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Isotopic age study of pre-Alpine rocks in the basal units on Naxos, Sikinos and Ios, Greek Cyclades

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Abstract

Isotopic dating proves the existence of pre-Alpine basement rocks on the islands of Naxos, Sikinos and Ios in the Greek Cyclades. The U-Pb systematics of a suite of zircons from the migmatite dome on Naxos shows that the main generation of zircons of late Paleozoic age contains a minor amount of old radiogenic lead. Rb-Sr analysis of whole rock samples of a metadiorite on Sikinos substantiates the existence of a late Paleozoic or early Mesozoic basement. K-Ar analysis of white micas from the augengneiss on Ios revealed ages of about 125 Ma to about 23 Ma, intermediate between the Hercynian and the Alpine orogenesis. On the basis of textural- and chemical characteristics it is suggested that some of these micas represent partially reset Hercynian micas, other Alpidic micas with excess radiogenic Ar, and a few reflect a complete rejuvenation during the Alpine orogenesis.

Introduction

The metamorphic complexes of the Cycladic islands (Fig. 1) form the middle part of the Attic-Cycladic Massif, the Alphine belt of regionally metamorphosed rocks of various metamorphic facies that stretches from mainland Greece into Turkey (Dixon 1968); Jansen & Schuiling 1976; Dürr et al. 1978, Van der Maar & Jansen 1983). Lithological correlation within the Massif is hampered by tectonic displacements (up into the Lower Pliocene and younger), the scattered distribution of the islands, and the scarcity of fossils due to the strong Alpine metamorphism. Only a few horizons containing iron-rich metabauxite (diasporite) in the marbles and lenses of metamorphosed eclogitic, volcanic, ultramafic and gabbroic rocks in the schists are considered to provide markers for lithological correlation between the Cycladic islands, the Menderes Massif in Turkey and the Euboea-Attica Massif in Greece (Jansen & Schuiling 1976; Van der Maar & Jansen 1983; Feenstra 1985).

The Attic-Cycladic Massif essentially is a nappe pile (Dürr et al. 1978). Within the Alpine metamorphic complexes of the Cycladic islands (currently designated as "massifs") at least two major thrust units can be recognised (Jansen & Schuiling 1976; Altherr & Seidel 1977; Dürr et al. 1978; Van der Maar et al. 1981; Henjes-Kunst & Kreuzer 1982; Van der Maar & Jansen 1983). The upper unit, designated here as the "Series", is an alternation of marbles and schists representing isoclinally folded metasediments and metavolcanics of presumably Mesozoic age (Dürr et al. 1978). The basal unit is complex, consisting of various schists, gneisses and metamorphic intrusives. Both the basal unit and the overthrust unit were affected by intense Alpine metamorphism, in which two phases are recognised (Schuiling 1973; Dürr et al. 1978; Van der Maar 1981): an older high-pressure/medium-temperature M1 phase under the conditions of the glaucophane-schist facies and a youn-

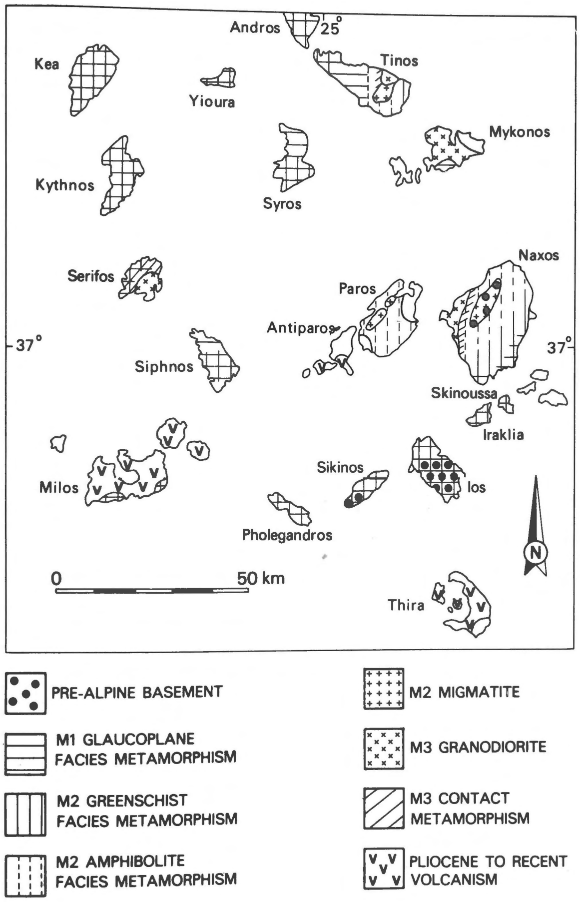

Fig. 1. Map of Cyclades, Greece, showing the distribution of the metamorphic rocks (after Van der Maar & Jansen, 1983).

ger Barrovian-type M2 phase under the conditions of different grades of the greenschist facies. Isotopic age studies on several Cycladic islands have attributed an age of approximately 45 Ma (Eocene) to the M1 phase and of approximately 23 Ma (Oligocene/Miocene) to the M2 phase (Andriessen et al. 1979); Altherr et al. 1982; Bonneau et al. 1980; Altherr et al. 1979; Wijbrans 1985; Wijbrans & McDougall 1986).

This paper reports the results of isotopic age studies of rocks from the basal unit on Naxos, Sikinos and los (Fig. 1). On Naxos (Fig. 2) the migmatitic gneiss dome in the NE part of the island is interpreted as the basal unit, separated from the upper part of the metamorphic complex by a thrustplane characterised by ultramafic lenses (Jansen 1973). During the M2 phase of Alpine metamorphism, 23 Ma ago, a temperature of some 600–700° C prevailed in the dome for several million years (Jansen & Schuiling 1976; Jansen 1977; Andriessen et al. 1979), leading to partial melting and thorough reworking of the constituent rocks and the development of a sequence of metamorphic zones surrounding the dome (Jansen & Schuiling 1976). After the termination of M2 a regime of relatively fast uplift and cooling prevailed between about 15 and 10 Ma ago (Andriessen 1982). The aplitic-pegmatitic phase of the granodioritic mass in western Naxos was dated at 11.1 ± 0.7 Ma (Andriessen et al. 1979), but the intrusion itself is probably somewhat older. So far, there was no isotopic evidence whatsoever to prove the existence of pre-Alpine components in the basal unit.

On Sikinos, the basal unit is exposed in the SE part of the island (Fig. 3). It consists of a sequence of quartz-chlorite-mica-garnet schists with several bodies of metadioritic intrusions (Van der Maar et al. 1981). These metadiorites resemble those in the basal unit of the adjacent island of Ios (see below) in geological setting, mineralogical composition (including brown hornblende and red-brown biotite) and replacement textures. A thrustplane separates the basal unit from the overlying marble-schist series (Fig. 3). Both the basal unit and the overthrust unit were affected by intense Alpine metamorphism. No isotopic evidence for a pre-Alpine history of the rocks of the basal unit has been reported so far.

Pre-Alpine ages were reported for rocks from the basal unit on Ios by Henjes-Kunst & Kreuzer (1982). The basal unit, which occupies the greater part of the island (Fig. 4), consists essentially of an orthogneiss dome mantled by an envelope of schists, augengneisses and bodies of intrusive granitic to tonalitic as well as gabbroic rocks. Henjes-Kunst & Kreuzer (1982) interpreted the isotopic data they obtained to indicate that an igneous mass of granitic-tonalitic composition has intruded between 520 and 460 Ma ago into a sequence of marble-free sedimentary rocks of unknown age, after which both the intrusion and the country rocks were metamorphosed in Hercynian time, approximately 300 Ma ago, under amphibolite-facies con-

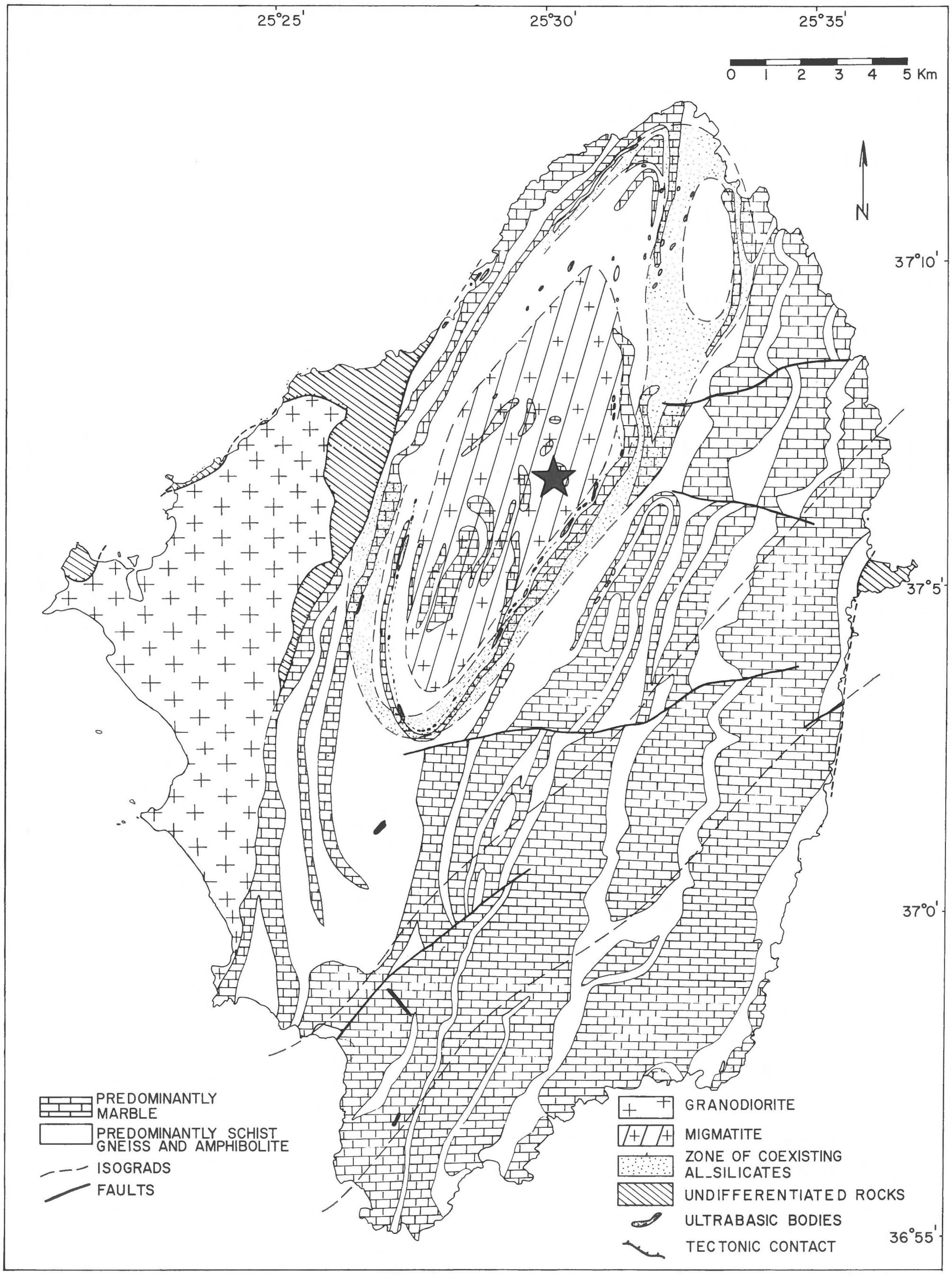

Fig. 2. Simplified geological map of Naxos, Greece (after Jansen, 1977). Asterisk, location of sample NAX 363.

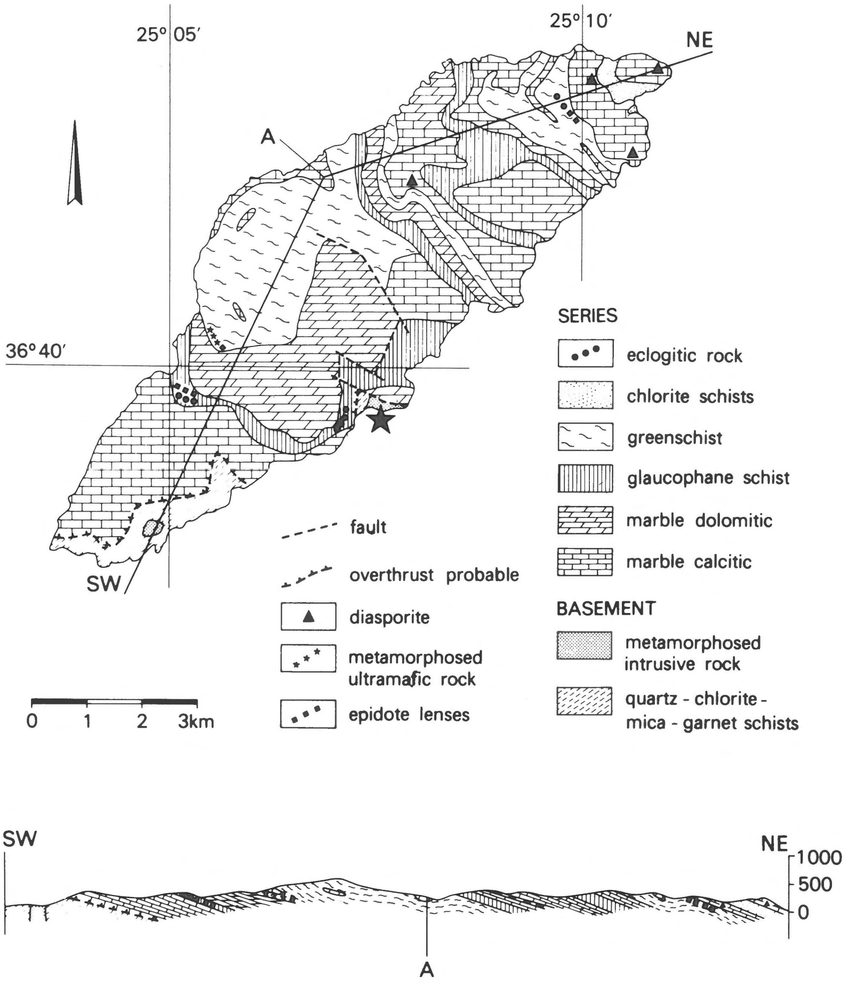

Fig. 3. Simplified geological map of Sikinos, Greece (after Van der Maar et al., 1981). Asterisk, location of the metadiorite samples SIK A to SIK E.

ditions. Both the Paleozoic basal unit and the overthrust sedimentary series of presumably Mesozoic age have been affected by intense Alpine metamorphism (Van der Maar 1981).

The purpose of the present study was to investigate whether any isotopic evidence could also be obtained for an older, pre-Alpine history in the basal unit on Naxos and Sikinos. K-Ar analyses were performed on minerals from the gneiss dome on Ios, to establish a possible relation between age, texture and chemical characteristics.

Experimental procedures and constants

Zircon was recovered from the ground sample by, successively, density separation using bromoform and di-iodomethane with a large overflow centrifuge (modified after Verschure & IJlst 1966), density separation using Clerici solution with a small overflow centrifuge (IJlst 1973), magnetic separation using a Frantz isodynamic separator, and hand-picking. Chemical decomposition and separation of uranium and lead were essentially according to Krogh (1973), followed by purification of the lead by anodic deposition (Arden & Gale 1974). U

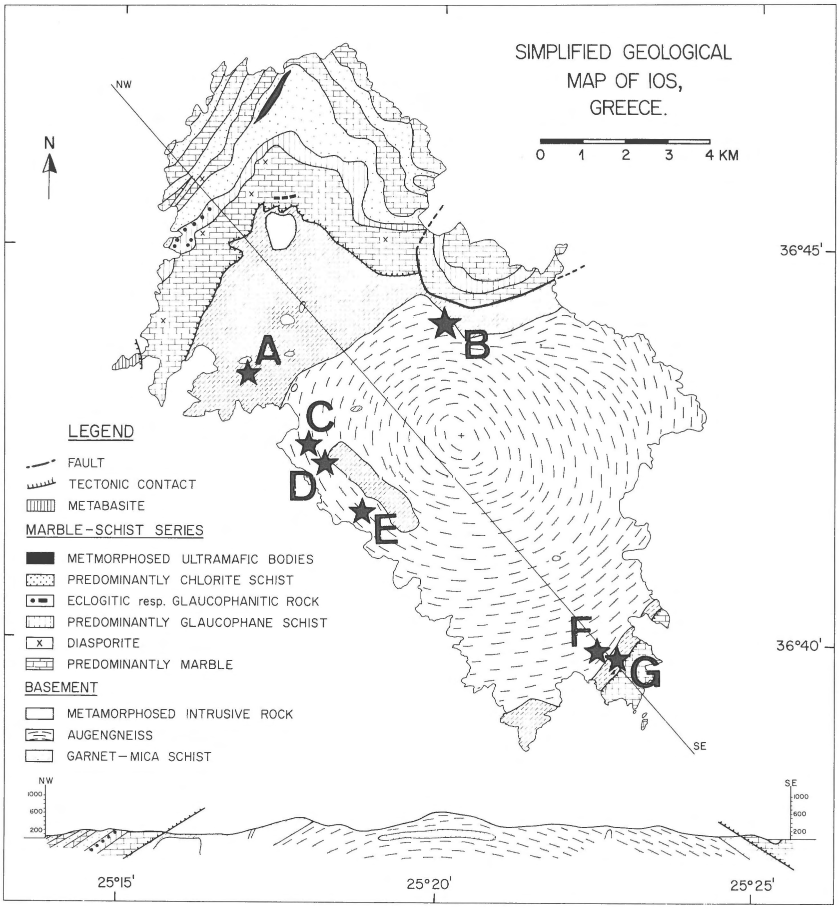

Fig. 4. Simplified geological map of Ios, Greece (after Van der Maar, 1981). Asterisks, sample locations: A, NIO-20 & NIO-21; B, NIO-1; C, NIO-2; D, NIO-9; E, NIO-4 & NIO-5; F, NIO-104; G, NIO-91.

and Pb isotope measurements were made on a computer-controlled Teledyne SS-1290 mass spectrometer with Faraday cage collector and digital output. Lead was mounted as nitrate on a single zone-refined Re filament with silica gel and phosphoric acid, and measured according to Barnes et al. (1973). Uranium was loaded as nitrate on the two zone-refined Re side-filaments of a triple filament source (Shields 1966). Rb and Sr contents and Rb/Sr ratios of the whole-rocks were measured on pressed-powder pellets by X-ray fluorescence spectrometry, using a Philips PW 1450/AHP automatic spectrometer. Mass-absorption corrections for both sample and external standard are based upon the Compton scattering of the Mo-Kα primary beam (Verdurmen 1977). The strontium isotope analyses were made directly on unspiked strontium, using a computer-controlled Varian CH5 mass-spectrometer with Faraday cage collector and digital output. The K contents were determined by flame photometry with a lithium internal standard and caesium chloride-aluminium nitrate buffer. Argon was extracted in a bakeable glass vacuum apparatus and determined by isotope dilution under static conditions in a Varian GD-150 mass-spectrometer. The analytical accuracy is believed to be within 1% for U and Pb, 0.5% for ^{208}Pb/^{206}Pb and ^{207}Pb/^{206}Pb, 1% for XRF Rb/Sr, 0.05% for ^{87}Sr/^{86}Sr, 1% for K and 2% for radiogenic Ar. These estimated overall limits of relative error are the sum of the known sources of possible systematic error and the precision of the total analytical procedures. Best-fit lines through the U-Pb and Rb-Sr data-points were calculated according to York (1969) and York (1966, 1967), respectively. The values of the Mean Squares Weighted Deviation (MSWD) were calculated according to McIntyre et al. (1966). The age calculations are based upon the constants $\lambda^{238}U = 1.55125.\ 10^{-10}a^{-1}$, $\lambda^{235}U = 9.8484.\ 10^{-10}a^{-1}$, $^{238}U/^{235}U = 137.88$, $\lambda^{87}Rb = 1.42.10^{-11}a^{-1}$, $\lambda_{\varepsilon}{}^{40}K = 0.581.10^{-10}a^{-1}$, $\lambda_{\beta}{}^{40}K = 4.962.10^{-10}a^{-1}$ and abundance $^{40}K = 0.01167$ atom percent total K.

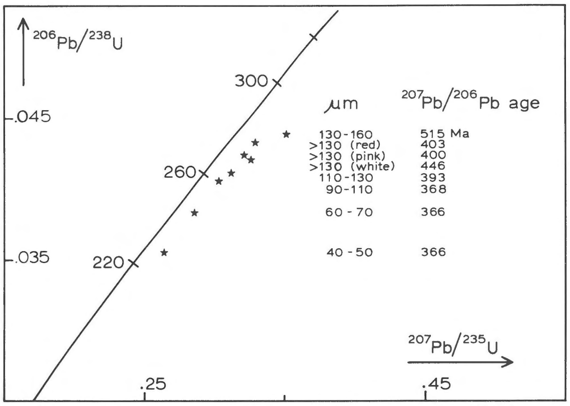

Fig. 5. Concordia diagram showing the U-Pb data points of the zircons from migmatite sample NAX 363 from Naxos.

The migmatitic gneiss dome on Naxos: U-Pb zircon investigation

A suite of eight zircons from a sample (NAX 363) from the central part of the migmatitic dome (Fig. 2) was investigated by the U-Pb method. The results are listed in Table 1 and plotted in Fig. 5.

The zircon data-points display a very rough linear correlation. A best-fit line calculated through all eight data-points would define upper and lower intercepts corresponding to ages of 678 ± 30 Ma and 178 ± 8 Ma (1σ), respectively. However, an interpretation of the U-Pb systematics of the whole suite of zircons in terms of a simple two-stage radiogenic lead-growth model, seems unrealistic in view of the high MSWD value of 69. The more so because a two-stage interpretation would imply that the intense 23 Ma old M2 metamorphism does

Table 1. Zircon U-Pb data of Nax 363.*

fraction (µm)	U ppm	Pb ppm	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	Calculated ages (Ma)		
								$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
130–160	920	40.1	3943	0.06129	0.08171	0.35064	0.04415	279	305	515
> 130 (red)	638	27.4	4155	0.05828	0.08746	0.32757	0.04338	274	288	403
> 130 (pink)	833	34.7	4100	0.05825	0.07564	0.32064	0.04252	269	282	400
> 130 (white)	1233	50.0	5489	0.05851	0.05804	0.32442	0.04213	266	285	446
110–130	890	35.9	4704	0.05763	0.07283	0.31056	0.04131	261	275	393
90–110	916	36.4	5290	0.05669	0.07195	0.30303	0.04075	258	269	368
60–70	891	33.3	9549	0.05540	0.07370	0.28562	0.03845	243	255	366
40–50	901	31.2	12559	0.05504	0.07529	0.26437	0.03559	225	238	366

* Columns 2 and 3: procedure blanks (chemistry and loading) are less than 1% (about 1–2 ng) of the total lead and less than 0.02% (less than 0.3 ng) of the total uranium.

Columns 4 through 7:, measured lead isotope ratios.

Columns 7 and 8: ratios radiogenic $^{207}Pb/^{235}U$ and radiogenic $^{206}Pb/^{238}U$, after correction for "common lead". The measured lead isotope ratios are first corrected for the procedure blanks by assuming that all contaminant lead has the "Average Modern Lead" (AML) composition ($^{206}Pb/^{204}Pb = 18.70$, $^{207}Pb/^{204}Pb = 15.628$ and $^{208}Pb/^{204}Pb = 38.63$; Stacey & Kramers, 1975). Then it is assumed that all remaining ^{204}Pb is a component of initial common lead, incorporated in the zircons during crystallization. The isotopic composition of this initial lead is approximated by a backward extrapolation from AML to the preliminary upper-intercept age of the appropriate suite of zircons.

not show up in the U-Pb systematics, whereas there is no evidence that the lower intercept at 178 Ma could have any geological significance. Clearly, a multi-stage radiogenic lead growth has to be invoked, with the 23 Ma old M2 metamorphism as one event of isotopic disturbance. It has been documented in several cases, e.g. Higgins et al. (1977), that such a multi-stage zircon history may very well result in an approximately linear array of data-points, a "false discordia" yielding ficticious intercept ages.

One possible way to interpret the U-Pb systematics of the suite of zircons is in terms of a three-stage radiogenic lead-growth model, involving the presence of a minor component of old radiogenic lead, a main generation of zircon, and isotopic disturbance during Alpine orogenesis, 40–10 Ma. Any inherited old lead component will particularly be present in the coarsest zircon fractions.

Of the investigated eight zircon fractions the five coarse fractions do indeed scatter below the alignment of the three finest fractions, as is also clear from the calculated $^{207}Pb/^{206}Pb$ ages: 366–368 Ma for the fine fractions and ranging from 393 to 515 Ma for the coarse fractions. Some old radiogenic lead must thus be present in the five coarse zircon fractions (Table 1). The three fine fractions define a line (MSWD = 0.06) intercepting concordia at $372(^{+28}/_{-24})$ Ma and 11 ± 35 Ma (1σ). The lower intercept falls within the age range of the M2 metamorphism and subsequent uplift and cooling history, which makes probable that the upper intercept also corresponds to a "true", geological meaningful age. The age of $372(^{+28}/_{-24})$ Ma is therefore taken to approximate the age of the crystallization of the main zircon generation.

Such an interpretation of the U-Pb data implies more than one period of crystal growth. A growth of new rims around older zircon crystals can be proven, for example, by the distribution of uranium. The image of the uranium distribution in a mineral is made visible in an external detector after irradiation with thermal neutrons, causing the isotope ^{235}U to fission and to produce fission tracks. The density of the induced fission tracks is than a measure for the uranium content. For the zircons of Naxos an inhomogeneous uranium distribution within the crystals is apparent, with in most crystals the outer rim having a much higher U-content than the core. This points to an overgrowth of old crystals with a younger generation, which supports the proposed multi-stage radiogenic lead-growth model.

The crystallization of the main zircon generation $372(^{+28}/_{-24})$ Ma ago may be related to the presence of late Paleozoic (late Caledonian or early Hercynian?) igneous components (acidic volcanics and/or granitoids) among the precursors of the migmatite, which were modified beyond recognition by the migmatization during M2. The minor component of older radiogenic lead of unknown age in the coarser fractions may be attributed to the presence of inherited older zircons in the late Paleozoic magma. This should indicate a generation of the magma from older continental source rocks, or from sediments derived from it. Both the inherited older zircon and the main zircon generation were affected to varying degrees by isotopic disturbance during the intense M2 metamorphism.

Taking into account the error limits, the age of $372\ (^{+28}/_{-24})$ Ma still might correspond to the whole-rock Rb-Sr isochron age reported by Henjes-Kunst & Kreuzer (1982) for the granodiorite-tonalite intrusion in the basal unit of Ios: according to various calculation models ranging from 469 ± 60 Ma to 520 ± 55 Ma.

Metadiorite on Sikinos: Rb-Sr whole-rock investigation

Rb-Sr whole-rock measurements were performed on a suite of five samples from a metadiorite intrusion on Sikinos (Fig. 3). The results are listed in Table 2 and plotted in Fig. 6. No isochron relationship is displayed, but the samples do show a crude linear array corresponding to an age of 275 ± 87 Ma with initial $^{87}Sr/^{86}Sr = 0.714 \pm 0.009$ (1σ). The scatter of the Rb-Sr data-points may possibly be related to the partial alteration of the plagioclase into albite and zoisite during Alpine metamorphism. Although no accurate age is defined by the Rb-Sr data, they do show that a late Paleozoic or early Mesozoic age must be assigned to the

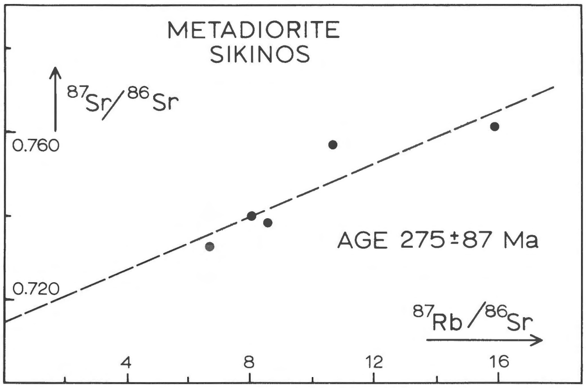

Fig. 6. Rb-Sr plot of metadiorite samples from Sikinos.

dioritic intrusions. More isotopic dating will be carried out.

K-Ar studies of a hornblende and white micas from the polymetamorphic gneiss dome on Ios

K-Ar analyses were made on eight white micas and a hornblende from augengneisses in the polymetamorphic gneiss dome on Ios (Fig. 4). The results are given in Table 3. The white micas yield ages between approximately 125 and 23 Ma. For the hornblende an age of 268 ± 27 Ma was obtained. All ages correspond to those reported by Henjes-Kunst & Kreuzer (1982).

The hornblende age is interpreted as a post-Hercynian cooling age, implying that the K-Ar system has not been disturbed by Alpine metamorphism. In order to remain closed towards the K-Ar system, the ambient temperature must have remained well below about 500° C, the closure temperature of hornblende (Hart et al. 1968; Andriessen 1978). This is in agreement with the estimated PT conditions deduced from the metamorphic mineral assemblages in the gneiss dome: 9–11 Kb and 350–400° C for the M1 glaucophane-schist facies, and 5–7 Kb and 380–420° C for the M2 greenschist facies (Van der Maar 1981).

Among the white micas two age groups can be distinguished (Table 3), one Alpine with ages between 23.0 and 47.6 Ma and another pre-Alpine with ages between 69.3 and 125 Ma. The first group is well-known from several other Cycladic islands (Andriessen et al. 1979; Altherr et al. 1979; Altherr et al. 1982) and can be related to the Alpine M1 and M2 phases of metamorphism, dated at approximately 45 Ma and 23 Ma, respectively. Taking into account the Hercynian amphibolite-facies metamorphism M0 that has affected the rocks about 300 Ma ago (Henjes-Kunst & Kreuzer 1982), the other group of ages can be interpreted as "intermediate" between Alpine and Hercynian. These intermediate ages may be explained in several ways, such as the presence of relicts of Hercynian micas side-by-side with an Alpine mica generation, or a partial resetting of Hercynian micas during Alpine metamorphism. An alternative explanation is that the micas (re)crystallised during the Alpine metamorphic event and incorporated varying amounts of excess radiogenic Ar.

Textural and chemical characterization of the white micas

According to Van der Maar (1981) and Henjes-Kunst (1980) at least three generations of white micas can be distinguished within the basement rocks of Ios:

– A first generation of undeformed coarse flakes, thought to represent relicts of the magmatic paragenesis of pre-Alpine intrusive rocks. The Si-content of these micas lies in the range of 3.05–3.08. A Rb-Sr analysis reported

Table 2. Rb-Sr whole-rock data of the metadiorite of Sikinos.

Sample	Sr (ppm Wt)	Rb (ppm Wt)	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$
Sik A	77.5	178	0.7325 0.7327	6.65
Sik B	59.5	175	0.7379 0.7379	8.51
Sik C	65.1	179	0.7397 0.7398	7.99
Sik D	42.0	154	0.7570 0.7567	10.6
Sik E	35.1	191	0.7611 0.7610	15.8

for such a muscovite and a coexisting brown biotite yielded ages of about 295 Ma and 220 Ma, respectively (Henjes-Kunst & Kreuzer 1982). Both ages are interpreted as cooling ages after the Hercynian metamorphism, MO.
A second generation of fine-grained crystals in the matrix of the garnet-mica schists and along biotite relicts in the metamorphosed intrusive rocks. The Si-content of these micas ranges from 3.34 to 3.46 for those from the garnet-mica schists (Van der Maar 1981) and from 3.28 to 3.35 for those from the augengneiss (Henjes-Kunst 1980). For phengites in rocks of the overthrust sedimentary series, which are related to the M1 phase and have Si-contents corresponding very well to those of the second-generation micas in the basement, Henjes-Kunst & Kreuzer (1982) have reported K-Ar ages of 39 to 33 Ma. On the basis of similar Si contents it is assumed that the (re)crystallization of the second-generation micas in the basement was also related to the M1 phase.

- A third generation of sericitic mica in the feldspar, thought to be associated with greenschist metamorphism of the M2 phase. No chemical data are available. For one mica of this generation, a K-Ar age of 25.7 Ma has been reported (Henjes-Kunst & Kreuzer 1982).

Two of the samples investigated in this study contain side-by-side all three generations of white mica: NIO-1 and NIO-104 (Table 4). Only in one case, NIO-1, it has been possible to separate two generations from a single sample: NIO-1B, coarse flakes of the first generation, and NIO-1A, fine flakes of the second generation. The Si values are 3.08–3.09 for NIO-1B and 3.33–3.35 for NIO-1A, indicating M0 and M1 crystallization, respectively. This is confirmed by the K-Ar ages yielded by the micas: a pre-Alpine age of 117 Ma for NIO-1B and an M1 age of 47.6 Ma for NIO-1A. Of the other

Table 3. K-Ar data and ages of minerals from the island of Ios.

Sample Nr.	Mineral	K* (% Wt)	Radiogenic ^{40}Ar (ppb Wt)	Atmospheric ^{40}Ar (% total ^{40}Ar)	Age (Ma)
NIO 1A	phengite	9.03	30.2	79	47.6 ± 1.8
			30.1	68	
NIO 1B	muscovite	8.38	70.3	16	117 ± 4
			70.5	22	
NIO 2	phengite	9.11	20.2; 17.0	40; 65	30.0 ± 1.5
			19.2; 19.7	59; 38	
NIO 4	phengite	8.55	53.1; 51.4	18; 33	89.1 ± 4.5
			57.9; 54.2	36; 29	
NIO 4	hornblende	0.44	7.41; 8.25	41; 45	268 ± 27
			8.89; 7.54	20; 32	
NIO 5	phengite	8.14	39.7; 38.4	26; 43	69.5 ± 3.5
			41.3; 40.1	39; 33	
NIO 9	phengite	8.90	14.3; 13.8	27; 36	23.0 ± 1.2
			14.5; 14.4	50; 31	
NIO 20	phengite	8.55	42.1; 45.3	36; 19	77 ± 4
			50.0; 49.1	24; 45	
NIO 21	phengite	8.29	25.2; 24.3	18; 37	42.8 ± 1.1
			24.8; 25.3	48; 36	
NIO 91	phengite	9.20	21.3; 20.5	22; 55	33.2 ± 1.6
			21.8; 21.8	22; 32	
NIO 104	muscovite with minor phengite	8.74	80.0; 80.7	9; 8	125 ± 6
			73.9	19	

* Mean value of duplicate analysis.

sample, NIO-104, only the coarse flakes of the first generation, which constitutes the bulk of the white mica in this rock, could be separated. Like NIO-1B, white mica NIO-104 has a low SI value of 3.06–3.09, along with a pre-Alpine K-Ar age of 125 Ma. In both cases there is thus a clear relationship between the textural characterization of the white mica as belonging to the first generation, low Si values pointing to M0 crystallization, and pre-Alpine ages. The ages are still far below the Hercynian range, however. This cannot be explained by a significant contamination of the investigated samples with white mica of the second and/or third generation, since such a mixing would show up in the measured Si values which were determined on powdered aliquots of the dated mica concentrates. The ages intermediate between M0 and M1 must thus be attributed to a partial resetting of the K-Ar systems during Alpine metamorphism. This phenomenon shows that Ar in the interlayer positions was expelled from the crystal lattice, whereas the low Si values indicate that the tetrahedral position of the lattice was not affected. Similar conclusions have been reported, for example, in a study of the Monte Rosa Granite, Western Alps (Frey et al. 1976), and of the adjacent island of Naxos (Wijbrans & McDougall 1986).

All other dated micas have Si values between 3.2 and 3.4, pointing to Alpine (re)crystallization. A thin-section study of NIO-2 and NIO-9 revealed the occurrence of only one generation of white mica, a recrystallised fine-grained mica in the matrix. The Si-content is 3.34–3.36 and 3.22–3.29, respectively, indicating an adjustment of the mica structure to the Alpine conditions. The K-Ar ages of 30.0 and 23.0 Ma, respectively, do support the textural and chemical observations. NIO-20 also contains only one generation mica. In this rock, however, the pre-Alpine mineral allanite with a rim of Alpidic epidote occurs, indicating according to Van der Maar (1981) a pre-Alpine fabric of the mineralogy, and an overprint in Alpine time. The K-Ar age of 77 Ma may be interpreted as a Hercynian mica, partially rejuvenated during the Alpine event. Why exchange took place on the tetrahedral place of the sheet mineral, whereas the interlayer position was less affected, is difficult to understand. In this case it is assumed that the mica has incorporated excess radiogenic Ar during the Alpine event.

The textural evidence regarding the white micas NIO-4, NIO-5 and NIO-21 is ambiguous, but no clear first generation appears to be present. In all three rocks the white mica forms part of the matrix. The Si-content of these micas varies between 3.24 and 3.42, pointing to M1 crystallization. However,

Table 4. Si-content of the investigated white micas from Ios, calculated on the basis of $O_{10}(OH)_2$ per unit formula.

Sample nr.	Structural Textural Information	Si-content (powder)	Si-content* (mica in situ)	Mg-content (powder)
NIO 1A	fine, second generation	3.33–3.35	3.32–3.39	0.14–0.16
NIO 1B	blast, first generation	3.08–3.09	3.06–3.07	0.09–0.10
NIO 2	fine, matrix (recrystalline)	3.34–3.36		0.18–0.19
NIO 4	fine, matrix	3.30–3.35	3.33–3.39	0.26–0.30
NIO 5	fine, matrix	3.24–3.31		0.24–0.30
NIO 9	fine, matrix (recrystalline)	3.22–3.29		0.10–0.14
NIO 20	coarse, first generation	3.32		0.27
NIO 21	fine, matrix	3.37–3.43		0.31–0.38
NIO 91	coarse, first generation	3.40–3.44		0.25–0.26
NIO 104	coarse, first generation	3.06–3.09	3.05–3.46* *	0.06–0.07

*The analyses of the minerals were performed at the electron microprobe laboratory of the Institute for Earth Sciences, State University of Utrecht.

* *The variation of the Si-content measured in the same mica flake.

only the age of NIO-21, 42.8 ± 1.1 Ma, is in accordance with the textural and chemical characterization. The ages of white micas NIO-4 and NIO-5 are 89.1 ± 4.5 and 69.3 ± 3.5 Ma, respectively. Both samples were taken from the same outcrop, a meta-basite. The hornblende of NIO-4 yielded a post-Hercynian cooling age, in accordance with the pre-Alpine fabric of this rock. These pre-Alpine mica ages may be interpreted in terms of either excess radiogenic Ar in Alpine mica, or a partial rejuvenation of Hercynian mica. We favour the first interpretation, as the occurrence of excess radiogenic Ar in minerals from meta-basites is a not uncommon phenomenon (Henjes-Kunst & Kreuzer 1982) and it seems difficult to understand how changes in the tetrahedral positions could have taken place whereas part of the K-Ar system on the interlayer positions remained unaffected.

Textural examination of NIO-91 clearly shows two generations of white mica, coarse flakes of the first generation and a second generation of fine flakes forming the matrix. Only the coarse mica has been separated. Surprisingly, the Si-content of this mica varied from 3.40–3.44, indicating an adjustment to Alpidic conditions. The K-Ar age of 33.2 ± 1.6 Ma confirms this interpretation. In this case a complete recrystallization of the white mica must have taken place.

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