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Autor: Andriessen, Paul A.M.

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K–Ar and Rb–Sr age determinations on micas of impure marbles of Naxos, Greece: the influence of metamorphic fluids and lithology on the blocking temperature

by *Paul A.M. Andriessen*[1]

Abstract

K–Ar and Rb–Sr age determinations are performed on micas from impure marbles from the Miocene medium to high grade metamorphic part of the migmatitic gneiss dome of the island of Naxos, Greece. This particular rock type was less infiltrated by prograde, peak and retrograde metamorphic fluids than the gneisses and the pelitic schists. The obtained ages, which are in all cases higher than those of the adjacent pelites, reflect the special lithological character of the rock type. In the high grade part of the gneiss dome the Rb–Sr and K–Ar mica ages are between 15 and 12.5 Ma and fit the cooling period of the latest stage of the post M2B metamorphic event. In the medium metamorphic part the M2A greenschist muscovite of 22–23 Ma survived the influence of the M2B high temperature phase, dated at 19–20 Ma. The ambient M2B metamorphic temperature of around 540 °C is normally high enough to reset the K–Ar and the Rb–Sr geochronometer, also for the mica of the schists. It is shown that metamorphic fluids and lithology influence the ages.

Keywords: K–Ar, Rb–Sr, age determination, metamorphic fluids, lithology, mica blocking temperature, Naxos.

Introduction

In "Introduction to geochronology" (JÄGER, 1979) it is written that "*the most important parameters that control the age results are temperature and the presence of fluid phases*". Further on in the same chapter explaining the blocking temperature concept for micas from the Central Alps the following statement was made "*in areas of amphibolite facies metamorphism, the metamorphic temperatures exceeding 500 °C, only cooling ages can be measured on micas, with both the Rb–Sr and K–Ar methods. Only in very resistent rocks, Rb–Sr ages on coarse-grained muscovites can survive this grade of metamorphism.*" No further explanation is given as to what is meant by "very resistent rocks". I, therefore take the liberty to associate the conception of a "very resistent rock" to the (near) absence of a fluid phase, or, in terms of metamorphic conditions, to mineral reactions and equilibria where no or practical no liquid or gas phase of H_2O is involved. In this contribution I focus only on the Rb–Sr and K–Ar mica system, but basically similar reasoning can be applied for other geochronometers as well. The following two examples will elucidate this principle. In the Gotthard Massif of the Alps an ultrabasic inclusion within a quartz diorite lens in the greenschist facies of the Alpine chloritoid zone, surrounded by a biotite-sillimanite gneiss is described by ARNOLD and JÄGER (1965). Pre-Alpine Rb–Sr and K–Ar biotite ages were obtained from the ultrabasic rock, Alpine Rb–Sr biotite and pre-Alpine K–Ar biotite ages from the diorite and likewise pre-Alpine K–Ar biotite and early-Alpine Rb–Sr biotite ages from the gneiss. The K–Ar results were explained by the occurrence of excess radiogenic Ar, the Rb–Sr results by the absence of fluids, so that owing to the lack of a transport medium no exchange took place. In the Nevado-Filabride complex of southern Spain basic intrusives occur. They contain relics of unmetamorphosed gabbroic rocks, despite the plurifacial Alpine metamorphic events recognized in the country rocks. K–Ar analysis revealed excess radiogenic Ar for the whole rock and the mineral constituents. The Rb–Sr isochron plot of whole rock and the

[1] Department of Earth Sciences/CIGO, Free University Amsterdam, de Boelelaan 1085, 1081 HV Amsterdam, The Netherlands.

mineral separates (biotite, hornblende, olivine, plagioclase and clinopyroxene) shows an undisturbed late Jurassic age (HEBEDA et al., 1980). The explanation of these results was based on the idea that certain domains of the basic intrusives were shielded against percolating fluids, inhibiting adjustment to the Alpine metamorphic conditions.

When a ^{40}K atom in a mica decays to ^{40}Ar, it is trapped within the crystal lattice and argon being a noble gas will not form bonds with other atoms in the crystal lattice. Because an argon atom is relatively big it can only escape when the lattice is severely weakened or no longer exists, for example when the mineral recrystallizes or is heated to a temperature that will allow the ^{40}Ar to diffuse through the lattice. Sr, belonging to the alkaline earths elements, forms ionic bonds, normally in eightfold coordination with nonmetallic elements, including oxygen. ^{87}Sr, the radioactive decay product of ^{87}Rb, however, is primarily admitted into K^+ sites in all of the important rock-forming minerals that contain potassium, because it forms the principal site of this widely dispersed trace element. So for Sr ions to escape in general similar chemical-physical conditions are necessary, i.e. at least a severe weakening of the crystal lattice to break the ion bonding. When ^{40}Ar and ^{87}Sr are no longer captured in the crystal lattice their behavior is different because of chemical characteristics peculiar to the elements. The transport of the inert gas ^{40}Ar is a function of diffusion, which can easily take place under dry and/or wet conditions. The transport of Sr ions normally takes place under wet conditions, when Sr is in solution in either a liquid or a gas phase.

In principle these factors determine the open-closed systems behavior of the geochronometers, because an open system means that no accumulation of the product formed takes place, and both the mother and the radiogenic daughter elements are free to move in and out of the system. This statement is far too general and it may only theoretically explain the behavior of the isotopic system. In practice there are many physico-chemical parameters that influence the open-closed behavior. For example, thermal conductivity and permeability of the host rock influence the probability that mineral reactions can take place and are achieved, that elements are exchanged, the availability of required transport media and paths, the presence of fluids and gasses, and local equilibrium conditions. In all these processes the time factor is very important.

It is not my intention to discuss all the factors that may be involved. This paper concentrates on metamorphic fluids, the lithology of rocks and the behavior of Rb–Sr and K–Ar mica systems, as observed for the high to medium part of the Miocene metamorphic complex of the Greek island of Naxos.

Geological setting

The Attic Cycladic Metamorphic Belt is located between the mainland of Greece and Turkey, in the eastern Mediterranean (Fig. 1). The island of Naxos is one of the Cycladic islands and is part of the Alpine orogenic belt of southern Europe. Structural analyses of the area have shown that Naxos, Ios and perhaps some other islands can be described as Cordilleran type metamorphic core complexes (LISTER et al., 1984; URAI et al., 1990), which were formed during a period of crustal extension with the crustal upper plate superimposed upon the crustal lower plate. In this region a value of crustal extension of a factor of two from 15 Ma ago to present is estimated from the neotectonics (MCKENZY, 1978). This extension is associated with a regional greenschist facies metamorphic event (M2A), dated at about 23–24 Ma, which, on a local scale like on Naxos, was followed by a high-temperature metamorphism (M2B) and subsequent cooling and uplift, dated at between 20–10 Ma (ANDRIESSEN et al., 1979; ALTHERR et al., 1982; SCHLIESTEDT et al., 1987; WIJBRANS and MCDOUGALL, 1988; ANDRIESSEN and JANSEN, 1990). The M2B event is related to the intrusion of several granitoids, of which the crystallization age is difficult to establish. Prior to the Miocene situation the Attic-Cycladic Massif underwent a compressional phase in Eocene times, owing to the existence of a subduction regime. Associated herewith is the high pressure-low temperature metamorphic phase, M1, dated at 45–50 Ma (ANDRIESSEN et al., 1979; WIJBRANS and MCDOUGALL, 1986). On several islands M1 is the most prominant metamorphic phase, but overprinting by the Miocene greenschist facies is recognized almost everywhere.

My attention was focussed on the Miocene metamorphism on the island of Naxos (Fig 1), where after the formation of the greenschist facies, high-temperature metamorphism gave rise to a migmatitic gneiss complex with anatexis and the formation of synkinematic granitic bodies in the central part as well as in the zones of decreasing metamorphic conditions wrapped around the dome (JANSEN and SCHUILING, 1976). The lithological constitution of the island shows the predominance of marbles with some pelitic schists and metabauxites in the eastern part, and mainly gneisses and pelitic schist, less abundant marbles, some amphibolites and late aplites and pegmatites in the central part (JANSEN, 1973). The difference in li-

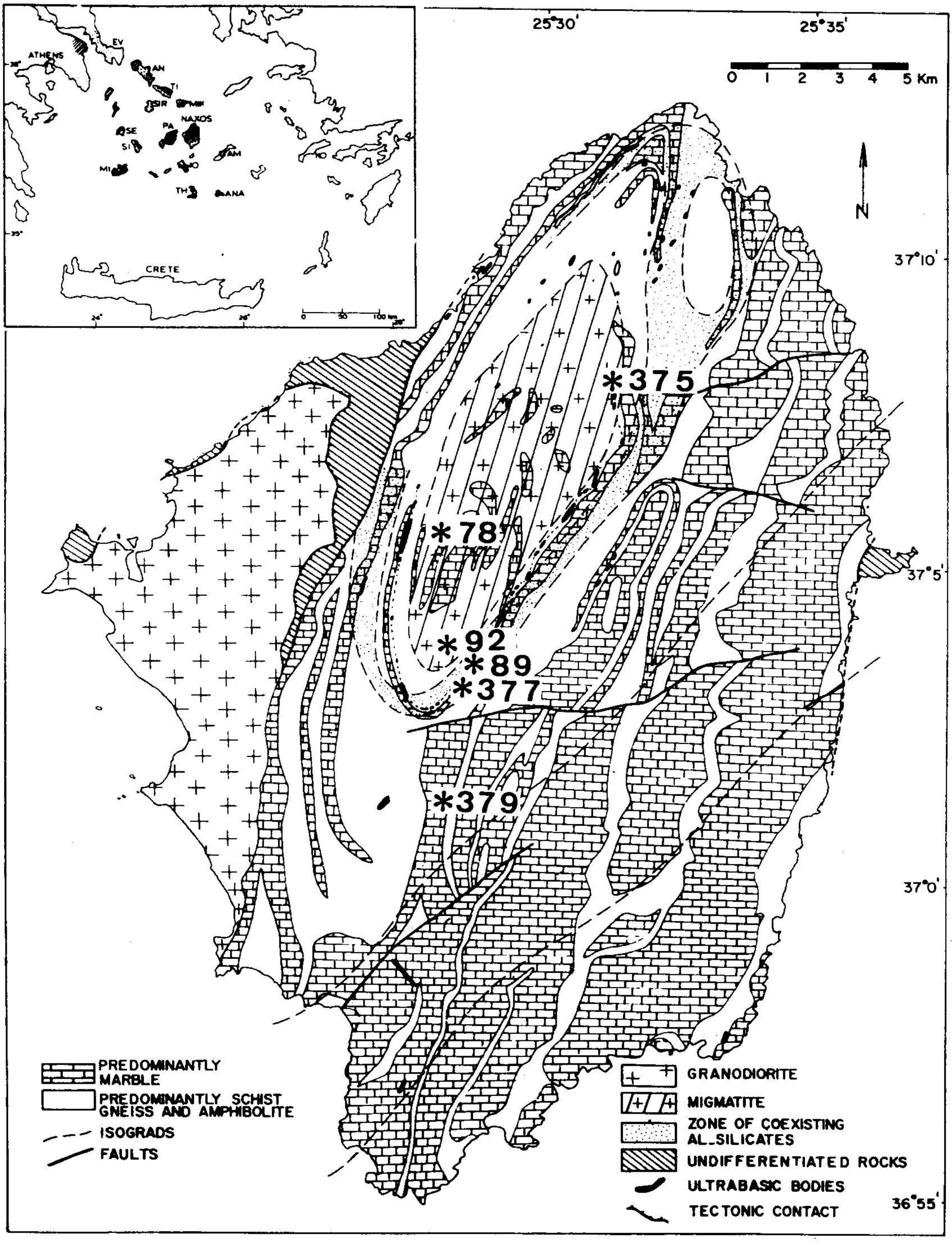

Fig. 1 Geological sketch map of Naxos, Attic Cycladic Metamorphic Belt. The M2B isograds from southeast to the central migmatite dome are in succeeding order: +corundum, +biotite, –chloritoid, +sillimanite, –kyanite, and +meltphase (after JANSEN, 1973). Numbers refer to sample sites.

thology is related to the occurrence of two pre-Alpine tectonic nappes, and the horizon of ultrabasic and ultramafic rocks is taken to represent an old thrust zone (ANDRIESSEN et al., 1987). The western part of the island is formed by a monzogranitic intrusion. Remnants of non-metamorphic nappe(s) lie on top of the metamorphic complex and the monzogranite (JANSEN, 1973).

Miocene metamorphic fluids, metamorphic zones and age determinations on micas

Recently the importance of fluid flow during metamorphism for chemical and heat transport and for development of deformation structures has been under debate (CHAMBERLAIN and RUMBLE, 1988; BAUMGARTEN and RUMBLE, 1988; BRADY, 1988; DAVY et al., 1989; ALLEN and CHAMBERLAIN, 1989) and in several papers the Miocene metamorphism on the island of Naxos has been used as a case study (RYE et al., 1976; SCHUILING and KREULEN, 1979; KREULEN, 1980, 1988; JANSEN et al., 1989; BICKLE and MCKENZIE, 1987; BICKLE and BAKER, 1990; BAKER et al., 1989). From the hydrogen, carbon and oxygen stable isotope studies three different flow events, pre-metamorphic, prograde, and peak-retrograde, can be recognized. For this study the pre-metamorphic fluid is not of direct importance. The prograde fluid in the marbles flowed either along grain edges or close-spaced cracks, but maintained local fluid-solid equilibrium. The peak and retrograde fluid flow was well channelled in calc-silicate and/or quartz veinlets in the marbles. The pelites, however, were very open to fluid infiltration. Recent studies contradict the earlier conclusions of large volumes of pervasive CO_2 (SCHUILING and KREULEN, 1979), and advocate dehydration and decarbonation of deeper lying pelitic schists. It was also suggested that when large enough volumes per unit area infiltrated the rocks the fluid could have caused heat advection to attain peak M2 metamorphic conditions (BICKLE and MCKENZIE, 1987). Although it is not very easy to put constraints on the composition of the fluids, the peak and retrograde fluids transported aqueous silica and the source of the fluids might have been "magmatic". In that case several alternatives can be considered: the migmatite core is probably a Hercynian or older basement consisting of granites and gneisses (ANDRIESSEN et al., 1987), but also the monzogranite now outcropping on the western part of the island may have a continuation in the deeper crust and could underly the migmatitic gneissdome (ANDRIESSEN, in prep.). Thermal models based on $^{40}Ar/^{39}Ar$ stepheating experiments suggest a heat source with the characteristics of both magmatic intrusion and fluid convection to satisfy a short living M2 event (WIJBRANS and MCDOUGALL, 1988).

Exchange of elements, adjustment and readjustment to prograde-, peak- and retrograde Miocene metamorphic conditions and therefore equilibration and homogenization of element- and isotope ratios was most effective in the pelites. High-temperature M2 mineral assemblages in the pelites and gneisses, but also the amphibolites, metabauxites and siliceous dolomites (JANSEN and SCHUILING, 1976; JANSEN, 1977; FEENSTRA, 1985; BUICK, 1988; BAKER et al., 1989; BUICK and HOLLAND, 1989) prove that at least in the central part of the island with a medium to high degree of metamorphism, complete crystallization and recrystallization of the mineral constituents took place, owing to the M2B event. Age determinations on micas from the higher grade part yielded ages of between 13 and 10.6 Ma, with regularly decreasing ages along with higher metamorphic grades (ANDRIESSEN et al., 1979; WIJBRANS and MCDOUGALL, 1988). In the lower grade part of the island approximately from the +biotite isograde and lower grades relicts of the regional greenschist facies and in the SE part M1 glaucophanitic greenschist mineral assemblages are recognized. In this particular part of the island infiltration of prograde fluids from the pelites in the marbles was only marginal (RYE et al., 1976; BAKER et al., 1989). K–Ar and $^{40}Ar/^{39}Ar$ age determinations on micas showed M1 age spectrums which were disturbed, either because of partial rejuvenation of M1 micas or because of the side-by-side occurrence of M1 and M2 micas. The dates obtained range from about 24 Ma to 50 Ma, but no pattern is observed (ANDRIESSEN et al., 1979, WIJBRANS and MCDOUGALL, 1986).

All age determinations from the higher grade part of the island were done on mineral samples from pelites, gneisses, amphibolites, granitic bands or pegmatites, i.e. from rocks that were most accessible to the infiltration of peak- and retrograde fluid flows. Micas in the high to medium grade part do, however, also occur in rocks described as impure marbles. This rock type is certainly influenced by prograde fluid flow, but marginal and limited by channelled peak- and retrograde fluids (BAKER et al., 1989; BICKLE and BAKER, 1990).

K–Ar and Rb–Sr dating of M2 micas of impure marbles of Naxos

To investigate the relationship between rock lithology, metamorphic fluids, dynamic deformation and K–Ar and Rb–Sr systematics of micas three samples were collected from the medium to high grade part of the island (Fig. 1):

– Nax 379 was taken near the –chloritoid isograd in the pelites, not far from the tremolite-calcite isograd of the siliceous dolomites. The rock consists mainly of coarse grained calcite, colourless mica and biotite. Part of the biotite is heavily chloritized. Minor components in the rock are K-feldspar, plagioclase, epidote and sphene.

– Nax 377 follows in metamorphic grade, from a site near the +sillimanite isograd in the pelites and not far from the diopside-calcite isograd in the siliceous dolomites. The rock consists mainly of coarse grained dolomite with biotite, colourless mica, plagioclase and epidote and it also contains some quartz, calcite and apatite. The rock shows development of metamorphic lineation, indicated by the orientation of mica flakes and epidote.

– Nax 375 was taken within the migmatite dome and is rich in carbonate. The rock consists of calcite together with plagioclase, K-feldspar and phlogopite. Minor amounts of fluorite, rutile, chlorite, epidote, sphene and graphite are present. Lineation is fairly well developed and the rock shows signs of strong deformation.

The samples form a cross-section through that part of the island which has a dominant M2B phase mineralogy, from the +biotite isograde onwards to the central migmatitic gneiss dome. A stable isotope study has been performed on the same part of the island and the conclusion of the occurrence of several metamorphic fluid flows is used to explain the age determinations. The estimated temperatures were around 540 °C for Nax 379, about 620 °C for Nax 377 and 660–690 °C for Nax 375 under the peak metamorphic conditions (JANSEN and SCHUILING, 1976; BUICK and HOLLAND, 1989). In all cases the prevailing metamorphic temperatures are thus certainly higher than the blocking temperatures of the Rb–Sr and K–Ar systems of biotite, phlogopite and muscovite. The radiometric data are therefore expected to be post-metamorphic cooling ages with possibly an Rb–Sr muscovite age of the lowest grade marble (Nax 375) that might approach the age of the culmination of the M2B metamorphic phase. Table 1 shows the results of the analyses.

K–Ar mica ages of Nax 375, Nax 377 and Nax 379

The phlogopite of Nax 375 yields a K–Ar age of 12.3 ± 0.3 Ma, the highest K–Ar mica age obtained so far from the central part of the island. The reported K–Ar mica ages of between 11.9 ± 0.4 and 11.4 ± 0.3 Ma (ANDRIESSEN et al., 1979) and $^{40}Ar/^{39}Ar$ mica ages of 11.8 ± 0.1 and 11.4 ± 0.1 Ma (WIJBRANS and MCDOUGALL, 1988) are all from gneisses from the migmatitic gneiss dome. It is interesting to note that the initial temperature steps of the $^{40}Ar/^{39}Ar$ analysis for both muscovite and biotite revealed lower ages than the plateau spectrum, indicating some loss of radiogenic argon after the time that accumulation of produced radiogenic Ar began (WIJBRANS, 1985). The fact that the K–Ar age of phlogopite from the marble is higher than K–Ar and $^{40}Ar/^{39}Ar$ ages of micas from the neighbouring gneisses can be explained by the higher blocking temperature for the K–Ar phlogopite system (MCDOUGALL and HARRISON, 1988) or by the fact that the micas from the gneisses were longer susceptible to the influences of infiltration of retrograde metamorphic fluids, whereas the phlogopite of the marble was better shielded because the fluid flow was channelled in the calc-silicate veinlets. In any case effective accumulation of radiogenic Ar started some 0.5 to 1 Ma earlier in the protected mica-marble system, than in the open mica-gneiss system.

The Rb–Sr age of the phlogopite-whole rock pair is 12.7 ± 0.2 Ma, not different from the K–Ar age. The age similarity supports the interpretation that during post-metamorphic cooling the marble was already a closed system, whereas the adjacent gneisses were still sensitive for exchange processes. Typical examples are two-mica gneisses from within the central part of the migmatitic gneiss dome, Nax 92 and Nax 78 (Fig 1). K–Ar analyses of biotite and muscovite yielded ages of 10.0 ± 0.3 and 12.1 ± 0.4 Ma for Nax 92 and 5.7 ± 0.2 and 11.4 ± 0.3 Ma for Nax 78 (ANDRIESSEN, 1978; ANDRIESSEN et al., 1979). $^{40}Ar/^{39}Ar$ analysis on biotite Nax 78 revealed a disturbed plateau spectrum with a total fusion age of 6.1 ± 0.2 Ma (WIJBRANS and MCDOUGALL, 1988). Rb–Sr measurements were made on the whole-rock, the biotite, the muscovite and the K-feldspar of both rocks (Tab. 2) and the data are plotted in an isochron diagram (Fig. 2). From the figure it is clear that muscovite and biotite of Nax 78 reacted differently to the Rb–Sr systems, and that Sr-isotopic equilibration was not attained between the two micas during the post M2 cooling, although the degree of M2 metamorphism was certainly sufficient to achieve Sr homogenization. The Rb–Sr age of the biotite/whole-rock pair is calculated at 5.7 Ma. The muscovite/whole-rock pair revealed an age of 14.3 Ma and dates the beginning of the uplift and deformation period of the deepest part of the migmatitic gneiss dome established at between 16 and 10 Ma ago (ANDRIESSEN et al., 1979; WIJBRANS and MCDOUGALL, 1988). The higher age corresponds to the higher blocking temperature of about 500 °C for the Rb–Sr muscovite system (PURDY and JÄGER, 1976). The Rb–Sr systematics of sample Nax 92 show a comparable case, with a complete Sr homogenization of the suite muscovite/whole-rock/K-feldspar, but not for biotite.The Rb–Sr age for

Tab. 1 K–Ar and Rb–Sr analysis of Nax 375, Nax 377 and Nax 379.

Sample	Mineral	K (%Wt)	$^{40}Ar_{rad}$ (ppb Wt)	$\frac{^{40}Ar_{rad}}{^{40}Ar_{tot}}$ (%)	Age (Ma)
Nax 375	phlogopite	6.35	5.46	23	
		6.35	5.43	36	12.3 ± 0.3
Nax 377	muscovite	8.80	8.08	38	
		8.79	8.35	47	13.4 ± 0.4
	biotite	7.90	7.01	23	
		7.89	7.12	39	12.9 ± 0.3
Nax 379	muscovite	8.44	13.08	57	
		8.46	13.62	56	22.7 ± 0.7
	biotite	7.81	7.54	49	
		7.81	7.63	64	14.0 ± 0.4

Sample	Material	Rb (ppm Wt)	Sr (ppm Wt)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Age(Ma)[1]
Nax 375	whole rock	5.63	210	0.078	0.70890	
					0.70874	
	phlogopite	555	8.57	187.9	0.74314	
		555	8.54	188.5	0.74254	12.7 ± 0.2
Nax 377	whole rock	42.5	406	0.303	0.70850	
					0.70853	
	muscovite	229	41.8	15.86	0.71175	
		230	41.9	15.92	0.71205	15.3 ± 0.3
	biotite	467	8.25	164.1	0.73731	
		468	8.19	165.6	0.73754	12.4 ± 0.2
Nax 379	whole rock	7.42	323	0.066	0.70795	
					0.70822	
	muscovite	279	28.5	28.3	0.71715	
		278	28.5	28.2	0.71701	22.5 ± 0.3
	biotite	316	8.05	113.8	0.73076	
		316	7.70	119.1	0.73129	13.9 ± 0.2

[1] age calculation based upon whole rock-mineral pair

the muscovite is 12.9 ± 0.2 Ma and the biotite/whole-rock shows an "age" of 2.5 Ma. In both cases Rb–Sr exchange processes took place between the mineral biotite and common Sr, which is different from the whole-rock Sr composition. This process took place during the last part of the post M2 period and therefore the "strange" common Sr is related to the retrograde fluids operating at that time. Similar processes may also have played a role for the impure marbles, but since the gneisses all have common Sr contents of only about 50 ppm and the marble about 200 ppm or more, the gneisses show a stronger Sr exchange influence than the marbles. Because of the different reaction of the minerals to the Rb–Sr system, it is possible that the mineral constituents have incorporated varying amounts of Sr from the circulating pore solutions. Both biotites from the gneisses have common Sr-contents higher than the muscovites, respectively 12.5 versus 5.1 ppm (Nax 78) and 8.7 versus 5.1 ppm (Nax 92) and the Sr content is certainly higher than that of biotites from comparable rocks having common Sr-contents around of 2 ppm (ANDRIESSEN, 1978). The isotopic composition of common Sr of the fluids involved is not known, however, when fluids with a $^{87}Sr/^{86}Sr$ ratio of 0.704 were involved a maximum age of 13.4 Ma was calculated for biotite Nax 92 and about 9 Ma for Nax 78. If, as is indicated by the stable isotope studies, peak and retrograde metamorphic fluids are products of the dehydration and decarbonation of underlying pelites, the intial $^{87}Sr/^{86}Sr$ values of the monzogranodiorite or the

Tab. 2 Rb–Sr analysis of pelitic rocks of Nax 92, Nax 78 and Nax 89.

Sample	Material	Rb (ppm Wt)	Sr (ppm Wt)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Nax 92	whole rock	148	55.5	7.7	0.74563
	muscovite	417	5.1		0.7898
		414	5.2	237	0.7855
	biotite	796	8.6		0.7561
		801	8.7	270	0.7542
	K-feldspar	296	101		0.74618
		298	101	8.5	0.74495
Nax 78	whole rock	35.3	46.6	22.1	0.76043
	muscovite	746	5.1		0.84398
		744	5.1	430	0.8428
	biotite	1196	12.5		0.73997
		1214	12.6	279	0.7398
	K-feldspar	574	91.3		0.7796
		602	91.5	18.8	0.7806
Nax 89	whole rock	62	345	0.5	0.71095
	biotite	402	3.7		0.7658
		393	3.7	313	0.7666
	K-feldspar	749	519	4.2	0.7114

synkinematicgranites, both considered to be melt products of the underlying crust, would be more appropriate. In this case Sr with $^{87}Sr/^{86}Sr$ ratio between 0.711 and 0.715 would be involved and ages of around 6–7 Ma for Nax 78 biotite and 10.5–11.5 Ma for biotite Nax 92 could be concluded. Both ages correspond closely to the K–Ar ages and the age of the biotite Nax 92 would then correspond to other Rb/Sr biotite ages of around 11 Ma, a very realistic cooling age for the central part of the dome.

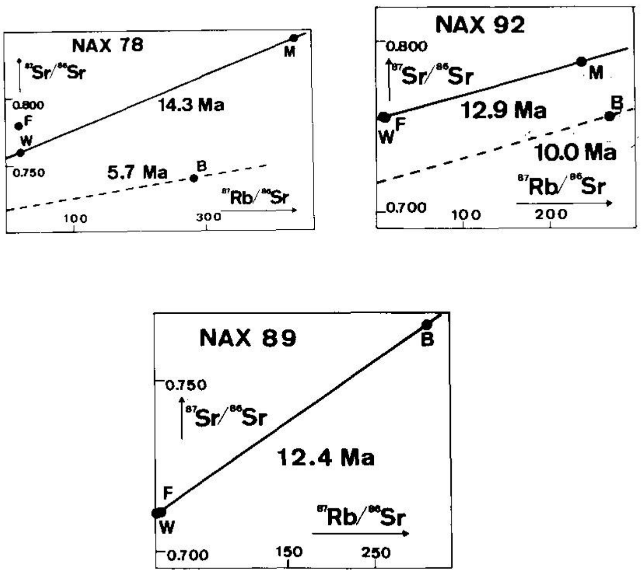

Fig. 2 Rb–Sr plots of whole rocks and minerals of Nax 78, Nax 92 and Nax 89 of pelites from the high grade part of the island of Naxos. Abbreviations used: W = whole rock; F = K-feldspar; B = biotite; M = muscovite.

The second marble sample investigated, Nax 377, was taken near the +sillimanite isograd and it contains both muscovite and biotite. The K–Ar ages obtained are 13.4 ± 0.4 Ma for muscovite and 12.9 ± 0.3 Ma for biotite. Both ages are 0.5 to 1 Ma higher than the K–Ar mica ages of between 13 and 12 Ma of the pelitic schists of this metamorphic zone (Andriessen et al., 1979; Wijbrans, 1985). There are no $^{40}Ar/^{39}Ar$ step heating experiments on micas reported. Rb–Sr analyses were made on the whole rock, the muscovite and the biotite. The whole-rock/muscovite pair defines an age of 15.3 ± 0.3 Ma and the whole-rock/biotite pair an age of 12.3 ± 0.2 Ma. The muscovite-biotite age difference of 3 Ma is very reasonable taking into account the difference in blocking temperatures of some 200 °C. A rather similar case is obtained for a nearby pelite. A hornblende-biotite-bearing granitic band, Nax 89, showed an age difference between K–Ar hornblende, 15.9 ± 0.6 Ma, and K–Ar biotite, 12.2 ± 0.4 Ma, comparable to that obtained on the minerals in the marbles. The difference in the K–Ar blocking temperature of hornblende and biotite, 500 °C versus 300 °C, is similar to that between the Rb–Sr blocking temperature of muscovite and biotite. Rb–Sr investigations were made on the whole-rock, the biotite and the K-feldspar (Andriessen, 1978). The three data points show complete Sr-homogenization and define an age of 12.4 Ma (Fig. 2), which is identical to the K–Ar biotite age. It is interesting to note that biotite in this rock has a low common Sr-content of 3.7 ppm, the whole-rock Sr-content is relatively high with 345 ppm, and the initial $^{87}Sr/^{86}Sr$ ratio of the biotite/whole-rock pair is 0.711. All these results confirm earlier statements that those systems having high common Sr in the mineral constituents are disturbed, and that the $^{87}Sr/^{86}Sr$ composition of the retrograde and peak metamorphic fluids most probably was between 0.711 and 0.715.

The mineral age results of the high-grade part show a period of at least 3 Ma of active retrograde metamorphic fluid flow, clearly related to the post metamorphic cooling and uplift era of the M2B event. Therefore, although the peak metamorphic event of M2B might only have been short, as suggested by WIJBRANS and MCDOUGALL (1988) and BAKER et al. (1989), retrograde fluids were still active for a long period following the peak of metamorphism, and it seems that the late stage M2B influences had the greatest effect upon the K–Ar and Rb–Sr mineral systems. The complete rejuvenation of Rb–Sr muscovite, phlogopite and biotite systems also strongly suggest recrystallization or at least chemical adjustment.

The lowest grade marble, Nax 379, located between the –chloritoid and +biotite isograd contains both muscovite and biotite. The K–Ar age of the muscovite is 22.7 ± 0.7 Ma and that of the biotite 14.0 ± 0.4 Ma. These are the highest ages obtained so far for typical M2 muscovite and biotite from the medium to high grade of the island. The metamorphic grade is estimated at a temperature of about 540 °C, which is higher than the blocking temperatures of K–Ar mica systems. Besides the normal cooling ages a few exceptionally high ages were obtained with both the K–Ar and $^{40}Ar/^{39}Ar$ method in the case of hornblendes and white micas of this metamorphic zone. These results were explained either by the incorporation of excess radiogenic Ar in the hornblende crystals or by a mixture of old phengite and new crystallized M2 muscovite. These results show that age determinations from amphibolites and pelites from this zone must be treated with special care. Rb–Sr investigations were made on the whole rock, the muscovite and biotite of Nax 379. The whole rock/muscovite pair shows an age of 22.5 ± 0.3 Ma and the whole rock/biotite pair an age of 13.9 ± 0.2 Ma, thus yielding identical ages according to the Rb–Sr and K–Ar decay systems. The muscovite-biotite age difference of 8–9 Ma cannot be explained by simply post-M2 cooling.

This zone more or less forms the transition between the medium to high grade part and the low grade part of the island, where apart from the influence of the high temperature phase greenschist facies rocks and even relicts of the high pressure M1 phase event occur. Thus, the overprinting by the younger, high temperature phase that was ubiquitous in the higher grade parts, was not strong enough to wipe out the effects of the previous geological events in the eastern part of the island. It is possible that the lithological character of the present rock types plays a role. Marble is dominant in the eastern part and as is shown by stable isotope measurements inside the marble bands, the stable isotope ratios indicate the survival of pre-metamorphic, perhaps even sedimentary signatures (RYE et al., 1976; BAKER et al., 1989). In a grain-size study of the marbles in relation to the metamorphic temperature and the deformation, it was observed that a discontinuity exists around the 500 °C zone (COVEY-CRUMP and RUTTER, 1989). In the marbles there are hardly any signs of deformation or metamorphic lineation. The investigated marble is coarse-grained, indicating recrystallization and the biotite age of 14 Ma correlates perfectly with the post-M2B uplift period between 15–10 Ma ago and, being located more at the margin of the migmatite gneiss complex, the higher age and minor deformation is only to be expected. The identical K–Ar and Rb–Sr biotite ages indicate complete Sr-homogenization between the marble whole rock and the biotite, and make the presence of excess radiogenic Ar rather unlikely. It may therefore be concluded that the biotite age of 14 Ma represents the time that the post-M2B temperature dropped below the blocking temperature of about 300 °C.

The muscovite in the marble also yielded identical ages for the Rb–Sr and K–Ar systems, a feature which needs a special explanation because of the difference in blocking temperature of 500 °C for Rb–Sr and 350 °C for K–Ar. Apparently concordant ages could be the result of a fast cooling, but this interpretation does not allow for the much lower biotite age. The incorporation of excess radiogenic Ar in muscovite could, by coincidence have resulted in a calculated age similar to the Rb–Sr age, but requires quite a volume of excess radiogenic Ar. A mixture of an older white mica and a new crystallized M2B mica as the explanation is also unacceptable, because microscopic investigation revealed only one generation of non-orientated crystals. It is also not very plausible that in such a case identical ages would be found. The results of the Rb–Sr analyses of the marble/muscovite pair give no reason to doubt the age obtained. Exchange of common Sr related to circulating fluids, as discussed earlier, would hardly have influenced the system, because it would have been completely buffered by Sr in the marble. There is no indication of large amounts of fluids flushing through the marbles, in fact the stable isotope studies suggest the contrary. The Rb–Sr age of 22.5 ± 0.3 Ma of muscovite therefore has to be accepted as a realistic age. The commonly accepted blocking temperature of the Rb–Sr muscovite system has been estimated at about 500 °C (PURDY and JÄGER, 1976) and the ambient metamorphic temperature for the location of this sample is also estimated at about 540 °C. The age of 22–23 Ma therefore refers to the formation of muscovite and the associated phase of metamorphism and not to a cooling stage after metamorphism. The crystallization of the muscovite is related to the M2 phase of metamorphism, either to the regional greenschist facies dated at about 23 ± 2 Ma ago (ALTHERR et al., 1979; SCHLIESTEDT et al., 1987), or to the local high temperature phase dated at 19–20 Ma (ANDRIESSEN and JANSEN, 1990). The age of 22–23 Ma supports the idea that the muscovite is a product of the M2A greenschist event and then the muscovite would actually date this metamorphic phase on the island of Naxos.

Accepting this interpretation for Rb–Sr, the high K–Ar age has still to be explained. In this respect it is interesting to note that a siliceous marble from the island of Ikaria yielded a muscovite K–Ar age of 22.3 ± 0.2 Ma (ALTHERR et al., 1982). The greenschist-lower amphibolite facies on this island, situated northeast of Naxos, is dated at 24–25 Ma (ALTHERR et al., 1982) and the muscovite K–Ar age could reflect the subsequent cooling. In any case the marble both on Ikaria and Naxos prevented later degassing and outgassing of the mica and the concept of blocking temperature cannot be applied. The concept of blocking/closure temperature is only valid when free pathways are available for the isotopes to move in and out of the crystal until a particular temperature zone is reached. Below this zone the isotopes produced are captured in the lattice of the mineral and the system is closed. If, however, the nature of the host rock blocks the free pathways, owing to, for example the dense structure like in glass or basalts cooled in a marine environment, then it is possible that a mineral becomes a closed system directly after its formation, although the ambient temperature is above the blocking temperature. Something similar could have happened in the case of the recrystallized marbles, where soon after the formation of the muscovite during the regional M2A greenschist facies hardly any exchange or degassing took place in the mineral. The mineral biotite is more probably a (re)crystallization product of the M2B high-temperature phase. The age of 14 Ma represents the time that the ambient temperature during the post-metamorphic cooling period felt to below 300 °C, the blocking temperature of biotite.

The interpretation is that in this particular lithological rock type the muscovite is a relic of the M2A greenschist phase, which was not influenced by the later M2B high-temperature event, which for this location was not much different in metamorphic conditions. This effect might also show up in the age determinations of micas from schists of a lower metamorphic grade. Indications of this can be found in the reported $^{40}Ar/^{39}Ar$ age spectra of white mica seperates from the zones where the transition occurs from M1 phengites to M2 muscovites, the two zones adjacent to the metamorphic zone where Nax 379 comes from (WIJBRANS and MCDOUGALL, 1986). The upward-convex age spectra obtained were explained as the result of the presence of two distinct generations of mica, and as a consequence of this, the author states that the low ages in the high temperature segment may provide an estimate for the age of the younger muscovite component. Indeed in several cases the ages of 20–25 Ma were obtained for the high temperature steps and therefore support the above interpretation.

Conclusions

K–Ar and Rb–Sr analyses of muscovite from an impure marble of medium metamorphic grade, near the +biotite isograde, of the metamorphic complex of the island of Naxos show a relic M2A greenschist age of 22–23 Ma. The particular lithological character of the marble prevented the open infiltration of metamorphic fluids during the later 19–20 Ma-old, M2B high temperature phase. The marble proved to be a well shielded system, both for the exchange of Sr and the degassing of Ar. Biotite from the same rock gave a typical post-M2B cooling age of 14 Ma, indicating that this mineral was rejuvenated during the younger uplift stage.

K–Ar and Rb–Sr ages of muscovite, phlogopite and biotite of impure marbles of the high grade metamorphic part of the migmatitic gneiss dome correlate perfectly with the post-M2B cooling and uplift period of the central part of the island at 16 to 10 Ma ago. The mica ages of the marbles, however, are some 0.5 to 1 Ma higher than those of corresponding minerals from the nearby gneisses and pelites, indicating that the flow of retrograde fluids ceased at an earlier time in the marbles than in the more open gneisses. Estimated values of the Sr-isotopic composition of between 0.711 and 0.715 of the peak and retrograde fluids support the derivation of dehydrating and decarbonating underlying pelites.

This investigation shows that metamorphic fluid flows and the difference of permeability of various rock types are important parameters for geochronological interpretation. Mineral ages in terms of resetting and cooling/uplift histories of metamorphic terranes must be interpreted with care, because certain rock types are either better shielded against percolating fluids or are closed systems at an earlier stage than the adjacent rocks.

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