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Dating the Events of Metamorphism and Granitic Magmatism in the Alpine Orogen of Naxos (Cyclades, Greece)

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Abstract. An isotopic dating investigation (66 K–Ar and 34 Rb–Sr analyses) provided the geochronological framework for the Alpine events of metamorphism and granitic magmatism on Naxos. The oldest phase of high-pressure/medium-temperature metamorphism, M1, was dated by Rb–Sr and K–Ar analyses of paragonites, phengitic muscovites and muscovites at 45 ± 5 Ma (Middle Eocene). Most of the record of the M1 phase has been eraded by a second phase of medium-pressure/high-temperature metamorphism, M2, which induced a metamorphic zonation with anatectic melting in the highest-grade part, the migmatite dome. Most K–Ar dates of M2 hornblendes, muscovites, biotites and tourmalines range from about 21 Ma in the lower-grade part (biotite-chloritoid zone) to about 11 Ma in the migmatite dome. From the pattern of K–Ar mineral dates it is concluded that the M2 phase took place 25 ± 5 Ma ago (Late Oligocene/Early Miocene) and was followed by a prolonged cooling history until about 11 Ma ago (Late Miocene), when the ambient temperature in the migmatite dome had decreased to below 400–360° C. A Rb–Sr whole-rock isochron analysis of a granodioritic mass dated the intrusion (and the associated M3 phase of contact-metamorphism) at 11.1 ± 0.7 Ma (Late Miocene), with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7112 ± 0.0001. A local phase of low-grade retrograde metamorphism, M4, probably related to Late Alpine overthrusting, was dated at about 10 Ma (Late Miocene).

Introduction

Naxos is the largest of the Cycladic islands in the Aegean Sea, Greece (Fig. 1). The islands form part of the Attic-Cycladic Massif, a crystalline belt of marbles, schists and intrusive rocks located between the crystalline areas of Attica/southern Evvoia in Greece and the Menderes Massif in Turkey. Recent to subrecent volcanism occurs along its southeastern margin. Several authors have proposed a pre-Alpine age for the crystalline basement, mainly on the basis of structural considerations, the occurrence of non-metamorphic Late Paleozoic and Triassic sediments (which in several cases were later proven to be allochthonous) and the correlation of emery-bearing marbles with similar marbles containing Mesozoic fossils in the Menderes Massif (see the recent reviews by Andriessen, 1978; Dürr et al., 1978). The only isotopic evidence for a pre-Alpine history reported so far are

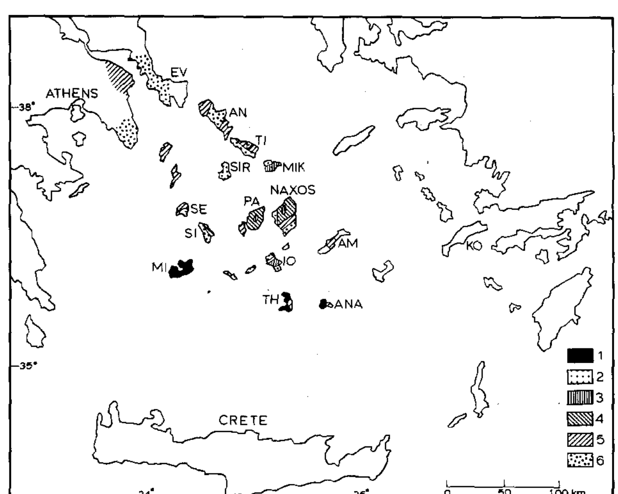

Fig. 1. Location of Naxos in the Attic-Cycladic Massif. *AM:* Amorgos; *AN:* Andros; *ANA:* Anafi; *EV:* Evvoia; *IO:* Ios; *KO:* Kos; *MI:* Milos; *MIK:* Mikonos; *PA:* Paros; *SE:* Serifos; *SI:* Sifnos; *SIR:* Siros; *TH:* Thira; *TI:* Tinos. Legend: *1:* (Sub-)recent volcanism; *2:* granitic intrusions; *3:* migmatites; *4:* amphibolite facies; *5:* greenschist facies; *6:* glaucophane schist facies

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the Rb−Sr and K−Ar ages of 166 Ma, 173 Ma and 217 Ma produced by three biotites on the island of Ios (Kreuzer et al., 1978), coming from granite and tonalite (Henjes-Kunst and Okrusch, 1978); they are interpreted as dates reflecting a partial resetting by later metamorphic events, implying that this basement is still older.

For Naxos a Triassic age of the marbles is suggested by the alleged occurrence of Triassic algae (Dürr et al., 1978). An Early Mesozoic age of at least part of the sediments might also find some support in the $^{87}Sr/^{86}Sr$ ratio of 0.7080 ± 0.0001 determined for the marbles on Naxos, which can be taken as approaching the original Sr isotopic composition of the marine limestones (Andriessen, 1978). The Late Paleozoic/Early Mesozoic is one of the time intervals of the Phanerozoic during which the isotopic composition of marine Sr corresponded to this ratio (Veizer and Compston, 1974).

Two different mineral assemblages are distinguished among the metamorphic rocks in the Attic-Cycladic Massif, in order from old to young (Schuiling, 1973; Dürr et al., 1978): (a) glaucophane-bearing assemblages formed under high to very high pressure and medium temperature, and (b) assemblages formed under medium pressure and high temperature, locally associated with migmatites.

The latter metamorphism was followed by granitic-granodioritic intrusions. Isotopic age determinations on several islands in the eastern Mediterranean showed that both metamorphic events and the granitic magmatism took place in the Tertiary; a summary of all available dates is given by Andriessen (1978). Glaucophane-bearing assemblages occur on the islands of Siros, Sifnos, Folegandros, a small part of Milos, northern and southern Ios, and the southeastern part of Naxos. Age determinations (Rb−Sr and K−Ar) on white micas from such rocks on Sifnos, Ios, Tinos and Siros yielded ages of around 40 Ma (Wendt et al., 1977; Altherr et al., 1976a; Kreuzer et al., 1978; unpublished data ZWO Laboratory of Isotope Geology, Amsterdam).

The medium-pressure/high-temperature mineral assemblages occupy the islands of Paros, part of Antiparos, Mikonos, Dilos, central Ios and the greater part of Naxos. For this phase of metamorphism only cooling ages (K−Ar, Rb−Sr and fission track), ranging from 15 to 7 Ma, have been reported for hornblende, muscovite, biotite, apatite and sphene; the dates were obtained on Tinos, Ikaria and Mikonos (Wendt et al., 1977). White micas from metamorphic rocks in the greenschist facies on Sifnos and Ios yielded ages of 24 and 25.6 Ma (Rb−Sr and K−Ar, Wendt et al., 1977; Kreuzer et al., 1978). Granitic-granodioritic intrusions occur in the Lavrion peninsula and on the islands of Makronissos, Tinos, Mikonos, Dilos, Ikaria, Serifos, Paros, Keros, Kos, Anafi and Naxos. The granitic magmatism took place in the Late Miocene, as was shown by K−Ar and Rb−Sr analyses of whole-rocks and separated minerals from the granites on Tinos, Serifos, Mikonos and Kos (Altherr et al., 1976b and c; Dürr et al., 1978; Wendt et al., 1977).

The present paper reports the results of isotopic age investigations in the crystalline basement of Naxos and the interpretation of the isotopic dates in terms of the Alpine orogenic evolution in this part of the crust. Very little was known about the ages in the basement of the island before this isotopic dating work, which forms part of the Ph.D. work of one of the authors (Andriessen, 1978). Six K−Ar dates of micas (three muscovites from pegmatites, one biotite from the granodiorite, and muscovite and biotite from a schist) have been published previously, all yielding ages between 13 and 11 Ma (Marakis, 1972).

Geological Setting

The following summary of the geology of Naxos is mainly taken from Jansen and Schuiling (1976) and Jansen (1977). Naxos is essentially composed of a metamorphic complex and a granodioritic mass. The metamorphic complex, a migmatitic gneiss dome surrounded by a sequence of metamorphic zones, is a metasedimentary-metavolcanic sequence mainly composed of interbedded mica schists and marbles (Fig. 2). The marbles are particularly abundant in the low-grade parts of the metamorphic terrain. In the higher-grade zones the schist-marble sequence contains interbedded amphibolites. Small, discontinuous bands of metamorphosed bauxites occur in the marbles throughout the metamorphic complex. Two horizons of ultramafic bodies are present near the migmatite dome. All rocks were folded with synmetamorphic lineations and foldaxes in N15E direction, as appears to be a characteristic feature of many metamorphic complexes in the eastern Mediterranean.

In addition to the high-pressure/medium-temperature (glaucophane-bearing) assemblages and the medium-pressure/high-temperature assemblages wide-spread in the whole Attic-Cycladic Massif, two other, less pronounced metamorphic phases can be distinguished on Naxos. Of the four phases the oldest, M1, was in the glaucophanitic greenschist facies, characterised by high pressure (7–9 Kb) and medium temperature (490–530° C). It is inferred that the M1 phase has affected the whole island, but most of its record has been eraded by the second phase of metamorphism, M2. This phase induced a metamorphic zonation with the highest grade in the central migmatitic gneiss dome, where conditions of high temperature (about 700° C) and medium pressure (about 5–7 Kb) prevailed and anatectic melts were formed, leading to the development of several bodies of synkinematic two-mica granite. From this migmatitic core outwards a sequence of distinct zones of decreasing metamorphic grades can be distinguished, as follows (Fig. 3):

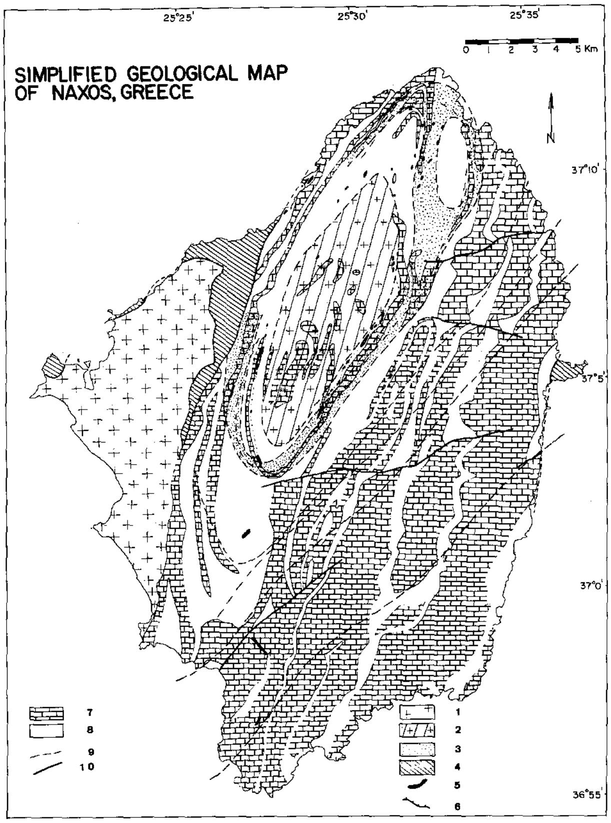

Fig. 2. Simplified geological map of Naxos (after Jansen, 1973). *Legend: 1:* granodiorite; *2:* migmatite dome; *3:* zone of coexisting Al-silicates; *4:* allochthonous rocks (undifferentiated); *5:* ultrabasic bodies; *6:* thrust planes; *7:* predominantly marbles; *8:* predominantly schists, gneisses and amphibolites; *9:* metamorphic isograds; *10:* faults

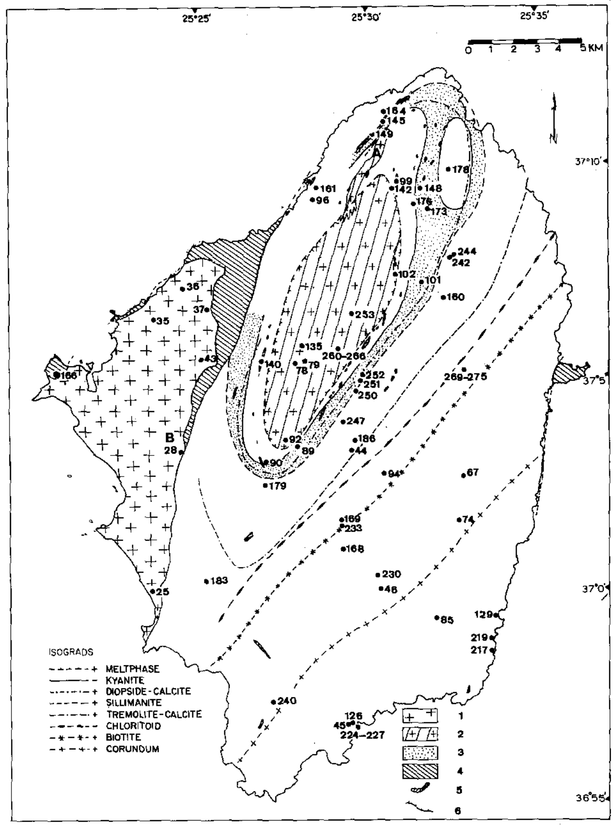

Fig. 3. Metamorphic map of Naxos showing the isograds (after Jansen and Schuiling, 1976) and the locations of the samples investigated in this study. *A:* largest body of synkinematic (anatectic) granite, from which the samples Nax 38–41, 50, 51, 97, 188, 196 and 210 were taken; *B:* suite of granodiorite samples Nax 11, 13, 29, 31, 48, 58, 63, 64, 104, 106, 107, 108, 110, 114, and 115. *Legend: 1* to *6:* see Fig. 2

	Metamorphic zone		Metamorphic Temperature
	zone of anatexis	sapphirine; bodies of synkinematic granite	~700 °C
VI		beginning of anatexis	690–660 °C
	sillimanite zone		
V		−kyanite isograd	~650 °C
	kyanite-sillimanite transition zone		
IV		+sillimanite isograd	~620 °C
	kyanite zone		
III		−chloritoid isograd	560–540 °C
	biotite-chloritoid zone		
II		+biotite isograd	~500 °C
	chlorite-sericite zone		
I		+corundum isograd	440–420 °C
	diaspore zone		
			380 °C

Relict minerals of the M1 phase are present up to the -kyanite isograd of the M2 phase. The M1 mineral assemblages glaucophane + epidote + albite + chlorite ± phengitic muscovite/paragonite are particularly frequent in the southeastern part of the island, within the diaspore and chlorite-sericite zones of the M2 phase. In the higher-grade part of the chlorite-sericite zone the phengitic muscovite gives way to muscovite.

The western part of Naxos is occupied by a granodioritic intrusion with a tourmaline-rich aplitic border facies representing the latest stage of crystallisation. Veins of aplitic and granodioritic composition have intruded into the country rocks. After its consolidation the granodioritic mass was severely affected by deformation. The intruding magma induced an about 1-km wide zone of contact-metamorphism of the andalusite-sillimanite type in the country rock, M3; this zone transects the metamorphic zonation of the M2 phase.

Some parts of the crystalline basement of Naxos are overlain by remnants of an overthrust nappe (or nappe system), probably coming from the north. The allochthonous rocks are mainly unmetamorphosed Oligocene-Middle Miocene sediments and minor gabbros, diabases and serpentinised peridotites; they occur in the western part of the island and in a small area on the east coast.

Another small remnant of the nappe on the east coast consists of unmetamorphosed Permian sediments. In the granodiorite streaks of pseudotachylite were observed within the thrust-plane zone. The fourth phase of metamorphism, M4, a very weak retrograde event recorded in the northwestern part of the island, was probably related to the Late Miocene/Pliocene overthrust movements.

Experimental Procedures, Analytical Errors and Constants

Whole-rock powder aliquots were taken from the crushed and pulverised samples. The minerals were seperated from the sieve-fractions $-250+125$ µm, using a laboratory overflow centrifuge (IJlst, 1973a) employing a set of stabilised heavy liquids (IJlst, 1973b) and a Frantz isodynamic magnetic separator adapted according to Verschure and IJlst (1969). A purity of over 99.9% was obtained for most mineral concentrates.

The Rb and Sr contents and Rb/Sr ratios of the whole-rocks were measured by X-ray fluorescence spectrometry. The samples were analysed on a Philips PW 1450/AHP automatic hardware programmed spectrometer. All samples were measured as pressed-powder pellets; the mass-absorption corrections for both sample and external standard are based upon the Compton scattering of the Mo$-$Kα primary beam (Verdurmen, 1977). For micas, the Rb and Sr contents were determined by mass-spectrometric isotope dilution. Sr isotopic compositions were determined directly on unspiked Sr for whole-rocks and calculated from the isotope dilution runs for minerals. The isotopic measurements were made on a computer-controlled Varian CH5 mass-spectrometer with Faraday cage collector and digital output [value of normalised $^{87}Sr/^{86}Sr$ of the NBS 987 Sr $(CO_3)_2$ standard measured as 0.71016 ± 0.00008]. The analytical accuracies are estimated at 1% for XRF Rb/Sr, 1% for isotope dilution Rb and Sr, and 0.05% for $^{87}Sr/^{86}Sr$.

The K contents were determined by flame photometry with a Li internal standard and CsAl buffer. Argon was extracted in a bakeable glass vacuum apparatus and determined by isotope dilution techniques in a GD-150 mass-spectrometer (Andriessen et al., 1978). For K and Ar the analytical accuracies are estimated at 1% and 2%, respectively, except for a few hornblendes (Table 1).

The best-fit lines through the Rb-Sr data were computed by means of a least-squares regression analysis according to York (1966, 1967). Errors in the calculated ages and initial $^{87}Sr/^{86}Sr$ ratios are quoted at the 95% confidence level as computed from the scatter of the analytical data about the regression line. The value of the Mean Squares Weighted Deviation (MSWD) was calculated according to McIntyre et al. (1966), using precisions of 0.5% for Rb/Sr and 0.03% for $^{87}Sr/^{86}Sr$ as estimated from duplicate analyses.

The age calculations are based upon the following constants: $\lambda^{87}Rb = 1.42 \times 10^{-11} a^{-1}$; $\lambda^{40}K_\beta = 4.962 \times 10^{-10} a^{-1}$; $\lambda^{40}K_e = 0.581 \times 10^{-10} a^{-1}$; isotopic abundance $^{40}K = 0.01167$ atom % total K.

The Isotopic Ages

A total of 65 minerals from the metamorphic complex on Naxos (phengitic muscovite, muscovite, paragonite, biotite, chlorite, hornblende, and tourmaline) were investigated according to the K$-$Ar method. The analytical data and calculated ages are listed in Table 1. Rb$-$Sr measurements were made on a meta-

Table 1. K$-$Ar data and calculated ages from the metamorphic complex and a pseudotachylyte in the granodiorite

Sample No.	Rock[a]	Material[b]	K[c] (wt%)	Radiogenic Ar[d] (ppm × 10^3)	Age[e] (Ma)
Diaspore zone					
Nax 45	s	mu+par	5.95	17.22 (29, 34)	41.5±1.3
85	s	mu	7.18	24.33 (20, 24, 25)	48.3±1.5
126	s	par+phg	1.67	5.44 (76, 80, 83)	46.5±1.4
129	s	chl+phg	2.21	4.29 (72, 83, 83)	37.9±0.9
217	s	chl+phg	4.39	11.30 (18, 19)	36.8±1.1
219	s	phg+chl	6.93	20.31 (16, 16)	41.8±1.3
219	s	chl+phg	1.85	4.17 (18, 18)	32.2±0.9
224	mv	par	0.86	2.61 (56, 56)	43.2±1.3
225	mv	phg	8.47	26.68 (13, 14)	44.9±1.4
226	mv	par	0.77	2.17 (54, 54)	40.2±1.2
227	mv	phg+par	6.34	18.03 (17, 22, 33)	40.6±1.2
227	mv	par	0.78	2.63 (59, 60)	47.9±1.5
Chlorite-sericite zone					
Nax 46	s	mu	8.46	24.13 (17, 19, 27)	40.5±1.2
67	s	mu	9.02	22.43 (15, 16)	35.5±1.4
74	s	mu	9.14	24.41 (10, 12)	38.1±1.4
168	s	mu	8.16	22.69 (10, 18)	37.6±1.4
230	s	mu	6.88	22.56 (10, 18)	46.7±1.4
240	s	mu	8.63	19.63 (11, 15)	32.5±1.0
Biotite-chloritoid zone					
Nax 94	am	hbl	0.70	1.04 (72, 72, 85, 90)	21.3±0.6
169	s	mu	8.69	17.81 (14, 20)	29.3±0.6
233	s	mu	8.10	10.79 (16, 22)	19.1±0.6
Kyanite zone					
Nax 44	s	mu	8.65	8.58 (26, 30)	11.4±0.4
96	gn	bio	7.65	5.94 (66, 76)	11.2±0.3
149	ub	hbl	0.18	0.20 (80, 88)	15.4±0.5
160	ap	mu	8.85	7.78 (50, 50)	12.7±0.4
160	ap	trm	0.20	0.21 (67, 73)	15.3±1.5
161	s	bio	7.66	5.76 (40, 61)	10.8±0.3
161	s	trm	0.99	0.93 (51, 56)	13.6±0.5
164	ap	mu	8.62	6.13 (33, 34)	10.2±0.2
164	ap	trm	0.11	0.13 (62, 80)	17.0±1.7
179	am	hbl	0.16	0.14 (60, 81)	15.2±0.5
183	s	mu	8.52	8.99 (29, 30)	15.2±0.5
186	s	bio	7.79	6.60 (16, 21, 50)	12.7±0.4
242	am	hbl	0.56	0.60 (50, 67)	15.4±0.5
242	am	bio	7.71	6.00 (20, 20)	11.2±0.3
244	ap	mu	8.79	7.41 (56, 59)	12.1±0.4
244	ap	trm	0.24	0.35 (62, 67)	17.9±1.8
247	s	mu+plg	6.39	6.51 (30, 31)	13.1±0.4
247	s	bio	7.81	6.65 (24, 26)	12.2±0.4
250	s	mu	8.11	7.03 (36, 36, 36)	12.4±0.4
250	s	bio	7.34	6.20 (10, 11)	12.1±0.4
Kyanite-sillimanite transition zone					
Nax 89	gb	hbl	1.64	1.82 (23, 52)	15.9±0.6
89	gb	bio	7.87	6.67 (20, 20)	12.2±0.4
101	s	bio	7.10	5.50 (53, 54, 57)	11.1±0.3
145	s	bio	7.35	4.94 (24, 32)	9.7±0.3
148	ub	hbl	0.37	0.35 (62, 78)	13.8±0.4
173	am	hbl	1.43	1.36 (38, 42)	13.8±0.5
178	am	hbl	0.28	0.20 (76)	9.4±1.0
251	s	bio	7.56	6.25 (17, 19, 22)	11.9±0.4
252	am	hbl	0.32	0.31 (55, 76)	14.0±0.5

Table 1 (Continued)

Sample No.	Rock[a]	Material[b]	K[c] (wt%)	Radiogenic Ar[d] (ppm × 10³)	Age[e] (Ma)
Sillimanite zone					
Nax 90	ap	mu	8.64	7.61 (59, 60)	12.7±0.4)
99	ub	hbl	0.39	0.40 (80, 100, 100)	(15.5)
140A	ub	hbl	0.17	0.27 (55, 62, 65)	(23)
140B	ub	hbl	0.27	1.03 (45, 46)	54±1.6
176	s	mu	9.07	7.32 (31, 36)	11.6±0.4
176	s	bio	7.06	5.53 (29, 48)	11.3±0.3
Migmatite dome					
Nax 78	gn	mu	8.57	6.80 (34, 35)	11.4±0.3
78	bp	bio	6.41	2.52 (73, 73)	5.7±0.2
79	gn	bio	7.74	6.32 (24, 24)	11.7±0.4
92	gn	mu	8.73	7.34 (32, 38)	12.1±0.4
92	gn	bio	7.28	5.06 (35, 40)	10.0±0.3
102	ub	hbl	0.06	0.80 (76, 81)	(189)
135	am	hbl	1.33	1.74 (49, 64)	18.8±0.6
142	ub	hbl	0.08	0.75 (75, 78)	(135)
253	gn	bio	7.54	6.20 (25)	11.9±0.4
Pseudotachylyte veinlet in granodiorite					
Nax166		WR	3.75	2.83 (40, 49)	9.9±0.4

[a] *Am:* amphibolite; *ap:* aplite; *bp:* biotite-rich patch in gneiss; *gb:* hornblende-biotite granitic band; *gn:* gneiss; *mv:* metavolcanic layer; *s:* schist; *ub:* ultrabasic body

[b] *Bio:* biotite; *chl:* chlorite; *hbl:* hornblende; *mu:* muscovite; *par:* paragonite; *phg:* phengitic muscovite; *plg:* plagioclase; *trm:* tourmaline; *WR:* sieve fraction whole-rock (−250±125 μm)

[c] Mean of duplicate analyses

[d] Single, duplicate or more analyses. The figures between brackets refer to the proportion of atmospheric ^{40}Ar (in % total ^{40}Ar) for each analysis

[e] The errors are based upon estimated errors of 1% for K and 2% for radiogenic Ar, except for the tourmalines and the whole-rock which display a poorer reproducibility of the Ar analyses. Ages between brackets are considered uncertain due to either very poor reproducibility in the Ar analyses (hornblende 99 and 140A) or to the high uncertainty in the flame photometric determination of very low K contents (hornblendes Nax 102 and 142)

Table 2. Rb−Sr data of the whole-rock and constituent micas of glaucophane schist Nax 227 (metavolcanic layer)

Material[a]	Rb[b] (ppm)	Sr[b] (ppm)	Rb/Sr[b]	$^{87}Sr/^{86}Sr$[c]	$^{87}Rb/^{86}Sr$
WR	8.6	228	0.0378	0.70930	0.1094
phg+par	175	29.1	–	0.71967	17.45
par	9.6	37.3	–	0.70957	0.7407

[a] *Par:* paragonite; *phg:* phengitic muscovite; *WR:* whole-rock

[b] X-ray fluorescence spectrometric analysis for the whole-rock and isotope dilution analysis for the minerals. Mean of duplicate analyses

[c] Direct measurements on unspiked sample for the whole-rocks and calculated from the isotope dilution runs for the minerals. Mean of duplicate analyses

Table 3. Rb−Sr data of whole-rocks from the synkinematic granite

Sample No.	Material[a]	Rb[b] (ppm)	Sr[b] (ppm)	Rb/Sr[b]	$^{87}Sr/^{86}Sr$[c]	$^{87}Rb/^{86}Sr$
Nax 38	gg	194	213	0.909	0.71540*	2.632
39	gg	197	204	0.966	0.71567*	2.796
40	gg	154	225	0.686	0.71541*	1.986
41	gran	250	136	1.85	0.71613*	5.348
50	gg	183	205	0.889	0.71484	2.577
51	gg	181	221	0.820	0.71486	2.376
97	gg	183	243	0.751	0.71489	2.178
188	peg	137	273	0.500	0.71418*	1.448
196	peg	235	149	1.58	0.71579*	4.563
210	ss	71.6	190	0.375	0.72282*	1.087

[a] *Gran:* granite; *gg:* gneissic granite; *peg:* pegmatite; *ss:* xenolith of sillimanite schist

[b] X-ray fluorescence spectrometry. Mean values of duplicate analyses

[c] Direct measurement on unspiked sample. Figures marked * are mean values of duplicate analyses

Table 4. Rb−Sr date of the granodiorite

Sample No.	Material[a]	Rb[b] (ppm)	Sr[b] (ppm)	Rb/Sr[b]	$^{87}Sr/^{86}Sr$[c]	$^{87}Rb/^{86}Sr$
Nax 11	ap/pc	341	114	3.00	0.71234**	8.668
13	ap/pc	291	73.8	3.94	0.71281**	11.40
25	gran	142	378	0.375	0.71141	1.084
28	gran	198	380	0.522	0.71140	1.510
29	ap/pc	311	38.2	8.13	0.71514**	23.55
31	ap/pc	286	101	2.85	0.71301**	8.246
35	gran	159	407	0.391	0.71106	1.130
36	gran	188	395	0.477	0.71132	1.381
37	gran	197	389	0.506	0.71145	1.465
43	gran	186	405	0.460	0.71153	1.331
48	kfsp	36.1*	695*	–	0.71140*	0.1506
58	ap/pc	225	302	0.745	0.71056	2.156
63	ap/pc	286	91.9	3.11	0.71259	8.987
64	ap/pc	237	190	1.25	0.71171	3.606
104	ap/pc	275	70.1	3.92	0.71285	11.34
106	ap/pc	249	118	2.11	0.71219	6.118
107	ap/pc	251	72.8	3.45	0.71271	9.991
108	ap/pc	260	151	1.72	0.71197	4.978
110	ap/pc	281	20.8	13.5	0.71724	39.15
114	ap/pc	246	103	2.38	0.71230	6.897
115	ap/pc	243	174	1.40	0.71154	4.043

[a] *Ap/pc:* aplitic/pegmatitic phase; *gran:* granodiorite *sensu stricto*; *kfsp:* K-feldspar

[b] X-ray fluorescence spectrometry, except for the figures marked * which were obtained by isotope dilution. Mean values of duplicate analyses

[c] Direct measurements on unspiked sample. Figures marked ** are mean values of duplicate analyses

volcanic rock and some of its minerals, and on suites of samples from a body of anatectic granite in the migmatite dome and from the granodiorite; the analytical data are given in Tables 2, 3, and 4. In Fig. 3 the locations of the investigated samples are shown.

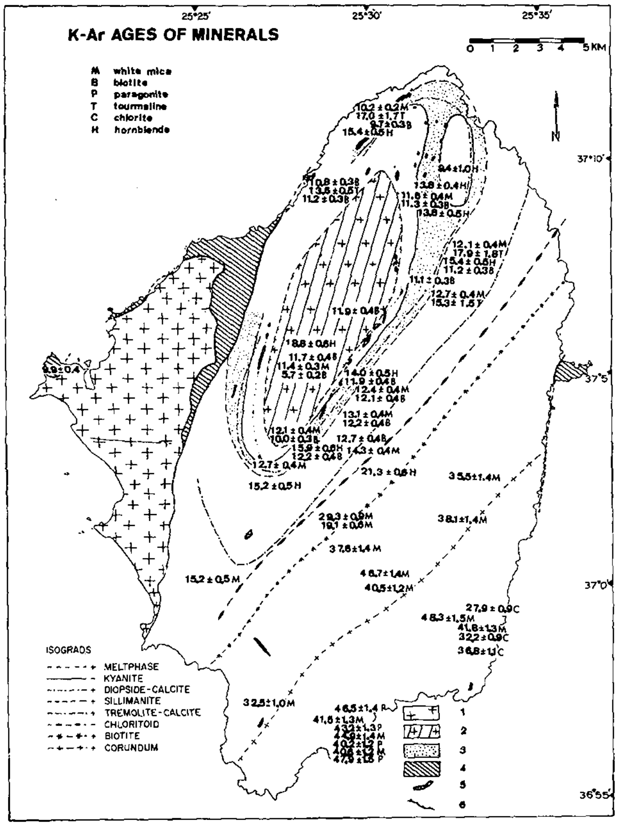

Fig. 4. Metamorphic map of Naxos showing the isograds (after Jansen and Schuiling, 1976) and the K–Ar ages of the investigated minerals from the metamorphic complex and one pseudotachylyte from the granodiorite. *Legend: 1* to *6*, see Fig. 2

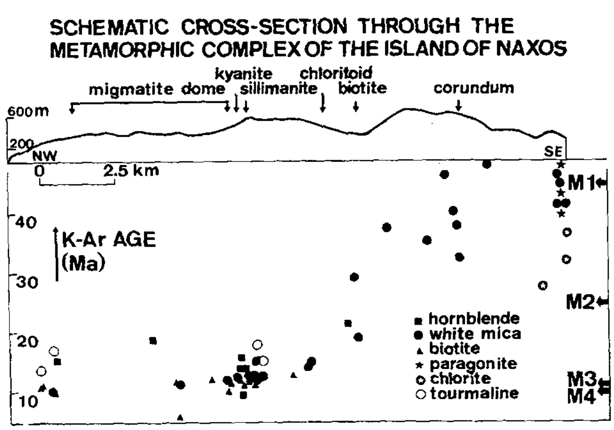

Fig. 5. Schematic cross-section through the metamorphic complex of Naxos showing the K–Ar mineral dates

The distribution of the K–Ar dates through the metamorphic complex is displayed in Fig. 4.

The K–Ar mineral age pattern in the metamorphic complex is clearly related to the metamorphic zonation (Fig. 5). A general pattern is observed of decreasing ages concurrent with an increase in the metamorphic grade: hornblende ages in amphibolites range from 21.3 Ma (biotite-chloritoid zone) to 13.8 Ma (kyanite-sillimanite transition zone), muscovite ages from 19.1 Ma (biotite-chloritoid zone) to 11.4 Ma (migmatite dome), and biotite ages from 12.7 Ma (kyanite zone) to 11.7 Ma (migmatite dome). Dating of phengitic muscovites and paragonites in the chlorite-sericite and diaspore zones yields ages between 48.3 and 27.9 Ma.

This age pattern, especially the distribution of the hornblende and muscovite ages, cannot be explained in terms of a single event of resetting of older mineral ages in the contact-aureole of an intruding granitic body (the migmatite dome), such as produced, for example, along the Tertiary quartz monzonite intrusives near Eldora in Colorado (Hart, 1964; Hart et al., 1968) and the Precambrian Duluth gabbro (Hanson and Gast, 1967). If the age pattern should be the result of a thermal disturbance of mineral ages due to the heat released from an intruding granite, the clustering of mica ages around 11.5 Ma in the migmatite dome and the adjoining sillimanite zone would set the event of granitic magmatism and mineral age resetting at this date. A complete resetting of the hornblende and mica ages would then be expected in the contact-metamorphic aureole down to an ambient temperature of about 500° C. This would lead to a homogeneity of the K–Ar mineral ages around a value of 11.5 Ma in the higher-grade part of the metamorphic complex, from the migmatite dome through the biotite-chloritoid zone. Two muscovites and one hornblende investigated from the latter zone, however, show K–Ar ages substantially higher than 11.5 Ma. Even in the kyanite zone (metamorphic temperature between about 550° and 620° C) several higher hornblende and muscovite ages were observed. The development of the migmatite dome with its surrounding metamorphic zonation must thus be older than 11.5 Ma. Also, the age pattern of increasing ages concurrent with decreasing metamorphic grade is characteristic for the cooling history of a regional metamorphic terrain.

The distribution of K–Ar mineral ages on Naxos is therefore interpreted in terms of the plurifacial metamorphism indicated by the geological petrological evidence. Regarding this relative chronology, it is clear that the M1 phase, in the glaucophanitic greenschist facies, is the oldest. Next came the M2 phase, leading to the development of the metamorphic complex. This phase was followed by the intrusion of the granodioritic mass, inducing the M3 of contact-metamorphism in a narrow zone along its contact and discordant to the M2 metamorphic zonation. The fourth phase of retrograde metamorphism, M4, was very local and probably related to the Late Miocene/Pliocene overthrust movements.

When this sequence of metamorphic phases is related to the distribution of the K–Ar mineral ages (Fig. 5), it seems obvious to relate the older age group (about 48 to 30 Ma) with the M1 event. These older ages occur exclusively in the lowest-grade metamorphic zones, the diaspore and chlorite-sericite zones of the M2 phase with abundant relict minerals of the M1 phase. The younger age group (about 21 to 11 Ma) should then be related to the M2 phase. Ages of this group are found from the biotite-chloritoid zone upwards, with the hornblende ages generally exceeding the corresponding mica ages and (up into the kyanite zone) the muscovite ages being up to about 2 Ma older than the corresponding biotite ages. Such a pattern strongly suggests a prolonged cooling history after an event of regional metamorphism. The age of the M3 phase is approximated by the age of the granodiorite intrusion. Four younger mineral dates (about 10 to 9 Ma) may be related to the local M4 phase of retrograde metamorphism.

Although no conspicuous discontinuity in the age pattern was observed, the transition between the inferred M1 and M2 age groups lies approximately at the +biotite isograd and appears to be related to the entry of biotite. This is shown by the muscovites from three schists taken within a distance of about 3 km across the +biotite isograd: Nax 168 with an age of 37.6 Ma (chlorite-sericite zone), Nax 169 with an age of 29.3 Ma (biotite-chloritoid zone) and Nax 233 with an age of 19.1 Ma (biotite-chloritoid zone). The two muscovites with ages belonging to the older age group are both from rocks where biotite is conspicuously absent, whereas the muscovite with an age belonging to the younger age group is from a biotite-containing rock.

Three hornblendes, all from ultrabasic bodies, give much higher ages than the older minerals. For two of them (Nax 102 and 142) the ages are suspect, however, because of the uncertainty in the flame photometric determination of their very low K contents. Regarding the age of 54 Ma displayed by the third hornblende (Nax 104B), it is impossible to decide whether this represents a relict of an older age, or a case of excess radiogenic Ar. One biotite (Nax 78) has an age as low as 5.7 Ma, but this rock shows the effects of incipient weathering.

Dating the Phases of Metamorphism and Granitic Magmatism

The M1 Phase

Near Cape Ormos Rhina on SE Naxos five white micas were separated from four cogenetic samples (Nax 224–227), taken from a single outrop of a meta-

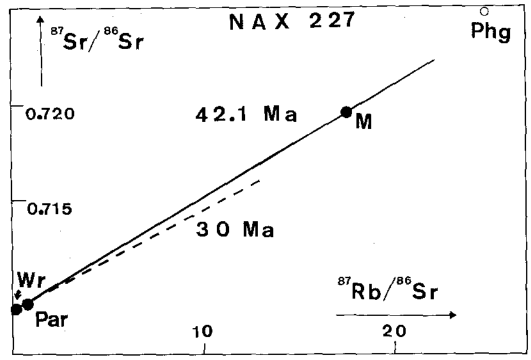

Fig. 6. Plot of the Rb-Sr data of glaucophane schist Nax 227 (metavolcanic layer). *M:* mixture of about 70% phengitic muscovite and 30% paragonite; *Par:* paragonite; *WR:* whole-rock; *Phg:* calculated point for the phengitic muscovite

volcanic layer with the typical mineral assemblage of the M1 phase. For one sample, Nax 227, Rb–Sr measurements were made on the whole-rock and the separated paragonite and phengitic muscovite, the latter still containing paragonite. The analytical data are listed in Table 2 and plotted in Fig. 6. An age of 30 Ma is calculated from the data-points of the paragonite and the whole-rock, but with a very large error because of the low enrichment of the paragonite. The pair whole-rock/mixture phengitic muscovite + paragonite defines an age of 42.1 Ma. From the K–Ar data of the paragonite and the mixture, and assuming a K content of 8% for the phengitic muscovite, it can be calculated that the composition of the mixture is roughly 70% phengitic muscovite and 30% paragonite, implying a Rb–Sr age of the order of 48 Ma for the pair phengitic muscovite/whole-rock. The K–Ar dates of the paragonites and the phengitic muscovites of Nax 224–227 range from 48 to 40 Ma; the same age range is displayed by different samples of pure paragonite (e.g., Nax 226, 40.2 Ma, and Nax 227, 47.9 Ma). This spread in ages over 8 Ma cannot be understood in terms of different cooling histories, as the samples were taken within a distance of 5 m. In order to explain a discordancy on such a small scale, one might invoke a partial resetting of some K–Ar systems during the M2 event, or the presence of minor amounts of M2 muscovite, or the occasional presence of excess radiogenic Ar.

Nevertheless, the general pattern of the K–Ar dates in the diaspore zone, as well as two K–Ar muscovite dates in the chlorite-sericite zone, falls within the same range of 48 to 40 Ma, suggesting a closure of the white mica systems to K–Ar within this time interval. The Rb–Sr age of about 48 Ma for the pair phengitic muscovite/whole-rock of sample Nax 227 also falls within this range, despite the difference in the temperature at which the phengitic muscovite in a cooling rock closes to diffusion loss of radiogenic Sr and Ar, i.e., the blocking temperatures to the Rb–Sr and K–Ar systems. The temperature at which phengitic muscovite closes towards Rb–Sr in a cooling rock is generally taken to be of the order of 500° C (Jäger, 1973), higher than the temperature of 420–440° C at which the system closes towards K–Ar under the metamorphic conditions on Naxos (Andriessen, 1978). From the equality of the Rb–Sr and the K–Ar ages of the phengitic muscovite it can thus be concluded that the culmination of the M1 phase, characterised by a metamorphic temperature of 490–530° C (Jansen and Schuiling, 1976), was followed by a relatively fast cooling. An approximate age of 45±5 Ma may therefore be assigned to the M1 phase of metamorphism, i.e., Middle Eocene according to Lambert's (1971) time-scale.

The white micas in the diaspore zone, and even some muscovites in the chlorite-sericite zone, have retained the radiogenic Ar accumulated since the M1 phase, although the host rocks clearly show the imprint of the M2 phase. The only exceptions are three chlorite-phengitic muscovite mixtures on the south-eastern coast of Naxos (Nax 129, 217, and 219), all from tectonically disturbed schists.

The M2 Phase and the Generation of Anatectic Granites

The M2 phase caused the generation of anatectic melts in the migmatitic terrain, from which intrusive bodies of granitic composition were formed. The intrusives are fine-grained two-mica granites containing pegmatitic parts. In the longest body, a laccolith (Fig. 3), several sillimanite-bearing xenoliths are found, similar to the surrounding sillimanite schists. From their concordant pattern of lineations it is concluded that the intrusive bodies are synkinematic (Jansen and Schuiling, 1976; Jansen, 1977). The largest of the intrusives was sampled for Rb–Sr whole-rock analysis of massive and gneissic granites *sensu stricto*, pegmatitic differentiates and an inclusion of sillimanite schist. The analytical data are listed in Table 3 and plotted in Fig. 7.

Six of the investigated samples have a narrow range in Rb/Sr, ranging from 0.69 to 0.97, but they fall apart in two groups of three samples each by having different $^{87}Sr/^{86}Sr$ ratios, about 0.7155 and 0.7148, respectively. Such a difference in Sr isotopic composition points to variations in initial $^{87}Sr/^{86}Sr$ after the generation of the granitic mass; no thorough Sr isotopic equilibration appears thus to have taken place through the melt. An incomplete homogenisation during the melt phase is also evidenced by the occurrence of xenolithic remnants of the country rock.

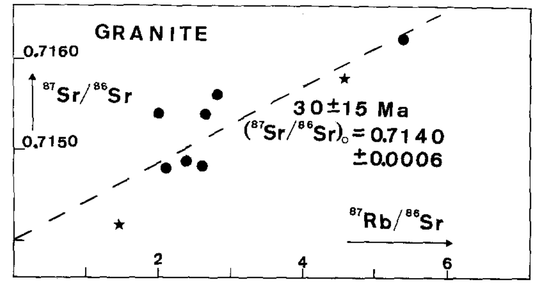

Fig. 7. Rb–Sr plot of a body of synkinematic (anatectic) granite. Closed circles, whole-rocks granite *sensu stricto*. Asterisks, whole-rocks pegmatites. One sample (Nax 210, a xenolith of sillimanite schist) falls far above the other data-points and is not shown

The high $^{87}Sr/^{86}Sr$ ratio of sample Nax 210 (a xenolith of sillimanite schist), far above the $^{87}Sr/^{86}Sr$ range of the other samples, can likewise be attributed to the presence of inherited radiogenic Sr in this domain due to incomplete Sr isotopic equilibration with the granitic magma.

A regression line through nine of the ten data-points, omitting Nax 210, would correspond to an age of 30±15 Ma and initial $^{87}Sr/^{86}Sr = 0.7140 \pm 0.0006$. Unfortunately, this result is far too inaccurate to approach the age of the culmination of the M2 phase of metamorphism. The high initial Sr ratio is in accordance with the generation of the granitic magma by processes of anatexis from sedimentary sequences with a prolonged pre-metamorphic history.

As is discussed in the foregoing paragraphs, the range of K–Ar mineral dates from about 21 to 11 Ma in the higher-grade part of the metamorphic complex (from the biotite-chloritoid zone up to into the migmatite dome) is related to the metamorphic zonation of the M2 phase. The isotopic dates of minerals in a regional metamorphic terrain, however, are not indicative of their crystallisation ages, but they reflect the blocking temperatures during the subsequent cooling history of the rocks. As the metamorphic minerals used for isotopic dating (hornblende, muscovite, biotite) have different blocking temperatures, the minerals in a metamorphic terrain usually display a range in isotopic dates. From several geochronological studies, both in contact-metamorphic zones and in regional metamorphic terrains, an order of closure of the K–Ar systems under conditions of decreasing temperature has been deduced leading to an age pattern as follows:

hornblende > muscovite > biotite.

It may thus be postulated that the highest mineral dates of the younger age group define a minimum age for the culmination of the M2 phase. The highest dates are hornblende Nax 94, 21.3 Ma, and muscovite Nax 233, 19.1 Ma. Regarding the hornblende, this mineral comes from the biotite-chloritoid zone, where a temperature of about 520±20° C has prevailed during the M2 phase of metamorphism (Jansen et al., 1977; Rye et al., 1976). This age is certainly a cooling age, but in view of the ambient temperature during the metamorphism and the blocking temperature of the hornblende of about 490° C (Andriessen, 1978), the age of 21.3 Ma may be taken as approaching most nearly the time of culmination of the M2 phase of metamorphism. The muscovite Nax 233 was taken near the +biotite isograd with a metamorphic temperature of about 500° C, while for the blocking temperature of the muscovite to K−Ar a temperature of about 440–420° C was established under the metamorphic conditions on Naxos (Andriessen, 1978).

Taking all evidence together, it may thus be inferred that an approximate age of 25±5 Ma can be assigned to the culmination of the M2 phase of metamorphism, i.e., Late Oligocene/Early Miocene according to Lambert's (1971) time-scale.

The cooling history subsequent to the culmination of the M2 phase lasted until about 11 Ma ago, i.e., Late Miocene (Tortonian) according to Van Couvering and Miller's (1971) time-scale of the Late Miocene. At that time the ambient temperature in the migmatite dome had decreased to below 400–360° C, the blocking temperature of the biotite to K−Ar under the metamorphic conditions on Naxos (Andriessen, 1978).

The Granodiorite Intrusion and the Associated M3 Phase

A granodioritic intrusion of rather variable composition, locally approaching that of monzonite, occupies the western part of the island (Fig. 2). A detailed mineralogical, petrological and geological description has been given by Jansen (1977), who distinguished the following sequence of events in the evolution of the granodiorite:

(a) Intrusion of a fairly fluid magma into the metamorphic complex, causing contact-metamorphism and metasomatism of the country rock (M3 phase). Xenoliths and biotite flakes became orientated according to the magmatic flow-directions. (b) Late-magmatic and post-magmatic formation of aplitic and pegmatitic dikes and of an aplitic border facies. Formation of myrmekite and perthite in the solidified mass. (c) Low-grade retrogressive alterations, including chloritisation, albitisation and epidotisation, probably contemporaneous with the mylonitisation

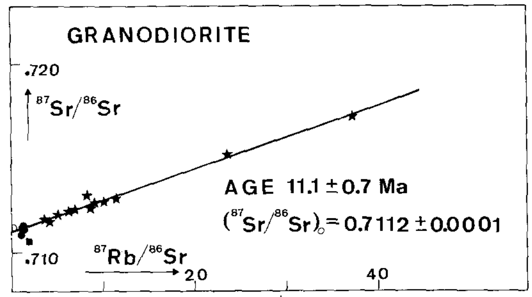

Fig. 8. Rb−Sr isochron plot of the granodiorite. Closed circles, whole-rocks granodiorite *sensu stricto*. Asterisks and square, whole-rocks pegmatites and aplites. Open circle, K-feldspar. One whole-rock (square) was omitted from the calculation

along the northern margin of the granodioritic mass. Development of schistosity.

Of the granodiorite 20 whole-rocks (14 aplites and pegmatites, and 6 granodiorites *sensu stricto*) and one separated K-feldspar were analysed according to the Rb−Sr method. The sampling sites are shown in Fig. 3. Table 4 gives the analytical data. Very little variation is shown throughout the granodiorite regarding the Rb/Sr ratio. Only the aplitic and pegmatitic phases have some spread in Rb/Sr. If we omit one whole-rock (Nax 58), the other 20 data-points, including the K-feldspar, appear to be very well linearly correlated (MSWD value of 0.83). They define an isochron of 11.1±0.7 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7112±0.0001. The isochron plot is shown in Fig. 8. Due to the homogeneity of the granodiorite regarding Rb/Sr, the isochron essentially dates the aplitic and pegmatitic phases, but this may be taken as most nearly approaching the age of the intrusion. Following the time-scale of Van Couvering and Miller (1971), this age falls in the Late Miocene (Tortonian). The initial $^{87}Sr/^{86}Sr$ ratio is rather high, indicating that older sialic crust must have played a role in the generation of the magma.

The isochron of the granodiorite also dates the M3 phase of contact-metamorphism. This age appears to coincide with the final stage of the cooling history of the metamorphic complex after the culmination of the M2 phase of metamorphism, when the temperature in the central part of the migmatite dome had decreased to below the blocking temperature of biotite to K−Ar. Two biotite dates of about 11 Ma from W of the migmatite dome (Nax 96 and 161) appear to be slightly too young for the metamorphic zone where they occur (probably corresponding to the kyanite zone E of the migmatite dome), and may possibly reflect a thermal resetting by the heat of the granodiorite intrusion. The granodiorite could very well have a northward submarine extension along the coast, as is suggested by the occurrence of the contact-metamorphic mineral diopside in NW Naxos (Jansen et al., 1977).

The M4 Phase

This phase of low-grade metamorphism is probably related to the overthrust movements. The frictional heat induced by the overthrusting caused locally some melting in the top of the granodioritic mass, from which streaks of pseudotachylite were formed. K–Ar analysis of such a pseudotachylite veinlet (Nax 166) yields an age of 9.9 ± 0.4 Ma. Four mineral dates of 10 to 9 Ma obtained at different places on Naxos (Fig. 4) may also be attributed to the M4 phase, reflecting a resetting due to the nearby overthrusting. Following the time-scale of Van Couvering and Miller (1971), an age of about 10 Ma would place the overthrusting in the Late Miocene (Tortonian).

Conclusions

1. The M1 phase of metamorphism (glaucophanitic greenschist facies) has taken place 45 ± 5 Ma ago. On other islands of the Attic-Cycladic region (Sifnos, Ios, Tinos and Siros) the high-pressure/medium-temperature metamorphism has also been dated at around 40 Ma. In the metamorphic complex of Naxos this M1 age has been retained in the diaspore zone and locally in the chlorite-sericite zone of the M2 phase.

2. The age of the M2 phase of metamorphism (a metamorphic zonation surrounding a migmatite dome with bodies of synkinematic anatectic granite) is of the order of 25 ± 5 Ma. In the Cycladic area similar ages have been reported from the islands of Sifnos and Ios. After the climax of the metamorphism the cooling history lasted until about 11 Ma (Late Miocene), as is indicated by biotite K–Ar ages in the center of the migmatite dome. On the islands of Tinos, Ikaria and Mikonos similar cooling ages have been found.

3. The pattern of regularly decreasing mineral ages with increasing grade of metamorphism from the biotite-chloritoid zone onwards indicates a smooth cooling over a period of some 10 to 20 Ma.

The muscovite K–Ar ages between 40 and 30 Ma in the chlorite-sericite zone are interpreted as reflecting a partial resetting of the M1 ages by the M2 phase of metamorphism. Along with the entry of biotite, the K–Ar ages drop sharply to about 20 Ma.

4. The granodiorite in western Naxos was dated by means of a Rb–Sr isochron analysis at 11.1 ± 0.7 Ma ago. This isochron also dates the M3 phase of metamorphism (contact-metamorphic zone along the granodiorite). Elsewhere in the Cycladic area, on the islands of Tinos, Mikonos, Dilos, Serifos and Kos and on the Lavrion peninsula, a Rb–Sr isochron investigation of one granite and mineral datings in a number of granitic intrusives have also produced Late Miocene ages. For Naxos the age of the granodiorite intrusion appears to coincide with the final stage of cooling of the metamorphic complex after the culmination of the M2 phase of metamorphism, when the temperature in the central part of the complex had decreased to below 360°–400° C.

5. The M4 phase of retrograde metamorphism, reflecting Late Alpine overthrust movements, has taken place about 10 Ma ago. The geological evidence also points to overthrusting in the Late Miocene/Pliocene.

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