamorphism as a result of continent–continent collision caused by the subduction of the Apulian microplate beneath the Eurasian continent; and (2) subsequent greenschist- to amphibolite-facies overprints which are interpreted to result from isothermal decompression during uplift and/or an independent prograde metamorphic event. The physical conditions inferred for the high-pressure episode are pressures at about 15 ± 3 kbar and temperatures of approximately 450–500°C (Schliestedt, Altherr & Matthews, 1987; Okrusch & Bröcker, 1990). Pressures attained during the greenschist-facies overprint are estimated at 4 to 7 kbar and inferred temperatures are between 450 and 500°C (Schliestedt, Altherr & Matthews, 1987; Okrusch & Bröcker, 1990). As a consequence of re-equilibration during the exhumation-related overprint, high-pressure mineral assemblages are widely replaced by medium-pressure parageneses, but small occurrences of eclogites and blueschists can be found on many islands closely associated with their greenschist-facies counterparts. K–Ar, 40Ar/39Ar and Rb–Sr dating of white mica from blueschists and eclogites yielded Eocene ages between about 55 and 40 Ma; dates between 25 and 18 Ma were obtained using white mica of greenschist and amphibolite-facies rocks (e.g. Altherr et al. 1979; Andriessen et al. 1979; Wijbrans & McDougall, 1986, 1988; Maluski, Bonneau & Kienast, 1987; Wijbrans et al. 1990; Bröcker et al. 1993).

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Unlike the structurally lower succession, the upper group of units was not affected by Tertiary polymetamorphism, and the last metamorphism is commonly considered as a Cretaceous event (e.g. Dürr, 1986; Avigad & Garfunkel, 1989; Patzak, Okrusch & Kreuzer, 1994). By use of the K–Ar method (hornblende, muscovite, biotite), a range of dates between 84 and 59 Ma was obtained for low-pressure/high-temperature rocks from several Aegean islands and Crete (Baranyi, Lippolt & Todt, 1975; Lippolt & Baranyi, 1976; Seidel et al. 1976, 1981; Dürr et al. 1978b; Reinecke et al. 1982; Altherr et al. 1979, 1994; Maluski, Bonneau & Kienast, 1987; Patzak, Okrusch & Kreuzer, 1994), indicating the former existence of a widespread late Cretaceous terrane (see, for example, Altherr et al. 1994; Patzak, Okrusch & Kreuzer, 1994). However, the significant spread in K–Ar dates indicates variable disturbance of the argon isotopic system during subsequent metamorphic and/or deformational processes.

Our knowledge of the metamorphic and deformational evolution of the Attic-Cycladic Crystalline Belt (ACCB) still is incomplete and many aspects of the complex P–T–t–d path are not well understood. A number of studies have shown that the Ar-based dating techniques, commonly used for timing of metamorphism in the lower group of units, can yield geologically meaningless dates because of undetected excess argon, even if well-defined "Ar−"Ar plateaus are developed (e.g. Tonarini et al. 1993; Li et al. 1994; Arnaud & Kelley, 1995). Unresolved questions also concern the exact timing of metamorphism in the heterogeneous group of upper units, dating of tectonic juxtaposition of the upper units onto structurally lower units and the relationship between magmatic activity and ductile deformation. These problems are addressed in the present paper which is concerned with the major phyllite/meta-gabbro/serpentinite exposures on Tinos (Figs 1, 2). On this island a representative spectrum of the rock units found in the Cyclades is exposed and the complete range of tectono-metamorphic and magmatic events affecting the ACCB is documented by numerous petrological and tectonic studies. Previous work has shown that exhumation of high-pressure metamorphic rocks by low-angle detachment faults (Avigad & Garfunkel, 1989, 1991; Gautier & Brun, 1994a,b) is associated with partial to almost complete rejuvenation of the Sr and Ar isotopic systems, mainly controlled by variable fluid fluxes (e.g. Altherr et al. 1979; Bröcker et al. 1993). Besides our attempt to add new constraints on the timing of metamorphic and deformational events, we examine the scale of infiltration-related overprinting along a complete section from the basal parts to the top of the Intermediate Unit on Tinos.

2. Local geology

On Tinos three tectonic subunits can be distinguished (Figs 2, 3). The Upper Unit (up to about 250 m in thickness) consists of serpentinites, meta-gabbros, opal-citcites, phyllites and amphibolite-facies rocks (Melidonis, 1980; Bröcker 1990a; Avigad & Garfunkel, 1989; Patzak, Okrusch & Kreuzer, 1994; Katzir et al. 1996; Stolz, Engi & Rickli, 1997). The tectonostratigraphy and various petrographical, mineralogical and geochemical aspects of the major phyllite/meta-gabbro/serpentinite exposures were reported by Katzir et al. (1996) who interpreted this rock association as a dismembered ophiolite. These authors showed that (1) all exposures consist of phyllites at the bottom which are overlain by serpentinites and meta-gabbros; (2) mylonitized phyllites and phyllonites are common; (3) locally small lenses of serpentinite and meta-gabbro are imbricated in phyllites and (4) phyllites, meta-gabbros and ultramafic rocks experienced green-schist-facies metamorphism and associated deformation. The amphibolite-facies rocks which occur at Cap Fokas (Fig. 2) were studied in detail by Patzak, Okrusch & Kreuzer (1994). It is not clear whether this exposure belongs to the ophiolite suite or represents an independent tectonic subunit (Bröcker, 1990a; Katzir et al. 1996). Amphiboles of metabasic layers from Cap Fokas yielded K–Ar dates between 77 and 66 Ma; for muscovite from paragneisses, dates between 60 and 53 Ma were obtained (Patzak, Okrusch & Kreuzer, 1994). Unpublished K–Ar results provided by different size fractions of amphibole from a meta-gabbro indicate a date around 265 Ma (Kreuzer, pers. comm.) but may be affected by incorporation of excess radiogenic Ar in the low potassium (<0.1 wt %) amphiboles. The major rock types of the Upper Unit (serpentinites, meta-gabbros, phyllitic rocks) have not previously been dated but a Late Cretaceous age is assumed for the ophiolite sequence (Avigad & Garfunkel 1989, 1991; Katzir et al. 1996). According to Avigad & Garfunkel (1989), the immediate contact with the structural lower unit is characterized by several metres of brecciation and fractured ultrabasites which show no indication of mylonitization or ductile flow. On the other
hand, Katzir et al. (1996) recognized at some places thin layers of sheared ultramafic rocks at the base of the Upper Unit, and locally mylonitized phyllites are found in immediate contact with schists of the underlying unit.

Most of the island belongs to the Intermediate Unit (Fig. 2; also referred to as ‘Lower Unit’ or ‘Blueschist–Greenschist Unit’) which has experienced Tertiary polymetamorphism. Marbles, calc-schists, siliciclastic metasediments, cherts and basic and acid metavolcanic rocks are the principal rock types which occur in a structurally coherent sequence (about 1250 m to 1800 m in thickness; Melidonis, 1980; Bröcker, 1990a). This sequence can be subdivided roughly by means of three marble units (m3, m2 and m1: Melidonis, 1980; Fig. 3).

In northern Tinos, a tectonically emplaced meta-gabbro or meta-diorite was recognized in the schist sequence (Melidonis, 1980). Relics of blue amphibole in a greenschist-facies mineral assemblage indicate that emplacement of this rock slice occurred before or during the high-pressure/low-temperature metamorphism. Most rock types of this tectonic unit display greenschist-facies mineralogies, but remnants of eclogite- and blueschist-facies rocks were recognized at many places all over the island (e.g. Melidonis, 1980; Bröcker, 1990a,b). The partial to complete change in mineralogy and associated resetting of isotopic systems was attributed by Bröcker et al. (1993) to channelized infiltration of fluids during the greenschist overprint(s). This non-pervasive fluid influx was related to structural or lithological constraints and/or limited availability of fluids (Bröcker, 1990b; Bröcker et al. 1993; Ganor et al. 1996).

The P–T conditions inferred for the peak of the high-pressure metamorphism are approximately 450–500 °C at minimum pressures of about 12 kbar (Bröcker, 1990a; Bröcker et al. 1993). The pressures at the culmination of the greenschist overprint were estimated at about 4 to 7 kbar. Temperatures ranging between 440 and 470 °C are indicated by oxygen isotope geothermometry (Bröcker et al. 1993). Previous geochronological studies indicate K–Ar and 40Ar–39Ar ages between 44 and 40 Ma for blueschist-facies rocks; some greenschists and late stage blueschists gave dates in the range of 34 to 28 Ma, which were related to an early phase of decompression on the uplift path. A second phase of renewed greenschist metamorphism is indicated by dates between 23 and 21 Ma (Altherr et al. 1982; Bröcker et al. 1993). Due to restricted preservation, all dated blueschist-facies rocks were collected at lithostratigraphic positions closely associated with the upper and intermediate marble sequences as mapped by Melidonis (1980); most of the dated greenschist-facies samples represent a similar lithostratigraphic position.
In the eastern part of the island (Fig. 2) the Upper and Intermediate Unit were affected by contact metamorphism (Avigad & Garfunkel, 1989) caused by a Miocene granitoid which was dated at about 18 Ma (Altherr et al. 1982, 1988). A small occurrence of S-type granite yielded a Rb–Sr whole-rock age of 14 ± 0.1 Ma (Altherr et al. 1982). The intrusion-related thermal overprint affecting both units and the absence of any indication for Tertiary polymetamorphism in the Upper Unit, led to the conclusion that tectonic emplacement of the Upper Unit occurred in the short time span between the greenschist overprint in the structurally lower unit (c. 23 to 21 Ma) and the granitoid intrusion (c. 18 Ma) (Avigad & Garfunkel, Katzir et al. 1996).

Based on the observation of apparent metamorphic and microstructural differences, Avigad & Garfunkel (1989) suggested that a basal dolomite–phyllite series in northwest Tinos represents a distinct tectonic unit which did not experience high-pressure metamorphism and which is separated by a low-angle thrust fault from the overlying Blueschist–Greenschist Unit. From dolomites of this Basal Unit, Melidonis (1980) described Upper Triassic fossils. No fossils are preserved at higher lithostratigraphic levels.

3. Petrography, sample description and field relations

In order to obtain better understanding of the complex metamorphic and tectonic history we have investigated (1) phyllitic rocks from the Upper Unit, (2) samples collected from the basal lithostratigraphic levels of the Intermediate Unit for which previously no radiometric data was available, (3) phengite aliquots of samples from the Intermediate Unit which were already dated with the 40Ar/39Ar method (Bröcker et al. 1993) and (4) a recently described occurrence of deformed leucogranite (Bröcker & Franz, 1994).

3.a. Upper Unit

For Rb–Sr dating we have selected eight samples from outcrops at Kionia, Cap Stavros and Kletofourni (Fig. 2). For detailed descriptions and columnar sections of the studied occurrences see Katzir et al. (1996). At Kionia and Kletofourni (Fig. 2), phyllites and phyllonites are the dominant rock types which occur in 50- and 200-m-thick sequences, respectively; small lenses of imbricated metabasalt and/or serpentinite occur locally (Katzir et al. 1996; Bröcker, unpub. data). From Kionia we have studied a meta-argillaceous phyllite (sample 1096) which was collected close to the tectonic contact between the Upper and Intermediate Units. From Kleftovouni we investigated two phyllonites. Sample 1159 was collected outside the contact aureole northeast of Kalloni. Sample 1157 was collected within the outer aureole. At Cap Stavros (Fig. 2), phyllitic rocks are tectonically overlain by a tabular body of meta-gabbro (about 10 m in thickness) which is discontinuously exposed over an area of about 800 m² (Fig. 4). The meta-gabbro has partially preserved the original magmatic layering of hornblende- and plagioclase-rich layers (Fig. 5). Some slices of meta-gabbro were strongly mylonitized during emplacement or subsequent deformation and were imbricated in the phyllite sequence. Unfortunately, most parts of the Stavros meta-gabbro are not suitable for application of the Rb–Sr method. We have investigated a deformed meta-gabbro from the marginal parts of the main lens with high modal amounts of white mica (sample 1054) and mafic phyllites underlying the meta-gabbro (samples 1059, 1060, 1061 and 1067). Argillaceous phyllites and phyllonites consist of the assemblage phengite–chlorite–albite–quartz (± calcite, ± titanite, ± biotite, ± opaques, ± epidote). Mafic phyllites have the assemblage chlorite–epidote–albite–actinolite (± phengite, ± calcite, ± biotite, ± titanite, opaques).

3.b. Intermediate Unit
In the area around Panormos, Isternia and Marlas (north-west Tinos, Fig. 2), a complete section of this unit is exposed from its basal levels to the contact with the Upper Unit (Fig. 3). However, above the uppermost marble sequence (m3) exposed rocks are strongly weathered and not suitable for application of the Rb–Sr method. Between the upper and intermediate marble horizons a monotonous, flat-lying series of metasediments (several tens of metres in thickness) is exposed. A meta-oligotostrome with subangular to rounded marble clasts, which in places are strongly deformed and flattened, can be used as a mappable horizon to subdivide this sequence (Bröcker, 1990a). White mica was separated from two calcite-bearing siliciclastic metasediments (samples 1191 and 1193) which were collected a few metres above and below this layer, respectively. Both samples display greenschist-facies mineral assemblages. No glaucophane is present and garnet is only preserved as relict, partially replaced grains. For two similar samples from this succession (samples 85-51, 85-206) only whole rocks were isotopically analysed. From a structurally lower position within the same profile we have dated white mica from partially overprinted blueschist-facies quartz micaschists collected a few metres above (sample 85-10) and below (sample 85-221) the m2 marble sequence (Fig. 3).

In addition, two glauconphanes (= metabasic blueschists) closely associated with the m2 marble were investigated. Sample 87-8 was collected on top of the marbles near Isternia. Sample 85-223 was collected from a loose block in a quarry within the m2 marbles. The exact lithostratigraphic position is uncertain but we believe that this sample is derived from a horizon either within or on top of the m2 marble.

From the basal parts of the Intermediate Unit we have studied two calcschists (samples 91 and 128) which were collected above the lowermost m1 marble east of Panormos (Figs 2, 3) and a calcschist (sample 1076) which overlies the basal dolomite near the bay of Panormos. The latter occurrence was tentatively assigned by Avigad & Garfunkel (1989) to the Basal Unit but correct assignment to the Basal Unit is uncertain.

The Rb–Sr method was additionally applied to some samples which had already been dated with the 40Ar–39Ar technique (Bröcker et al. 1993). For this purpose we have selected three high-pressure rocks (samples 85-47, -61, -221) and four severely overprinted greenschist-facies rocks (85-90, -155, -340, 87-14). Sample descriptions and 40Ar–39Ar results are reported in Bröcker et al. (1993). Note that different splits of the same mica concentrates were used. Furthermore, the isotopic composition of metabasic rocks (blueschists: 119, 220, 343; greenschists: 85, 188, 196, 590) collected in various parts of the island was determined. Sample locations are indicated in Figure 2.


3.c. Garnet-bearing leucogranite

From the eastern part of the main intrusion, Bröcker & Franz (1994) described a deformed garnet-bearing leucogranite (Fig. 2) with the main assemblage quartz–potassic feldspar–plagioclase–garnet ± biotite.
Muscovite, tourmaline, allanite and Fe-ore may occur as additional constituents. In most cases, garnet can already be identified in hand-specimen with the unaided eye or by use of a hand lens. Modal proportions of biotite only reach up to about 2 vol. %. The leucogranite was affected by pervasive solid-state deformation and shows locally a weak gneissic texture (Fig. 6). Foliation is mainly defined by elongated quartz aggregates and microshear bands (Fig. 7).

4. Analytical methods

For the purpose of this study, we have only determined phengite chemistry in order to characterize the mica populations used for dating. Mineral analyses were carried out on the SX-50 CAMECA microprobes at the Department of Mineralogy in Würzburg and at the GeoForschungsZentrum in Potsdam. Operating conditions were 15 kV acceleration voltage, 10 nA beam current and counting times of 20–30 sec. The beam diameter was set at 3–5 μm. For standardization, natural and synthetic minerals were used. The raw data were corrected with a ZAF procedure using the PAP software provided by Cameca. Selected electron microprobe analyses are reported in Tables 1 and 2.

Isotope analyses were performed at the ‘Zentrallaboratorium für Geochronologie’ in Münster. For Rb–Sr analyses samples of about 1–2 kg weight were crushed with a jaw-breaker and in several steps further ground in a tungsten carbide mill for a few seconds. After sieving fines were removed and mineral separation was carried out by standard routines (Frantz magnetic separator, adherence to a piece of paper or a pane of glass). Mica pre-concentrates were ground under ethanol using an agate mortar to remove contaminants. Epidote was hand-picked under the stereomicroscope. All mineral concentrates (optically pure > 99 %) were washed in ethanol (p.a.) and H₂O (three times distilled) in an ultrasonic bath. Size fractions used range between 63 and 250 μm and are indicated for individual samples in Tables 3 and 4.

Mineral separates (white mica: 5–50 mg; epidote: 2–7 mg) and whole-rock powders (about 100 mg) were mixed with a 87Rb–86Sr spike in teflon screw-top vials and dissolved in a hot HF–HNO₃ (5:1) mixture. Rb and Sr were separated by standard ion-exchange procedures using 2.5 N HCl as eluant. Rb was loaded as chloride on a double Ta-filament assembly and analysed on a NBS-type Teledyne mass spectrometer with single Faraday collector. Sr was loaded with H₃PO₄ on single Ta filaments and analysed on a VG Sector 54 multicolonlector mass spectrometer in dynamic mode. Repeated measurements of the NBS-987 Sr standard yielded a mean 87Sr/86Sr ratio of 0.710252 ± 0.000046 (2σ; n = 137) during the period of this study. No corrections by reference to the NBS-987 standard values were made. 87Sr/86Sr ratios were corrected for mass fractionation by normalizing to a 86Sr/88Sr ratio of 0.1194. Rb ratios were corrected for mass fractionation using a factor deduced from measured values of Rb standard NBS 607. Total procedural blanks did not exceed 0.05 ng for Rb and 0.1 ng for Sr (87Sr/86Sr ratio of blank: 0.71). The 87Rb/86Sr ratios were assigned uncertainties of 1%; uncertainties for the 87Sr/86Sr ratios are reported on the 2σ level and include the within-run precision, an estimated uncertainty of 0.1 % for the 87Sr/86Sr spike ratio, the error magnification based on the spike/sample ratio and the blank correction. Rb–Sr ages were calculated using the least square regression technique of York (1969); errors are reported on the 2σ level. A decay constant of λRb 1.42 × 10⁻¹¹/a⁻¹ (Neumann & Huster, 1974) was used for age calculations. The analytical results and apparent ages are reported in Tables 3, 4 and 5.

5. Results

5.a. Mineral chemistry

Previous work has shown that greenschist-facies rocks from the Cyclades commonly contain mixed white mica populations composed of phengites with different Si values which are related to various stages of the metamorphic evolution (e.g. Wijbrans, Schliestedt & York, 1990; Bröcker et al. 1993). In many cases, high-Si phengite...
which crystallized under high-pressure conditions still is present in samples which experienced a pervasive re-equilibration during the greenschist overprint. Because dating of mica populations composed of multiple generations may result in mixed ages without geological significance, we have analysed phengite compositions of most samples studied (Table 1, 2) in order to characterize compositional variability. Mica compositions of samples already dated with the 40 Ar–39 Ar method were reported in Bröcker et al. (1993).

New microprobe data for metasediments from the Intermediate Unit and previously published analyses indicate that most phengites of blueschist- and greenschist-facies rocks contain 6.6 to 6.9 Si p.f.u. (based on 22 oxygens). A bimodality in the Si values was recognized, indicated by the presence of variable amounts of phengite with about 7.0 to 7.4 Si p.f.u. (Table 1). In a few greenschist-facies samples, a limited degree of recrystallization during the overprint was recognized by Si-values at 6.7–6.8 and 7.1–7.2, respectively. Molecular proportions of paragonite component (100*Na/(Na+K+Ca+Ba)) are variable and reach up to 7.8 mol. %. \( \text{XMg} = \frac{\text{Mg}}{(\text{Mg}+\text{Fe}^\text{tot})} \) varies between 0.63 and 0.83. The sum of interlayer cations (K, Na, Ca, Ba) is between 1.66 and 1.88.

In the Upper Unit, phengite compositions mainly vary between 6.3 and 6.9 but mostly have Si values of 6.7 and 6.8 (Table 2). In samples from Stavros, Si values may reach up to 7.1, however, because of the small grain size we cannot rule out beam overlap on neighbouring phases. Within-sample variation appears to be smaller than in the Intermediate Unit. Micas from sample 1096 are characterized by low Si values which range between 6.3 and 6.5. Many phengite analyses are characterized by unusually high Mg [Mg > (Si-6)] which indicate the presence of submicroscopic mica–chlorite intergrowths. Note that the small amounts of secondary white mica in meta-gabbros (sample 1054) are very rich in Cr₂O₃ with concentrations in the range from 1.6–8.8 wt %.

### 5.b. Rb–Sr dating

For Rb–Sr analyses we selected eight samples from the Upper Unit, 24 samples from the Intermediate Unit, one sample from the Basal Unit and four samples of leucogranite. Altogether about 80 Rb–Sr analyses were carried out. Analytical data and ages are reported in Tables 3, 4 and 5. A compilation of all available radiometric data from Tinos is depicted in Figure 3 which shows a schematic columnar section of the metamorphic sequence. Our results can be summarized as follows.

#### 5.b.1. Upper Tectonic Unit

For phyllitic rocks from the Upper Unit we have obtained phengite–whole-rock apparent ages of 20.8 ± 2.1 Ma (Kionia, sample 1096), 28.3 ± 1 Ma (Stavros, sample 1060) and c. 92 Ma (Kleftovouni, sample 1159). A con-
tact metamorphic phylite from the outer aureole (sample 1157) provided an age of 16.6 ± 0.5 Ma. Sample 1054 collected from the strongly deformed marginal parts of the meta-gabbro at Stavros yielded a Rb–Sr date of about 39 Ma.

The considerable difference in Rb and Sr concentrations obtained for two phengite aliquots of sample 1096 (Table 3) is difficult to explain. Sample contamination is considered unlikely. These differences may indicate that the two bulk concentrates are composed of different mixtures of compositionally heterogeneous phengites. This assumed compositional range is not recorded in electron microprobe analyses which provided rather homogeneous major element compositions (Table 2). Note that chemical zoning was not investigated.

In addition to conventional dating of phengite–whole-rock pairs, we have also applied the Rb–Sr thin-slab method to sample 1059. A small-scale profile (12 cm long, 2 cm broad, 1 cm thick) was cut into small slabs according to variation in compositional layering; each slab was treated as a whole-rock sample. Examination of nine slabs indicated overall low Rb/high Sr concentrations resulting in a very low spread of the Rb/Sr ratios which did not allow calculation of a geologically meaningful age. Initial *Sr*/Sr ratios of metabasic phyllites (1059, 1060, 1061, 1067) calculated for an assumed Jurassic protolith age (180 Ma) range from 0.7033–0.7041.

5.b.2. Intermediate Unit (= Blueschist–Greenschist Unit)

Two metasediments collected between the m3 and m2 horizons (sample 1192 and 1193) recorded white mica ages of 37.4 ± 0.4 and 39.9 ± 0.7 Ma, respectively. For partially overprinted blueschist-facies metasediments (85-10, 85-221) apparent phengite ages of 39.5 ± 0.4 Ma and 32.5 ± 0.6 Ma were obtained. Whole-rock samples of five metasediments from the same structural level yielded measured *Sr*/Sr ratios between 0.70961 and 0.71359 and define an errordochron date of 42.2 ± 7 Ma (MSWD = 6). The metabasic blueschist 223 yielded an apparent white mica age of 37.4 ± 0.4 Ma. No meaningful result could be calculated for the metabasic blueschist sample 8 and 530 because white mica is paragonite with very low Rb concentrations (< 1 ppm).

Greenschist-facies calcschists collected above the marble horizon m1 (samples 91, 128) yielded phengite ages which range between 23.5 and 22.4 Ma. A similar age (21.7 ± 0.2 Ma) was obtained for sample 1076 which was collected from a calcschist overlying the basal dolomite near the bay of Panormos which Avigad & Garfunkel (1989) tentatively assigned to the Basal Unit.

Meta-acidic greenschist-facies rocks of the Intermediate Unit which were dated with both the Rb–Sr (whole rock, phengite, epidote) and *Ar*/Ar (phengite) methods yielded almost concordant ages which cluster between 23 and 21 Ma (Table 4). For blueschist-facies rocks dated with both methods, Rb–Sr ages are about 3–12 Ma younger than *Ar*/Ar dates. The greatest age difference is observed for sample 221 (Table 4) which shows the strongest greenschist-facies overprint, suggesting that the resetting of the Rb–Sr date mainly reflects
disturbance of the whole-rock system.

Rb concentrations of metabasic rocks collected in various parts of the island range between < 1 and 77 ppm. Sr contents vary between 43 and 310 ppm. Measured \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios of blueschists and greenschists range from 0.7054 to 0.7087 and 0.7046 to 0.7071, respectively (Table 4; Fig. 8). Both groups display no isochron relationship in a Rb/Sr vs. Sr/Sr diagram (Fig. 8). Initial strontium ratios calculated for an estimated Jurassic protolith age of 180 Ma vary between 0.7044 and 0.7068 for blueschists and between 0.7027 and 0.7065 for greenschists. Blueschists and greenschists have similar bulk-rock compositions and display affinities to mid-ocean ridge basalts or island-arc tholeiites (Bröcker, 1991). Both rock types show large compositional variations, especially in the CaO and CO\(_2\) contents, which were related to carbonate admixture, spilitization or synmetamorphic redistribution processes (Bröcker, 1991). Although it cannot be ruled out that the observed range in initial \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios (0.7045–0.7087) reflects primary characteristics of the mantle source or variable contamination by crustal material, we consider seawater alteration as the most likely reason for the heterogeneous isotopic compositions.

5.b.3. Leucogranite

The four studied samples of leucogranite have relative uniform Rb and Sr concentrations which range from 269–299 ppm and 11–22 ppm (Table 5). The isotopic whole-rock compositions yield an isochron which corresponds to an age of 15.1 ± 0.6 Ma (Fig. 9), interpreted as the estimate for the time of intrusion.

6. Discussion and conclusions

6.a. Time constraints for metamorphism and tectonic juxtaposition of the Upper Unit

Avigad & Garfunkel (1989, 1991) recognized that tectonic juxtaposition of the Upper Unit (Figs 1, 2) took place at least 18 Ma ago apparently in the time interval between the greenschist metamorphism of the Lower Unit and the intrusion of the granite which thermally overprinted both units. Our limited Rb–Sr results suggest that tectonic juxtaposition may have occurred earlier than deduced from field relations. Phyllitic rocks from the Upper Unit collected at three different locations yielded inconsistent apparent ages (phengite–whole-rock) between c. 92 and 21 Ma, clearly indicating disturbance of the isotopic system. It is currently uncertain if this disturbance occurred before or after tectonic juxtaposition or is related to the emplacement process. However,

---

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type*</th>
<th>Grade†</th>
<th>Rock or mineral</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>(^{87}\text{Rb}/^{86}\text{Sr})</th>
<th>(^{87}\text{Sr}/^{86}\text{Sr}) ± 2σ</th>
<th>Age (Ma) ± 2σ‡</th>
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<td>1096</td>
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<td>Phengite(^{1})</td>
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<td>61.2</td>
<td>15.22</td>
<td>0.71653 ± 2</td>
<td>20.8 ± 2.1‡</td>
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<td>0.71429 ± 2</td>
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<td>0.71422 ± 2</td>
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</tr>
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<td>GS</td>
<td>Whole rock</td>
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<td>0.08</td>
<td>0.70427 ± 2</td>
<td>28.3 ± 1†</td>
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<td>GS</td>
<td>Whole rock</td>
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<td>27.4</td>
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<td>0.70872 ± 3</td>
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<td>GS</td>
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<td>0.71091 ± 2</td>
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<td>119.6</td>
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<td>39.0 ± 0.4</td>
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<td>MS</td>
<td>CM</td>
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<td>108.7</td>
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<td>1157</td>
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<td>GS</td>
<td>Phengite(^{3})</td>
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<tr>
<td>1159</td>
<td>MS</td>
<td>GS</td>
<td>Phengite(^{3})</td>
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<td>0.73439±4</td>
<td>92.4 ± 1.4</td>
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<td>MB</td>
<td>GS</td>
<td>Whole rock</td>
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<td>198.8</td>
<td>0.003</td>
<td>0.70373±2</td>
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<td>Whole rock</td>
<td>2.3</td>
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<td>0.70386±2</td>
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<td>0.70388±2</td>
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<td>Whole rock</td>
<td>6.0</td>
<td>191.8</td>
<td>0.09</td>
<td>0.70387±2</td>
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<td>0.70376±2</td>
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<td>Whole rock</td>
<td>15.2</td>
<td>222.6</td>
<td>0.20</td>
<td>0.70394±2</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations:
* MB = metabasic phyllite; MG = meta-gabbro; MS = meta-argillaceous phyllite.
† GS = greenschist facies; CM = contact metamorphism.
‡ All phases included in age calculation.
\(^1\) = 125–63 \(\mu\)m; \(^2\) = 180–125 \(\mu\)m; \(^3\) = 200–180 \(\mu\)m.
we assume that this spread results from emplacement-related non-pervasive rejuvenation of the Rb–Sr system. In our view, the strongly deformed and partially mylonitized phyllite sequence (which in part is imbricated with small lenses of serpentinite and meta-gabbro) represents an emplacement-related ductile shear zone. The youngest age obtained from a sample collected close to the tectonic contact is believed to date the timing of juxtaposition. We suggest that tectonic stacking and related deformation of the phyllite sequence occurred already in the course of the metamorphic events which caused greenschist overprints in both units. \(P-T\) constraints for the last metamorphism in both units appear to be similar (\(T: 400–500\, ^\circ\text{C};\) \(P: 4–7\, \text{kbar};\) Bröcker, 1990a; Katzir et al. 1996; Stolz, Engi & Rickli, 1997), and the youngest apparent age obtained from a phyllite collected close to the tectonic contact (\(\sim 21\, \text{Ma}\)) corresponds very well to \(^{40}\text{Ar}/^{39}\text{Ar}\) and Rb–Sr phengite ages of greenschist-facies rocks from the structurally lower unit (\(\sim 21\) to 23 Ma; Altherr et al. 1982; Bröcker et al. 1993). This interpretation is supported by results of Stolz, Engi & Rickli (1997) who recognized identical mesoscopic structural characteristics.

### Table 4. Rb-Sr data from the Intermediate and Basal Unit on Tinos

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type*</th>
<th>Grade†</th>
<th>Rock of mineral</th>
<th>(\text{Rb}) (ppm)</th>
<th>(\text{Sr}) (ppm)</th>
<th>(^{87}\text{Rb}/^{86}\text{Sr})</th>
<th>(^{86}\text{Sr}/^{86}\text{Sr})</th>
<th>(\pm 2\sigma)</th>
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<td><strong>Intermediate Unit</strong></td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>47 MB BS</td>
<td>BS</td>
<td>Whole rock</td>
<td>56.4</td>
<td>110.4</td>
<td>1.48</td>
<td>0.70820 ± 3</td>
<td>36.9 ± 0.4</td>
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<td>61 MB BS</td>
<td>BS</td>
<td>Whole rock</td>
<td>257.8</td>
<td>5.3</td>
<td>141.64</td>
<td>0.78165 ± 3</td>
<td>(43.8 ± 0.2)†</td>
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<td>223 MB BS</td>
<td>BS</td>
<td>Whole rock</td>
<td>48.2</td>
<td>182.4</td>
<td>0.76</td>
<td>0.70060 ± 2</td>
<td>39.0 ± 0.1</td>
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<td>BS</td>
<td>Phengite²</td>
<td>225.8</td>
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<td>102.87</td>
<td>0.76332 ± 3</td>
<td>(42.3 ± 0.2)†</td>
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<td>530 MB BS</td>
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<td>Whole rock</td>
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<td>79.0</td>
<td>0.01</td>
<td>0.70590 ± 3</td>
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<td>119 MB BS</td>
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<td>Whole rock</td>
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<td>0.70636 ± 3</td>
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<td>Whole rock</td>
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<td>43.6</td>
<td>0.07</td>
<td>0.70563 ± 2</td>
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<td>220 MB BS</td>
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<td>236.2</td>
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<td>0.70543 ± 2</td>
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<td>0.70516 ± 2</td>
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<td>Whole rock</td>
<td>300.2</td>
<td>15.1</td>
<td>57.69</td>
<td>0.72865 ± 3</td>
<td>(32.5 ± 0.2)†</td>
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<tr>
<td>1192 GS</td>
<td>BS</td>
<td>Whole rock</td>
<td>54.4</td>
<td>222.0</td>
<td>0.71</td>
<td>0.70961 ± 2</td>
<td>37.4 ± 0.4</td>
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<td>Whole rock</td>
<td>352.0</td>
<td>19.6</td>
<td>51.89</td>
<td>0.73681 ± 3</td>
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<td>187.6</td>
<td>121.3</td>
<td>4.48</td>
<td>0.71209 ± 2</td>
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<td>0.76310 ± 3</td>
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<td>Whole rock</td>
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<td>210.6</td>
<td>0.86</td>
<td>0.70993 ± 2</td>
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<td>59.8</td>
<td>7.03</td>
<td>0.71359 ± 2</td>
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<td>8.9</td>
<td>66.10</td>
<td>0.72562 ± 2</td>
<td>21.0 ± 0.9‡</td>
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<td>Whole rock</td>
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<td>159.5</td>
<td>0.88</td>
<td>0.70614 ± 2</td>
<td>(21.6 ± 0.1)†</td>
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<td>Whole rock</td>
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<td>10.6</td>
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<td>0.72120 ± 2</td>
<td>(23.3 ± 0.1)†</td>
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<td>1076 CS GS</td>
<td>BS</td>
<td>Whole rock</td>
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<td>831.5</td>
<td>0.16</td>
<td>0.70842 ± 2</td>
<td>21.7 ± 0.2</td>
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</tr>
</tbody>
</table>

Abbreviations:

* MB = metabasic rock; QMS = quartz micaschist; CMS = calcareous micaschist; CS = calcschist; MA = meta-acidic rock.
† BS = blueschist facies; GS = greenschist facies.
‡ All phases included in age calculation.
† In parentheses and italics ages obtained by Bröcker et al. (1993) using the \(^{40}\text{Ar}/^{39}\text{Ar}\) technique are reported.

Table 4. Rb-Sr data from the Intermediate and Basal Unit on Tinos.
in both units. These authors concluded that tectonic juxtaposition of the Upper Unit and subsequent deformation of both units occurred during the same episode of green-schist-facies metamorphism. A more complete understanding of the deformational and metamorphic processes requires additional geochronological studies (currently in progress), especially on the fine and very-fine grained size fractions (< 20 \( \mu \text{m} \)) of phengite which probably will allow dating of the youngest tectono-metamorphic phase.

The age of the main meta-gabbro–serpentinite–phyllite association is poorly constrained and the commonly assumed Late Cretaceous age (\( \approx 70 \) Ma) is currently not supported by published geochronological data. Only for amphibolitic rocks, K–Ar dates around 70 Ma were previously reported (Patzak, Okrusch & Kreuzer, 1994). The phyllonite 1159 from the Kleftovouni area was dated at \( \approx 92 \) Ma using phengite and plagioclase of the size fraction 200–180 \( \mu \text{m} \) which obviously represents a texturally earlier stage than the dominant smaller phengite size fractions. The geological significance of this date needs to be substantiated by further studies. In any case, this preliminary result indicates an age \( > 70 \) Ma and suggests that the Tinos ophiolite sequence is older than previously assumed. Unfortunately, the meta-gabbros and ultrabasic rocks are not very suitable for geochronological studies, but on mainland Greece and on Crete, Jurassic ophiolites are widespread (see, for example, Seidel et al. 1981; Koepke, Kreuzer & Seidel, 1985).

### 6.b. Comparison between Rb–Sr and \( \text{\textsuperscript{40}}\text{Ar–\textsuperscript{39}}\text{Ar} \) results from the Intermediate Unit

Time constraints for the metamorphic evolution of the Intermediate Unit were established by previous geochronological studies using the \( \text{\textsuperscript{40}}\text{Ar–\textsuperscript{39}}\text{Ar} \) and K–Ar technique (Altherr et al. 1982; Bröcker et al. 1993). However, combined application of different isotopic systems to the same samples has indicated that the \( \text{\textsuperscript{40}}\text{Ar–\textsuperscript{39}}\text{Ar} \) method can yield geologically meaningless dates even if well-defined plateaus are developed, because of undetected excess argon (e.g. Tomarini et al. 1993; Li et al. 1994; Arnaud & Kelley, 1995).

Despite considerable differences in assumed closure temperatures (\( \text{\textsuperscript{40}}\text{Ar}–\text{\textsuperscript{39}}\text{Ar} \): 350±50°C for phengite; \( \text{Rb–Sr} \): 500±50 °C for phengite) the \( \text{Rb–Sr} \) method always gave lower dates for blueschist-facies rocks than the \( \text{\textsuperscript{40}}\text{Ar–\textsuperscript{39}}\text{Ar} \) technique for samples from Tinos. For greenschist-facies rocks both methods yielded concordant results. We assume that the younger \( \text{Rb–Sr} \) dates of blueschist-facies rocks result from partial rejuvenation of the \( \text{Rb–Sr} \) system during retrograde processes as already suggested by Altherr et al. (1979) for similar rocks from Sifnos, but it should also be noted that previously published Ar age spectra (Bröcker et al. 1993) show variable internal complexity and disturbance which is not fully understood. Possible explanations include: (a) Ar retention was disturbed by multiple episodes of dynamic recrystallization; (b) mixed paragonite/phengite populations are influenced by different degassing behaviour; (c) incorporation of undetected excess Ar; and (d) disturbance caused by breakdown-reactions during uplift (all blueschists show at least incipient retrogression). An unambiguous inter-

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**Table 5. Rb–Sr data of leucogranite whole rock samples from Tinos**

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \text{Rb} ) (ppm)</th>
<th>( \text{Sr} ) (ppm)</th>
<th>( \text{\textsuperscript{87}}\text{Rb}/\text{\textsuperscript{86}}\text{Sr} )</th>
<th>( \text{\textsuperscript{87}}\text{Sr}/\text{\textsuperscript{86}}\text{Sr} ) ± 2σ</th>
<th>Age (Ma) ± 2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1118</td>
<td>285.8</td>
<td>12.7</td>
<td>65.47</td>
<td>0.72449 ± 2</td>
<td>15.1 ± 0.6</td>
</tr>
<tr>
<td>1124</td>
<td>269.0</td>
<td>11.2</td>
<td>69.44</td>
<td>0.72503 ± 2</td>
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</tr>
<tr>
<td>1125</td>
<td>290.0</td>
<td>11.6</td>
<td>72.52</td>
<td>0.72590 ± 2</td>
<td></td>
</tr>
<tr>
<td>1128</td>
<td>298.6</td>
<td>22.0</td>
<td>39.40</td>
<td>0.71877 ± 3</td>
<td></td>
</tr>
</tbody>
</table>

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**Figure 8.** \( \text{\textsuperscript{87}}\text{Rb}/\text{\textsuperscript{86}}\text{Sr} \) vs. \( \text{\textsuperscript{87}}\text{Sr}/\text{\textsuperscript{86}}\text{Sr} \) diagram for metabasic rocks from the Upper Unit (phyllites) and Intermediate Unit (blueschists and greenschists).

**Figure 9.** Rb–Sr isochron diagram for whole-rock samples of deformed garnet-bearing leucogranite.
preparation of the $^{40}$Ar–$^{39}$Ar and Rb–Sr isotopic results is not possible but in any case the phengite dates obtained with both isotopic systems at least constrain a lower time limit for the blueschist metamorphism. The relatively small age difference obtained for high-pressure samples suggests that contamination with excess argon, if at all, is only of limited importance. Thus, combined application of both dating techniques broadly confirms the geological significance of previously published K–Ar and $^{40}$Ar–$^{39}$Ar data from the Intermediate Unit.

If we suppose that the estimates for closure temperatures are correct, the concordant greenschist dates may indicate (a) very rapid cooling from $T_{\text{max}}$ (estimated at 450–500 °C) through the closure temperature of Ar in phengite (350 ± 50 °C) in a time interval which cannot be resolved by combination of the Rb–Sr and $^{40}$Ar–$^{39}$Ar methods; or that (b) recrystallization of phengite occurred below $T_{\text{max}}$ around or below the closure temperature for Ar in phengite. It should be noted that white mica populations of greenschist-facies rocks are compositionally heterogeneous because of incomplete re-equilibration during the overprint (Bröcker et al. 1993). Variable amounts of phengites related to the blueschist event often still are present and cause the typical convex-upward Ar release patterns observed in many overprinted rocks of the Cyclades (Wijbrans & McDougall, 1986; Bröcker et al. 1993). The $^{40}$Ar–$^{39}$Ar and Rb–Sr dates obtained from these mixed mica populations can only be interpreted as upper time limit for the last overprint.

6.c. Extent of infiltration-controlled overprinting in the Intermediate Unit

Petrographic studies (Bröcker, 1990a; Bröcker et al. 1993) have documented an intimate interlayering of blueschist- and greenschist-facies rocks in the upper parts of the Intermediate Unit. The results of this study and previously published $^{40}$Ar–$^{39}$Ar data indicate a gradient in metamorphic ages, at least for northwest Tinos. The youngest apparent ages (24–21 Ma) were obtained for samples from the lower part of the Intermediate Unit suggesting that the basal parts experienced a stronger overprint (cf. Melidonis, 1980). Older apparent ages (> 37 Ma) were obtained for samples from the upper parts of the Intermediate Unit, except for a greenschist horizon (c. 29 Ma) within the m3 marbles (Fig. 3). Even for samples which show pervasive greenschist-facies overprint (1192, 1193), as indicated by the complete replacement of blue amphibole by chlorite and albite, Rb–Sr ages of 37–40 Ma were obtained. The higher degree of isotopic homogenization at structurally lower levels and within the m3 marble is interpreted as a result of higher rates of fluid influx, possibly controlled by variable intensity of deformation which enhanced permeability (Ganor et al. 1996). Note that also on Sifnos and Syros the basal parts of the succession experienced a stronger greenschist-facies overprint (see also Ganor et al. 1996), whereas well-preserved high-pressure rocks occur at higher lithostratigraphic positions. From Tinos, similar field relations were already described by Melidonis (1980).

6.d. Relationship between magmatism and deformation

In contrast to the main pluton which only shows a weak magmatic foliation (see, for example, Faure, Bonneau & Pons, 1991; Boronkay & Doutsos, 1994) the studied leucogranite was affected by solid-state deformation (e.g. ductilely deformed quartz, fractured feldspars). Obviously emplacement of the main intrusion and subsequent solidification occurred in a period of relative tectonic quiescence. During our brief examination of the leucogranite, detailed structural mapping was not performed and we have not collected orientated samples from the granite and the associated wall-rocks. It is therefore uncertain whether the deformational characteristics indicate forcible emplacement or are related to regional strain. However, we note that the young intrusion on the neighbouring island of Mykonos (12–10 Ma, K–Ar and Rb–Sr amphibole and biotite: Altherr et al. 1982) experienced strong post-emplacement deformation (e.g. Faure et al. 1991; Lee & Lister, 1992) and tentatively attribute the deformation of the Tinos leucogranite to the same regional process. Rb–Sr whole-rock dating of the leucogranite yielded a whole-rock isochron of 15.1 ± 0.6 Ma which is slightly older than the 14.0 ± 0.1 Ma age reported by Altherr et al. (1982) for a similar garnet-bearing granite from the southern apex of the main intrusion. This suggests intrusion of different leucogranitic magma pulses with distinct emplacement ages.

7. Summary

Previously published age-data (mainly based on the $^{40}$Ar–$^{39}$Ar and K–Ar technique) has resulted in an apparently straightforward picture of the evolution of the Attic-Cycladic Crystalline Belt recognizing two important Tertiary metamorphic episodes in the group of lower units (Eocene and Oligocene–Miocene events) and Cretaceous ages for metamorphic rocks which belong to the group of upper units. Our study on Tinos indicates a more complex pattern of age data than previously documented. The results of this study strongly suggest that the ophiolite sequences of the Cyclades belong to the group of Jurassic ophiolites in the Hellenides which is in contrast to the previously assumed Cretaceous origin. The spread to younger ages in the Upper Unit is related to variable rejuvenation and resetting during tectonic juxtaposition onto the Blueschist–Greenschist Unit. Together with petrological and structural observations (Katz et al. 1996; Stolz, Engi & Rickli, 1997), the new geochronological data support the interpretation that emplacement of the Upper Unit on the Intermediate Unit occurred during an episode of greenschist-facies metamorphism affecting both units contemporaneously. This conclusion also provides a sound explanation for the considerable scatter in Cretaceous K–Ar dates reported for upper unit
rocks from the Cyclades (e.g. Patzak, Okrusch & Kreuzer, 1994, and references therein), which appears to be related to variable Ar loss due to thermal rejuvenation or deformational resetting during Tertiary events.

Timing of thrusting of the structurally higher units over the Basal Unit probably also coincides with the greenschist metamorphism. Note that the metamorphic grade indicated by the mineral assemblages of phyllitic rocks from the Basal Unit is not different to the greenschist conditions in the overlying units. Although we have not systematically investigated this hypothesis, the stronger greenschist-facies resetting in the lower parts of this unit, as indicated by clustering of ages at 24–21 Ma, suggests a relationship between thrusting of the Intermediate Unit on the Basal Unit and degree of overprinting. The gradient in ages from the top to the bottom of the Intermediate Unit is suggested to represent the greater effects of fluid infiltration in the lower parts of this unit, probably enhanced by thrust zone-related increase in permeability. Matthews et al. (1995) recognized that the tectonic contact between both units is defined by a small mylonitic zone (2–3 m wide), but deformation-related microfabrics were observed in an approximately 100-m-wide section. Oxygen isotope studies suggest fluid-lubricated fault movement with channeled fluid-infiltration (Matthews et al. 1995). We assume that fluid flux was not restricted to the immediate thrust zone but may have affected larger rock volumes at the base of the Intermediate Unit where deformation-enhanced fluid infiltration has catalysed retrograde mineral reactions and associated resetting of the Sr isotope system. If this is true, the group of ages between 23 and 21 Ma provides at least an upper time limit for thrust zone activity.

In conclusion, available geochronological and petrological data indicate synmetamorphic stacking of all three tectonic units during an Oligocene–Miocene greenschist event. Chronological differences between discrete fault movements on top and at the base of the Intermediate Unit cannot currently be established from field observations or geochronological results. Application of the Rb–Sr method to white micas already dated by means of the Rb–Sr isotope system. If this is true, the group of ages between 23 and 21 Ma provides at least an upper time limit for thrust zone activity.

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