The geology of the polymetamorphic complex of Ios, Cyclades, Greece and its significance for the Cycladic Massif.

By Paul A. van der Maar and J. Ben H. Jansen, Utrecht *)

With 4 figures and 3 tables

Zusammenfassung

Die Kykladeninsel Ios besteht zur Hauptsache aus einem Gneisdom. Der Kern dieses Doms ist ein Augengneiskomplex, welcher von Granat-Muskovit-Schiefern umhüllt wird. Auf dieses Grundgebirge ist eine Marmor-Schiefer-Serie überschoben worden, eine tektonisch bedingte Wechselfolge von Metasedimenten und Metavulkaniten, wahrscheinlich mesozoischen Alters.

Die petrologischen Gegebenheiten und Isotopendatierungen bezeugen Polymetamorphose. Es konnten zwei metamorphe Phasen alpidischen Alters nachgewiesen werden, M_1 und M_2, sowie die Spuren einer hochgradigen, metamorphen oder magmatischen Phase M_0, welche nur die Basis betroffen hat.

Radiometrische Alterbestimmungen bestätigen die Deutung, daß das Grundgebirge voralpidisches Alter hat. Die Phasen M_1 und M_2 wurden datiert auf 43 Mj. und 25 Mj. Die Druck-Temperatur-Bedingungen der M_1 und M_2 wurden abgeschätzt auf 9—11 Kb und 350—400° C für die M_1 und auf 5—7 Kb und 380—420° C im Falle der M_2. Der metamorphe Werdegang der Kykladen wird diskutiert sowie die mutmaßliche Existenz eines vergleichbaren voralpidischen Grundgebirges auf den Nachbarinseln Sikinos und Naxos.

Abstract

The geological structure of the island of Ios, Cyclades, Greece, is a dome consisting of an augengneiss core and a mantle of garnet-mica schists that together form the Basement which is overthrust by a marble-schist Series. This Series is mainly made up of metavolcanics and metamorphosed sediments, presumably Mesozoic in age. It is a tectonically composed pile of marbles alternating with glaucophane schists, actinolite schists and chlorite schists. Petrological relations and isotope dating indicate the polymetamorphic character of Ios. Two Alpine metamorphic phases, M_1 and M_2, and relicts of a high grade metamorphic or magmatic phase (M_0), that only affected the Basement, are demonstrated. Radiometric ages obtained for the Basement confirm the interpretation that the M_0 phase is Pre-Alpine. The M_1 and M_2 were dated at 43 Ma and 25 Ma respectively. The P-T conditions of metamorphism are estimated as 9—11 kb and 350 to 400° C for the M_1 phase and 5—7 kb and 380—420° C for the M_2 phase. The metamorphic history of the Cyclades is discussed and it is suggested that Pre-Alpine Basement occurs also on Sikinos and Naxos.

Résumé

La structure géologique de l'île d'Ios (Cyclades, Grèce) est un dôme. Le noyau du dôme est un complexe d'augengneiss enveloppé par des schistes à grenat et mica. Ce noyau, qui constitue le socle, est chevauché par une série composée d'une succession tectonique de marbres et de schistes à glaucophane, de schistes à actinote et de schistes à

---

*) Authors' addresses: P. A. van der Maar and J. .B. H. Jansen, Department of Geochemistry, Institute of Earth Sciences, State University of Utrecht, Budapestlaan 4, 3584 CD Utrecht, The Netherlands.

chlorite. Les relations pétrologiques et les datations isotopiques indiquent le caractère polymétamorphique de l'île d'Ios. On y peut démontrer deux phases de métamorphisme alpin (M 1 et M 2) ainsi que des témoins d'une phase métamorphique ou magmatique antérieure qui n'a influencé que le socle. Les datations radiométriques obtenues pour le socle confirment l'âge préalpin de la phase M 0. Les phases M 1 et M 2 sont datées à 43 et 25 Ma respectivement. Les conditions du métamorphisme des phases M 1 et M 2 sont estimées respectivement à 9—11 kb avec 350—400° C, et 5—7 kb avec 380—420° C. L'histoire métamorphique des Cyclades est discutée ainsi que la présence probable d'un socle Préalpin comparable dans les îles voisines de Sikinos et de Naxos.

Краткое содержание

Остров Kykladen Ios состоит главным образом из единого гнейсового купола. Ядро его — комплекс глазкового гнейса, окруженного сланцами, содержащих гранат и мусковит. На этот фундамент, в результате тектонических процессов, надвинулась мраморно-сланцевая серия, вероятно мезозойского возраста, чередующая ся с метаседиментами и метавулканитами. С помощью петрологических и изотопных данных удалось установить две метаморфные фазы альпийского возраста в данных породах (M_1 и M_2) и следы высокой Метаморфной, или магматической деятельности (фаза M_0), Которая охватила только основание.

Геохронологические исследования подтвердили, что фундамент имеет доальпийский возраст. Возраст фаз M_1 и M_2 — 43, и 25 миллионов лет. Условия давления и температуры для M_1 считают 9—11 кб и 350—400° С, а для M_2 — 5—7 кб и 380—420° С. Дискутируются процессы метаморфизма на о. Kykladen и сравнивается течение этого процесса с таковым в до-альпийских фундаментах соседних островов Sikinos и Naxos.

Introduction and Geological Setting

The island of Ios belongs to the Cycladic Archipelago in the Aegean sea and is situated about 200 km SE of Athens (fig. 1). It is part of the Attic-Cycladic Massif, which is an intermediate part of the Alpine orogenic belt found on the Greek and Turkish mainland. The Massif mainly consists of regionally metamorphosed rocks of different metamorphic grades. Glaucophaneschist facies rocks (blueschists) are found on most islands (Table III). Nearly all the glaucophaneschist facies rocks on the islands show the overprinting effect of a greenschist facies or amphibolite facies metamorphic phase (fig. 1).

Ios can be divided geologically into two main units: the Basement and the overlying marble-schist Series (fig. 2) (v. D. MAAR and JANSEN, 1981). The Basement consists of a domeshaped augengneiss complex and a garnet-mica schist mantle. Bodies of metamorphosed intrusive rocks only occur in the Basement. The augengneiss is interpreted as a metamorphosed granitic intrusion, or as a migmatite complex and it contains parts of the garnet-mica schists as roof-pendants (v. D. MAAR, 1980). The marble-schist Series is a sequence of mainly calcitic marbles alternating with chlorite schists, actinolite schists and glaucophane schists. The marbles contain Fe-rich lenses and meta-bauxites (diasporites), which are probably of lateritic origin. Zones of small eclogitic and glaucophanitic lenses are found embedded respectively in the glaucophane schists proper and in the glaucophane-bearing schists in the lower marble zone (fig. 2). In the chlorite schists a zone of lenses of ultramafic composition occurs. Because of this zone the Series is interpreted as a tectonically assembled pile rather than as one continuous strati-

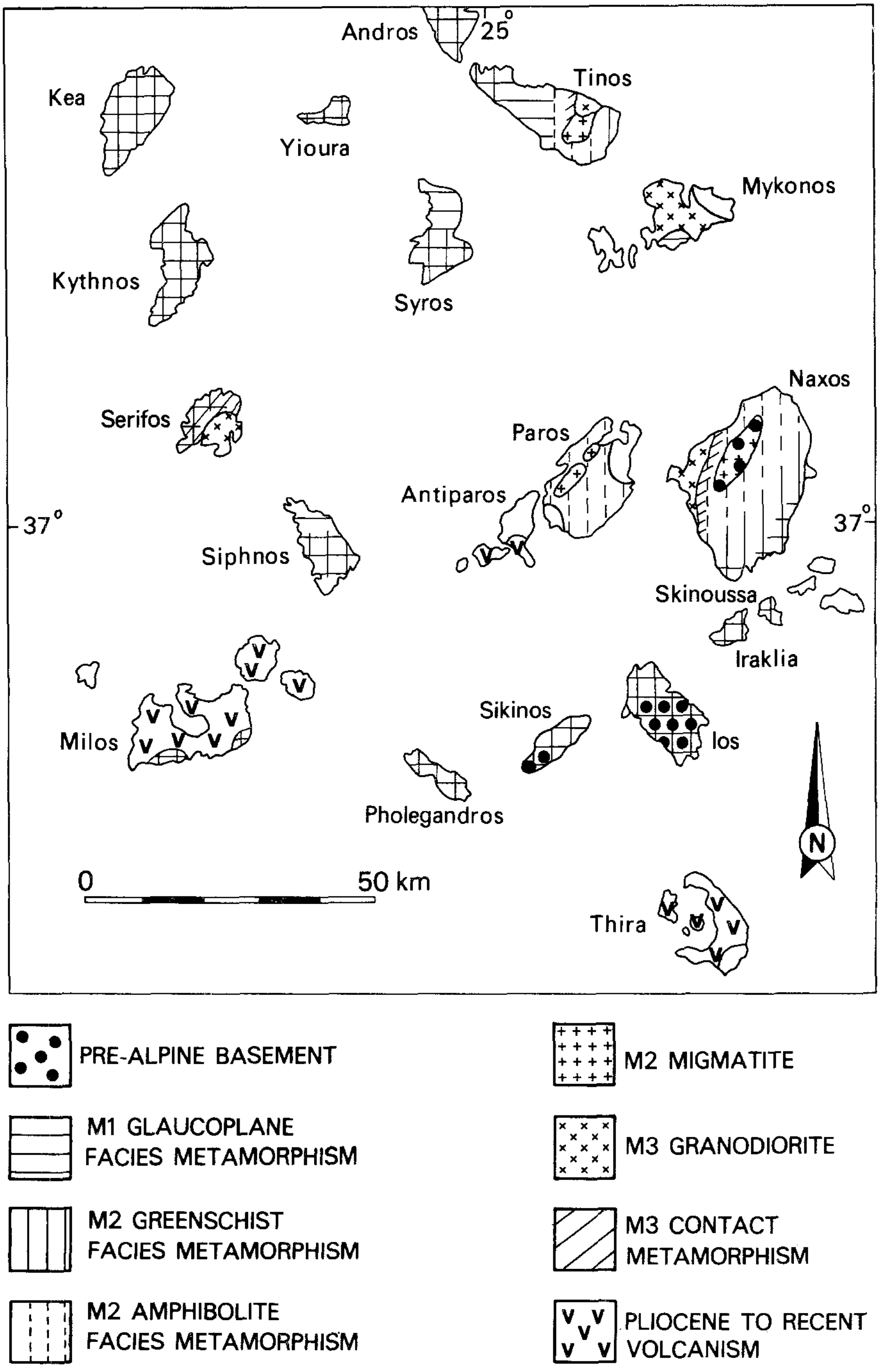

Fig. 1. Map of Cyclades, Greece, with the distribution of metamorphic rocks. For references: see Table III.

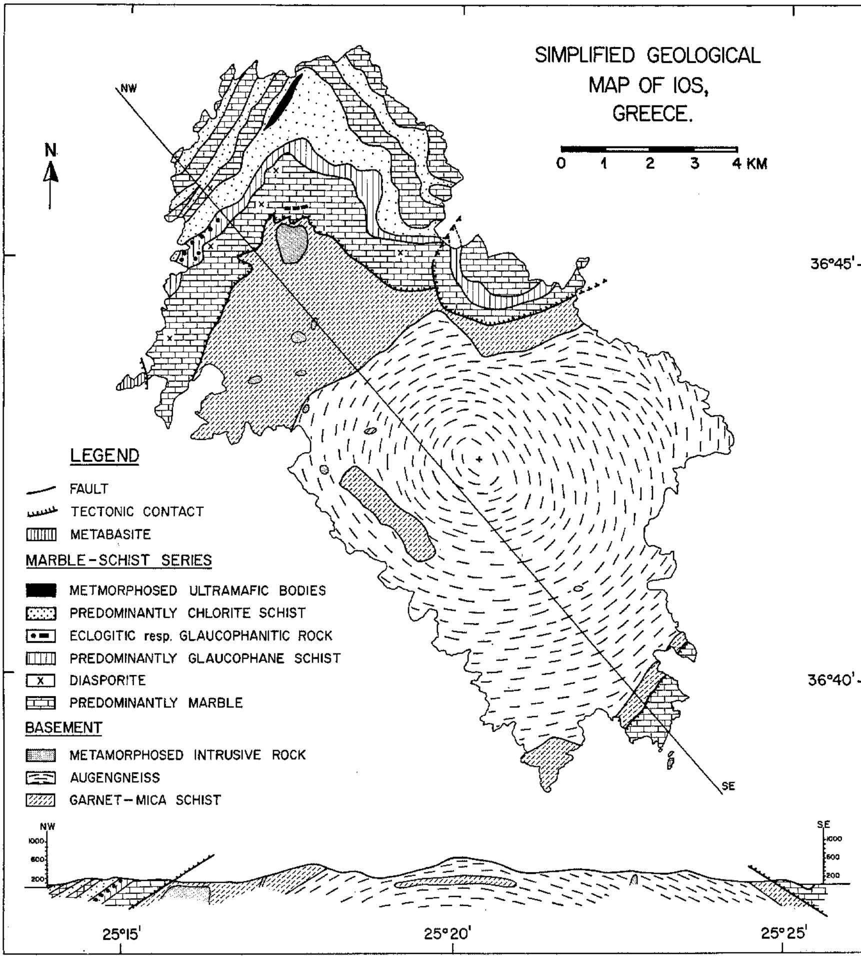

Fig. 2. Simplified geological map of Ios, with a schematic NW—SE cross section.

graphic sequence that was formed in situ. The boundary between the Basement and the Series on Ios is interpreted as a metamorphosed major thrustplane (v. d. Maar, 1980).

Metamorphic phases and their preliminary isotope dating

Mineral assemblages and textural relations in the rocks of Ios reveal the influence of at least three successive metamorphic phases. The mineral content of selected rocks from the marble-schist Series and from the Basement is summarized in Tables I and II respectively. An extensive petrological description is given in an earlier paper (v. d. Maar, 1980).

The Alpine metamorphic phase M 1 that is characterized by glaucophane-schist facies conditions is most obvious in the mineral parageneses of the Series. Glaucophane and crossite occur in association with: garnet-phengite-quartz; albite-phengite; phengite-calcite-sphene; albite-phengite-epidote. The glaucophane is occasionally rimmed with actinolite. Chloritoid is sometimes present as inclusions in glaucophane and garnet. Rectangular pseudomorphs after lawsonite have been preserved in the actinolite-chlorite-rich parts of the metamorphosed ultramafic bodies and in carbonate lenses in the same horizon. They consist of a mixture of phengite, zoisite, quartz and calcite. Small carbonate lenses within dense rock such

Table I. Minerals in rock types from the marble-schist Series and the metabasite

Sample number	Coordinates Latitude	Longitude	Quartz	Albite	Chlorite	Muscovite 3)	Biotite	Garnet	Actinolite	Glaucophane	Crossite	Epidote	Calcite	Apatite	Sphene	Mag. / Hematite	Other Minerals
Marble 2)																	
22.4-16	36°45'43"	25°17'50"		X	X	X		X	+ 5)	X	X	X		X	X		Ae
24.4	36 45 35	25 18 15						X		Ri			X			X	Ae
Diasporite																	
22.1	36 44 05	25 15 33				Ma			Ctd				X	X	Di	X	Ky
Io 83	36 44 05	25 15 39				Ma			Ctd				X	Ru	Di	X	
Glaucophane schist																	
29	36 44 29	25 20 34	X		+	X 6)	+	X	Ctd 4)	X						X	
39	36 45 41	25 18 31		X			+			X						X	
45 E	36 45 00	25 16 09	X		+	X	+			X	X		X		X	X	
83	36 45 03	25 16 04	X	X	+	X	+		X 5)	X	X	X		X	X	X	
Eclogitic rock																	
32	36 44 58	25 15 48	O					X		Ri			X			X	Ae
108 C	36 45 02	25 16 03	X	X			St	X		Ri		X			X	X	Ae
Glaucophanitic rock																	
15	36 45 42	25 17 32		O	+			X	X 5)	X	X	X	X	O	X	X	
16-17	36 45 44	25 18 30		X						X	X	X	X	X	O	X	
Chlorite schist																	
18	36 45 52	25 16 18		X	X							X	X	X	X		
63	36 45 47	25 16 24	X		X	X		X	X					X	X		
Metamorphosed ultramafic bodies																	
68 A 1)	36 46 45	25 17 05			X	Fu			X			X					Ta
Metabasite																	
5 D	36 43 30	25 15 10		X	X	X	X		X			Zo	X	O	X	X	

X= major constituent; O= minor constituent; += secondary mineral;
Ctd= chloritoid; Di= diaspore; Ae= aegerine; Fu= fuchsite; Ky= kyanite; Ma= margarite;
Ri= riebeckite; Ru= rutile; St= stilpnomelane; Ta= talc; Zo= zoisite.
1) pseudomorphs after lawsonite
2) samples are taken from silica-rich layers in the marble zones
3) predominantly phengite or phengitic muscovite
4) relicts in glaucophane and garnet
5) actinolite rims around glaucophane and/or crossite crystals
6) also paragonite
Io .. : sample collected by B.W.Vink.

as the eclogitic and glaucophanitic rock or metabauxites contain calcite with a columnar habit which is interpreted as pseudomorphic after aragonite; optically the carbonate is biaxial while X-ray diffraction shows it to be calcite. Iron-rich crossite is found with aegerine augite, garnet, epidote, calcite and magnetite in the eclogitic rock. The assemblage magnesioriebeckite-aegerine-garnet-magnetite-calcite is found in metamorphosed iron-rich lenses in the marbles. In the metabauxites the assemblage diaspore-chloritoid-calcite is found. The main M 1 assemblage in the Basement, especially in the garnet-mica schists and in the meta-intrusive bodies, is garnet-phengite-albite-quartz often with epidote and actinolite. Chloritoid is locally present in the garnet-mica schist. Glaucophane relicts are also found in the Basement but they are extremely rare. The M 1 phase is dated with the K-Ar method on phengite and paragonite. These minerals obtained from the glaucophane schists of the Series yielded ages of 43 ± 1.3 Ma for the M 1 phase (Andriessen, 1978). Kreutzer et al. (1978) found the age of the glaucophane schist to be older than 39 Ma. Some micas from gneisses of the Basement also yielded M 1 ages (Henjes-Kunst, 1980). Recent measurements carried out at the Z. W. O. Laboratorium voor Isotopen Geologie in Amsterdam confirm the M 1 age of part of the micas from the Basement (Andriessen, pers. comm.).

Influence of the Alpine M 2 greenschist facies overprint is found in the rocks of the Basement and the Series. The effects are usually less obvious than those of the

Table II. Minerals in rock types from the Basement

Sample number	Coordinates Latitude	Longitude	Quartz	K-feldspar	Albite	Chlorite	Mica	Biotite 2)	Chloritoid	Garnet	Actinolite	Amphibole	Epidote	Apatite	Sphene	Mag. / Hematite	Calcite
Garnet-mica schist																	
40 1)	36°43'50"	25°17'00"	X		X		X										
57	36 43 50	25 16 04	X		X	+	X	+		X							X
72	36 43 43	25 16 08	X		X	X	X	+		X	X		X				
36	36 42 00	25 18 58	X		X		X			X	X		X	X	X		
34	36 40 10	25 23 04	X		X		X			X	X		X	X			
90 B	36 43 13	25 17 26	X		X	X	X		X	X			X			X	
6.6	36 42 25	25 18 20			X	+	X	+		X	X 3)	Gl	X			X	
Augengneiss																	
3	36 43 09	25 19 58	X	X	X		X						+		X	X	
Metamorphosed intrusive rock																	
12	36 45 19	25 17 34	X	X	X		X	R		O			+	X		X	
84 B	36 44 13	25 17 47	X		X		X	R		X		R	Zo 4)				O
10.7 B	36 43 31	25 16 55	X		X		X	R		X			+				

X= major constituent; O= minor constituent; += secondary mineral; R= relict mineral; Gl= glaucophane; Zo= zoisite.

1) aplitic rock

2) most biotite occurs as small secondary flakes in the garnet-mica schist and augengneiss and as relictic blasts in the metamorphosed intrusive rocks

3) actinolite rims around glaucophane crystals

4) allanite relicts also present

M 1 phase. Typical M 2 assemblages all over the island are: biotite-chlorite-albite-actinolite and chlorite-actinolite-phengite-epidote. The minor amounts of biotite are formed preferentially around the minerals garnet, glaucophane, phengitic muscovite, chlorite and magnetite. The biotite is mostly pleochroic from light greenish-brown to green colours. Chlorite replaces garnet, glaucophane and primary M 1 actinolite. It occurs particularly in pressure-shadows around garnet and glaucophane and in cracks through these minerals. Green M 2 actinolitic rims replace most of the sodic amphiboles. Small euhedral crystals of glaucophane and crossite have only been preserved in albite blasts of the actinolite-rich chlorite schist. Stilpnomelane occurs in riebeckite-garnet rich parts of the eclogitic rock, it is a breakdown product of the riebeckite. In the metabauxites the kyanite and the margarite apparently are M 2 minerals. Sericite, chlorite and fine grained epidote parageneses are developed in fissures in the augengneiss.

The M 2 phase was apparently dated by KREUTZER et al. (1978). They found a K-Ar age of 25.6 Ma for phengite from a phengite-albite gneiss.

Some relictic minerals and mineral assemblages in the Basement of Ios do not correspond with the mineralogies that are characteristic for glaucophaneschist facies metamorphism. These minerals are especially observed in the metamorphosed intrusive rocks that can be divided into metagranites and metalamprophyres. Both rock types contain large crystals of dark brown pleochroic biotite that is characteristically replaced along its rim by garnet and phengite. These coronas were presumably caused by the M 1 event. The metalamprophyres also contain relicts of allanite, of brown hornblende and of assemblages of biotite and hornblende. Pseudomorphs consisting of fine-grained mixtures of albite, zoisite and phengite may represent the original Ca-rich plagioclase. The pseudomorphs are present in most of the metamorphosed intrusive rocks. HENJES-KUNST et al. (1978) reported the occurrence of plagioclase with up to 50 % An in the metamorphosed intrusive rocks. The augengneiss dome is a monotonous complex consisting almost entirely of the granitic assemblage microcline-albite-quartz-muscovitic phengite. The albite crystals contain numerous zoisite and mica inclusions which indicate that they originated from Ca-rich plagioclase. The microcline is perthitic and its twinning and extinction pattern suggest that it originally was orthoclase.

K-Ar datings on hornblendes from metamorphosed intrusive rocks show model ages that range from 1577 to 1004 Ma (KREUTZER et al., 1978, HENJES-KUNST, 1980). These ages together with an age of 784 Ma obtained for a biotite from the same rocktype were interpreted as "excess argon" results. K-Ar datings and Rb-Sr datings on some biotites from the metamorphosed intrusive rocks show ages ranging from 166 to 217 Ma. These results were regarded as "mixed ages". These radiometric measurements lend support to the interpretation that Ios is a window structure through which a metamorphosed remnant of Pre-Alpine crystalline basement is exposed.

Inferred P-T conditions for the Alpine phases on Ios

The metamorphic conditions of the M 1 phase can be estimated from the preserved and pseudomorphic mineralogies. Relevant metamorphic reactions are shown in fig. 3. Aragonite was not found on Ios but as discussed above, some calcite is pseudomorphic after aragonite. The M 1 conditions must consequently be placed on the high pressure side of the experimentally determined curve (2) of the aragonite-calcite transition (JOHANNES and PUHAN, 1971). The pseudomorphs after lawsonite support this conclusion and show that the M 1 conditions were confined to the low temperature side of the lawsonite breakdown reaction (6) (NITSCH, 1974). The reaction jadeite + quartz to albite was not demonstrated on Ios. On account of the presence of albite-quartz assemblages the range of the M 1

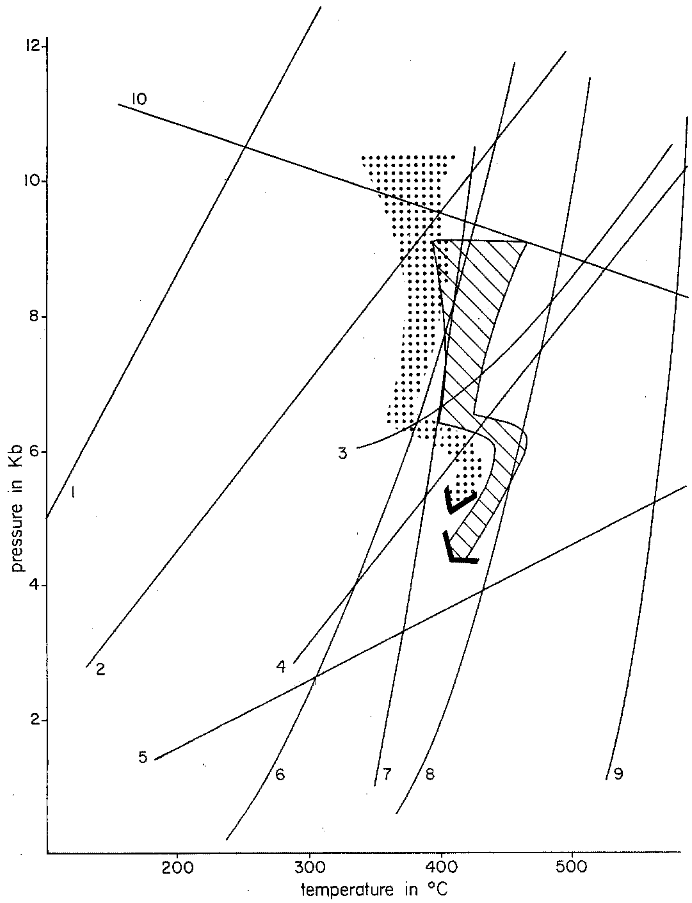

Fig. 3. P-T curves of mineral equilibria relevant to the mineralogies observed on Ios. 1, jadeite + quartz = albite (BOETTCHER and WYLLIE, 1969); 2, aragonite = calcite (JOHANNES and PUHAN, 1971); 3, crossite + epidote = albite + actinolite + chlorite + magnetite/hematite (BROWN, 1978); 4, actinolite + muscovite + stilpnomelane = biotite (BROWN, 1978); 5, kyanite = andalusite (average value using ALTHAUS, 1967 and RICHARDSON et al., 1969; see JANSEN and SCHUILING, 1976); 6, lawsonite = margarite + zoisite + quartz + H_2O (NITSCH, 1974); 7, diaspore + pyrophyllite = kyanite + H_2O (HAAS, 1971); 8, diaspore = corundum + H_2O (HAAS, 1971); 9, breakdown of chloritoid (RICHARDSON, 1968); 10, omphacite = Ca-amphibole + albite (BROWN, 1978). Dotted arrow and hatched arrow: estimated change in P-T conditions for Ios respectively SE Naxos.

phase conditions is limited to the low pressure side of the reaction curve (1) (BOETTCHER and WYLLIE, 1969). In the eclogites and in the Fe-rich bodies jadeite-bearing pyroxene is present. Its conversion to riebeckite plus albite and actinolitic amphibole, can be deduced. Conditions for a similar reaction (10) are given by BROWN (1978). The M 1 conditions are confined to the high P side of this curve. The evidence discussed above, indicates a minimum pressure for the M 1 of 9—11 kb with a temperature range of 350—400° C. The upper pressure limit for the same temperature range is about 15 kb.

The P-T conditions of the M 2 phase can be approximated based on the occurrences of the following minerals and mineral assemblages. Aragonite has been replaced by calcite and sodic pyroxene has reacted to produce riebeckite and actinolitic amphiboles. Lawsonite is replaced by the assemblage zoisite-mica-calcite-quartz. The M 2 conditions are thus confined to the low pressure sides of reactions (2) and (10) and to the high temperature side of the reaction curve (6). Corundum has not been found in the metabauxites so the temperature range of the M 2 phase is limited to the low temperature side of the curve (8), diaspore to corundum, determined by HAAS (1971). Kyanite occurs in the metabauxites with diaspore and the reaction (7) gives an idea of the minimum conditions of the coexistence of kyanite and diaspore (HAAS, 1971). The M 2 conditions must have been well above the kyanite-andalusite transition conditions because kyanite is the only Al-silicate found on Ios (5), (average value using ALTHAUS, 1967 and RICHARDSON et al., 1969; see JANSEN and SCHUILING, 1976). Moreover chloritoid seems to remain stable in the metabauxites as well as in the garnet-mica schist near the augengneiss dome. This indicates that M 2 conditions were below those of the — chloritoid curve (9) (RICHARDSON, 1968). Estimates of the M 2 pressure conditions can be refined considering the M 2 breakdown products of M 1 minerals in the glaucophane-bearing schists. BROWN (1978) describes a reaction, crossite + epidote to albite + actinolite + chlorite + magnetite or hematite (3), which may explain the existence of the actinolite rims around the blue amphiboles. According to this curve the upper stability limit of the actinolite rims is about 6—7 kb for a temperature between 350 and 420° C. Stilpnomelane is found in parts of the eclogitic rocks and neo-formation of biotite is observed in most rocks of Ios. Although the complete assemblage belonging to the reaction (4) muscovite + stilpnomelane + actinolite to biotite is not found, this reaction gives an idea of the stability field of stilpnomelane and of the conditions of the appearance of biotite. The pressure and temperature conditions of the M 2 stage are deduced as 5—7 kb and 380—420° C. From the inferred P-T conditions it can be concluded that the M 2 phase was initiated by a small rise in temperature following a pressure drop of at least 4 kb (see fig. 3). In fig. 3 the P-T-loop for Ios is drawn in comparison with the P-T-loop for the SE part of Naxos (JANSEN et al., 1977).

During the M 1 phase the geothermal gradient was approximately 12° C/km and during the M 2 phase it was at least 22° C/km. The rates of uplift and denudation of Ios since the M 1 phase can be calculated from the pressure and temperature estimates and the radiometric data assuming an average density of 3 gr/cm^3 for the rocks. During the 18 Ma between the M 1 phase and the M 2 phase the average rate of uplift was at least .7 mm/a. Since the M 2 phase the pressure has been dropped 6 kb which equals the removal of a rockpile of 18 km thickness and the corresponding average rate of uplift must have been .7 mm/a.

P. A. VAN DER MAAR and J. B. H. JANSEN

Extension of the Series and the Alpine metamorphic phases in the Cycladic area

Subrecent and Quaternary vertical tectonic activities have divided the Cycladic Massif in several segments that possibly moved independently up and downward. Therefore a correlation of the lithological units and a comparison of the effects of the Alpine metamorphic phases among the islands is difficult. Also the degree of metamorphism during each metamorphic phase may have varied lateraly in the area. Nevertheless, sequences of marbles and schists, similar to the Series of Ios have been reported from Andros, Iraklia, Kea, Kythnos, Milos, Naxos, Paros, Pholegandros, Serifos, Sikinos, Siphnos, Skinoussa, Syros, Tinos and Yioura; for the references see Table III. The occurrences of a few horizons of metamorphosed Fe-rich bodies and metabauxites in the marbles and of lenses of eclogitic, metavolcanic, ultramafic and gabbroic rocks in the schists provide markers for lithological correlation among the islands. Except on Milos, Skinoussa, Tinos and Yioura metamorphosed Fe-rich bodies, occurring in the marbles, have been reported from all the islands mentioned. Especially on Ios, Iraklia, Naxos, Paros and Sikinos also metamorphosed bauxites are found. On Ios, Kythnos, Naxos, Pholegandros, Sikinos and Syros bodies of metamorphosed ultramafic and gabbroic rock are exposed and from Andros, Ios, Milos, Naxos, Sikinos, Siphnos, Syros and Yioura eclogitic lenses have been reported. So we may conclude that the marble-schist Series generally extended all over the Cycladic area. However, the specific sequences within the Series may vary because of original lateral variations of the sediments and because on several islands the Series is tectonically assembled (JANSEN, 1977; v. D. MAAR, 1980). The sedimentary age of the whole Series is not well defined. In a comparison of the Cyclades with Attica and the Menderes Massif DÜRR et al. (1978) discuss a Mesozoic age of the marble-schist Series in the Cycladic area. DÜRR and FLÜGEL (1978) definitively reported an Upper-Triassic age of marbles on Naxos.

Except on Antiparos and Paros rocks on all other mentioned islands locally show convincing remnants of glaucophaneschist facies or glaucophane-greenschist facies metamorphism of the M 1 phase (fig. 1 and Table III). On Paros the M 2 and M 3 phases were intensive and probably all remnants of the M 1 phase were obliterated. On Antiparos no glaucophane schist facies minerals have been found, due to the fact that the main part of the island consists of weakly metamorphosed rocks that belong to high tectonic units superimposed on the Series after the M 3 phase (for Naxos, see JANSEN, 1977). The upper tectonic units are found on several Cycladic islands, however, they fall beyond the scope of this paper (see footnote [1]). The remaining part of Antiparos consists of volcanics of Pliocene age (ANASTOPOULOS, 1963). On Mykonos and Thira, that largely consists of recent volcanic rocks, glaucophane schist is reported by MARINOS (1978). DAVIS (1972) proposed the absence of glaucophane in the rocks of Kea but recently its presence was demonstrated by Schuiling (pers. comm.).

In schists on Kythnos and in the extreme northern part of Serifos glaucophane

[1]) Similar remnants of upper tectonic units occur on the northern part of Andros (PAPANIKOLAOU, 1977), on the south-western and eastern part of Paros (PAPANIKOLAOU, 1979) on several locations on Naxos (JANSEN, 1977), on Mykonos (PAPASTAMATIOU, 1963), on Thira (TATARIS 1964) and probably also on the utmost western peninsula on Ios (VAN DER MAAR, 1980).

Table III. Distribution of the metamorphic and magmatic phases on the Cycladic islands, mentioned in figure 1.

Island	Phase	Type	Pressure in Kb	Temperature in °C	Age in Ma	References (see below)
Andros	M1	glauc	HP	LT		22,25,37
	M2	green	MP	MT		
	M?	low gr	LP	LT		
Antiparos	M?	low gr	LP	LT		2,26,37
	V	volcan.	LP	HT	Pliocene	
Ios	M0	Basement	MP	MT-HT	Pre-Alpine	3,11,16,17,18,20,37
	M1	glauc	9 11	350-400	43	
	M2	green	5-7	380-420	25	
	M?	low gr	LP	LT		
Iraklia	M1	glauc	HP-MP	LT		29,37
	M2	green	MP	LT		
Kea	M1	glauc	HP-MP	LT		6,30,37
	M2	green	MP	LT		
Kythnos	M1	glauc	HP-MP	LT		30,33,37
	M2	green	MP	LT		
Milos	M1	eclog	15	MT-LT	33-64	9,15,37
	M2	green	MP	MT		
	V	volcan.	LP	HT	1-2.5	
Mykonos	M1	glauc	HP	LT		8,23,27,35
	M3	contact	MP-LP	HT	10	
	M?	low gr.	LP	LT		
Naxos	M0	Basement	MP	MT-HT	Pre-Alpine	3,12,13,14,28,37
	M1	glauc	8	400-500	45	
	M2	green-amf.	5-7	380-700	25	
	M3	contact	2	max 600	11	
	M?	low gr.	LP	LT		
	M4	retrogr.	.5-1	250-350	10	
Paros	M2	green-amf	MP	500-600		26,37
	M3	contact	LP	MT		
	M?	low gr	LP	LT		
Pholegandros	M1	glauc	HP-MP	LT		30,37
	M2	green	MP	LT		
Serifos	M1	glauc	HP-MP	LT		8,21,32,35,37
	M2	green	MP	LT		
	M3	contact	.5-1	max.600	9 8	
Sikinos	M0	Basement	MP	MT-HT	Pre-Alpine	10,18,29,30,37
	M1	glauc	HP-MP	LT		
	M2	green	MP	LT		
Siphnos	M1	eclog	15	450	41-48	1,5,24,37
	M2	green	MP	LT	21-24	
Skinoussa	M1	glauc	HP	LT		8,23,37
	M2	green	MP	LT		
Syros	M1	eclog	14	450	40-80	4,7,35,37
	M2	green	MP	LT	mixed 35	

Table III (continued)

Thira	M1	glauc	HP	LT		23,34,37
	M?	low gr.	LP	LT		
	V	volcan.	LP	HT	Recent	
Tinos	M1	glauc	HP	LT	mixed 33	8,19,35
	M2	green-amf.	MP	MT-HT	27	
	M3	contact	LP	HT	13-15	
Yioura	M1	eclog	HP	LT		30,31,36
	M2	green	LP	LT		

eclog: eclogite facies; glauc: glaucophaneschist facies; green: greenschist facies; green-amf.: greenschist facies metamorphism ranging into amphibolite facies; contact: contact metamorphism along granites and granodiorites; volcan.: volcanism; low gr.: lower part of the greenschist facies; Basement: high grade Pre-Alpine Basement (see text); M?: low grade metamorphism occurring in high tectonic units of which the metamorphic age is unknown; HP, MP, LP and HT, MT, LT are used for high, medium and low pressure, respectively temperature; mixed: mixed dates between M1 and M2 ages.

References belonging to Table III:

References: 1. Altherr et al. (1979); 2. Anastopoulos (1963); 3. Andriessen et al. (1979); 4. Blake et al. (1981); 5. Davis (1966); 6. Davis (1972); 7. Dixon (1968); 8. Dürr et al. (1978); 9. Fytikas et al. (1976); 10. Geyssant et al. (1979); 11. Henjes-Kunst (1980); 12. Jansen (1973); 13. Jansen et al. (1976); 14. Jansen et al. (1977); 15. Kornprobst et al. (1979); 16. Kreutzer et al. (1978); 17. van der Maar (in press); 18. van der Maar et al. (1981); 19. Marakis (1972); 20. Marinos (1942); 21. Marinos (1951); 22. Marinos (1954); 23. Marinos (1978); 24. Okrusch et al. (1977); 25. Papanikolaou (1977); 26. Papanikolaou (1979); 27. Papastamatiou (1963); 28. Papavasiliou (1909); 29. Papavasiliou (1913); 30. Phillipson (1901); 31. Psarianos et al. (1951); 32. Salemink (in press); 33. de Smeth (1975); 34. Tataris (1964); 35. Wendt et al. (1977); 36. Zwart et al. (1973); 37. Unpublished data, Department of Geochemistry, State University of Utrecht, Holland.

relicts have been observed which are of M 1 origin. On Sikinos regular glaucophane schists occur similar to those on Ios. It can be concluded that in the Cycladic area the Alpine high-pressure metamorphic phase M 1 affected all the rocks of the Series and the underlying units, like the Pre-Alpin Basement on Ios. The distribution of the remnants of the M 1 stage of metamorphism suggests that the most intensely metamorphosed M 1 records are exhibited in the SSW-NNE zone Milos-Siphnos-Syros-Tinos (fig. 1, Table III). To the northwest at Serifos and Kythnos the barely noticeable M 1 influence is of glaucophanitic greenschist facies character and to the southeast at Ios and Naxos the remnants of the M 1 phase preserve mineral assemblages that crystallized in the range of 8—10 kb total pressure. The zone Milos-Tinos represents the deepest part exposed of the Aegean plate. After the M 1 phase the Cycladic Massif as a whole was uplifted and denudated for a period of about 20 Ma. This has caused a drop in pressure down to 6 kb and a decrease in temperature to about 350° C. In practically the entire Massif the M 2 phase induced a relatively small temperature rise to at least 400° C. But in the central part of Naxos, on Paros and locally on Tinos the M 2 phase was an amphibolite facies metamorphism with local migmatization. After the Barrovian-type M 2 phase the Massif continued to rise and during this period of uplift Late-Alpine granitic or granodioritic magmas were emplaced at Tinos (15—13 Ma), Naxos

(11 Ma), Mykonos (10 Ma), Serifos (9.8 Ma) and Paros. As a rule these intrusions caused local contact metamorphic aureoles at low pressure conditions (.5—2 kb). On Naxos the intrusion of the granodiorite and the resulting contact metamorphic zone were postulated as the M 3 phase (JANSEN et al., 1977; ANDRIESSEN et al., 1979). The average rates of uplift since the M 1 phase for the islands of the Cycladic Massif are: Ios, .7 mm/y (this paper); Milos .7—1.4 mm/y (from data by FYTIKAS et al., 1976); Naxos .5 mm/y (ANDRIESSEN, 1987); Siphnos .9 mm/y (from data by ALTHERR et al. 1979) and Syros .9 mm/y.

Distribution of Basement in the Cycladic area

The Basement-Series boundary on Ios is interpreted as a major thrustplane along which the Series was emplaced on top of the Basement before the M 1 phase took place (v. D. MAAR, 1980). This thrustplane is placed along a horizon of lenses of actinolite-chlorite schist in the uppermost part of the Basement just above a zone of chloritized garnet mica schist. The actinolite-chlorite schist lenses are thougt to be the metamorphosed remnants of an ophiolite sheet. Between the thrustplane and the lowest marble zone of the Series there occurs a chlorite-rich albite-garnet schist of variable thickness (10—30 m) that also contains calcite; unlike the schists in the Basement. The lowest marble zone of the Series consists of 3—5 beds alternating with schist layers.

It can be argued that a similar Basement-Series configuration occurs on the adjacent islands Sikinos and Naxos. In the southern part of Sikinos, at the tectonically lowest levels, metadiorites are exposed in a chlorite-rich schist. The schist itself is overlain by the marble-schist Series. The metadiorites are rich in relicts of brown hornblende and biotite and in plagioclase pseudomorphs consisting of muscovite and zoisite. Minor amounts of allanite, sphene and quartz are present. Biotite-rich lenses in the metadiorites have been intensely chloritized. The original igneous minerals show the same effects of metamorphism as do the minerals in the metamorphosed intrusive rocks from the Basement of Ios hence the metadiorites from Sikinos are likewise interpreted as Pre- M 1 phase Basement rock (v. D. MAAR et al., 1981).

If the metamorphic complex of Naxos is divided into an upper part and a lower part along the innermost horizon of ultramafic lenses, similarities with the geological constitution of Ios become obvious (see figs. 4 a, 4 b). The upper part of the metamorphic complex of Naxos represents the marble-schist Series. Especially the onset of the Series on Ios and Naxos is comparable notwithstanding the large differences in metamorphic grade imposed by the M 2 phase. On Naxos a 10—50 m thick biotite-sillimanite schist is situated on top of the innermost horizon of ultramafic lenses. The overlying, lowest marble zone consists of 4—5 beds alternating with biotite-muscovite schists. The ultramafic lenses are supposed to be remnants of an ophiolite sheet that may indicate a major metamorphosed thrustplane (JANSEN, 1977). In comparison with the situation on Ios we presume that the major thrust movements on Naxos preceeded the M 1 phase. In this respect it is interesting to notice that K-Ar dating of some hornblendes from the ultramafic lenses yielded ages of 189 Ma and 135 Ma (ANDRIESSEN et al., 1979). Because of the uncertainty in the determinations of the very low K-content these were regarded

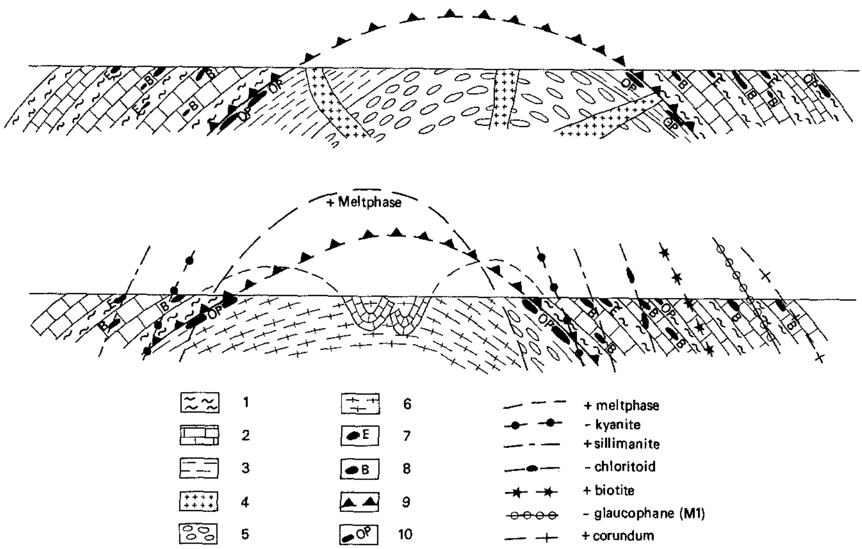

Fig. 4. Schematic profiles of Ios (upper profile) and of Naxos (lower profile). 1: schist; 2: marble; 3: massive schist and gneisses; 4: metamorphosed intrusive rock; 5: augengneiss; 6: migmatite (M_2); 7: eclogitic rock; 8: meta-bauxite; 9: thrustplane; 10: remnants of ophiolite sheet.

to be unreliable. It remains possible that the results reflect a Mesozoic age of the pre-metamorphic ophiolite sheet. Mesozoic ages are reported for the east Mediterranian ophiolites (Dürr et al., 1978).

In the lower part of the metamorphic complex augengneiss and banded biotite-muscovite gneisses occur which are much more massive than the biotite-sillimanite schists on top of the alleged thrustplane, although they were subjected to similar metamorphic conditions during the M 2 phase. The elliptical isograd pattern of which the + meltphase isograd is defined as the line where the first signs of migmatization appear, is discordant with the thrustplane and the lithological boundaries of the Series (fig. 4 b). The M 2 phase apparently imposed a metamorphic overprint on a configuration that probably resembled the present-day situation on Ios (fig. 4 a).

The lower part of the metamorphic complex of Naxos may represent a Basement but a few contradictory facts still remain. No metamorphosed intrusive rocks as found on Ios and Sikinos are recognized on Naxos. If present they would be undetectable due to the migmatization processes during the M 2 phase. In the assumed Basement on Naxos several calcitic and dolomitic marble blocks are found which is not the case on Ios. The lowest marble zone of the Series can be followed across the + meltphase isograd into the migmatite where it abruptly ends (Jansen, 1973 a). The folded marble blocks with irregular inclinations can be interpreted as roof pendants that were emplaced into the migmatite dome during the high grade M 2 phase (fig. 4 b); an idea that was already suggested by Papavasiliou (1909).

On account of the resemblances in geology discussed for Ios, Sikinos and Naxos we assume that the Basement on Sikinos and Naxos is Pre-Alpine and we expect a wider occurrence of this Basement in the Attic-Cycladic Massif, presumable on Mykonos, Paros, Serifos and Syros.

Acknowledgments

Part of this work is based on data about the Cyclades gathered over the years by students and staff members of the Geochemistry Department of the State University of Utrecht.

We like to thank B. W. Vink and B. Manders for providing samples of Ios and Sikinos. This paper benefited from the critical reviews and comments of Drs. M. Barton, A. Feenstra, D. J. Papanikolaou and R. D. Schuiling. We thank Dr. P. A. M. Andriessen for his criticism on age determinations and the Stichting voor Isotopen-Geologisch Onderzoek, supported by the Netherlands Organization for Advancement of Pure Research (Z.W.O.) for the unpublished datings.

References

ALTHAUS, E.: The triple point andalusite-sillimanite-kyanite. Contr. Mineral. Petrol., **16,** 29—44, 1967.

ALTHERR, R., SCHLIESTEDT, M., OKRUSCH, M., SEIDEL, E., KREUTZER, H., HARRE, W., LENZ, H., WENDT, I., WAGNER, G. A.: Geochronology of high-pressure rocks on Sifnos (Cyclades, Greece). Contr. Mineral. Petrol., **70,** 245—2, 1979.

ANASTOPOULOS, J.: Geological study of Antiparos Island group. Geol. and Geophys. Res., vol. VII, no. 5, 235—375 (in Greek with English summary), 1963.

ANDRIESSEN, P. A. M.: Isotopic age relations within the polymetamorphic complex of the island of Naxos (Cyclades, Greece). Verh. ZWO-Laboratorium voor Isotopen-Geologie, Amsterdam, no. 3, (Thesis) 1978.

ANDRIESSEN, P. A. M., BOELRIJK, N. A. I. M., HEBEDA, E. H., PRIEM, H. N. A., VERDURMEN, E. A. Th., VERSCHURE, R. H.: Dating the events of metamorphism and granitic magmatism in the Alpine orogeny of Naxos (Cyclades, Greece). Contr. Mineral. Petrol., **69,** 215—225, 1979.

BLAKE jr., M. C., BONNEAU, M., GEYSSANT, J., KIENAST, J. R., LEPVRIER, C., MALUSKI, H. and PAPANIKOLAOU, D.: A geologic reconnaissance of the Cycladic blueschist belt, Greece. Geol. Soc. Am. Bull., Part 1, **92,** 247—254, 1981.

BOETTCHER, A. L., WYLLIE, P. J.: Phase relationships in the system $NaAlSiO_4$-SiO_2-H_2O to 35 kilobars. Am. J. Sci., **267,** 875—909, 1969.

BROWN, E. H.: A P-T grid for metamorphic index minerals in high pressure terranes. G. S. O. Am. abstracts with programs, Annual meeting, vol. 10, no. 7, p. 373, 1978.

DAVIS, E. N.: Der geologische Bau der Insel Siphnos. Geol. Geophys. Res., vol. X, no. 3, 161—220 (in Greek with German summary), 1966.

—: Der geologische Bau der Insel Kea. Geol. Soc. Greece Bull., **9,** 252—265 (in Greek with German summary), 1972.

DIXON, J. E.: The metamorphic rocks of Syros, Greece. Ph. D. Thesis (unpubl.) University of Cambridge, 1968.

DÜRR, S., ALTHERR, R., KELLER, J., OKRUSCH, M., SEIDEL, E.: The median Aegean Belt; stratigraphy, structure, metamorphism, magmatism. In: Alps, Apennines, Hellenides. Closs, H., Roeder, D., Schmidt, K. (Eds.) Stuttgart, 1978.

DÜRR, S., FLÜGEL, E.: Contribution à la stratigraphie du cristallin des Cyclades: mise en évidence de trias supérieur dans les marbres de Naxos (Grèce). XXVI Congrès-Assemblée plénière, Antalya, Comité de géologie et géophysique marines, 1978.

FYTIKAS, M., GUILIANI, O., INNOCENTI, F., MARINELLI, G., MAZZUOLI, R.: Geochronological data on Recent magmatism of the Aegean Sea. Tectonophys., **31**, T29—T34, 1976.

GEYSSANT, J., LEPVRIER, C.: Plis couchés à axes NS et métamorphisme haute-pression dans les Cyclades: l'île de Sikinos (Grèce). C. R. Acad. Sc., **288**, Série D, 1263—1265, 1979.

HAAS, H..: Equilibria in the system Al_2O_3-SiO_2-H_2O involving the stability limits of diaspore and pyrophyllite and thermodynamic data of these minerals. Thesis, 1971.

HENJES-KUNST, F., OKRUSCH, M.: Polymetamorphose auf Ios, Kykladen-Kristallin (Griechenland). Fort. Miner., **56**, Beiheft 1, 38—39, 1978.

HENJES-KUNST, F.: Alpidische Einformung des Präalpidischen Kristallins und seiner Mesozoischen Hülle auf Ios (Kykladen, Griechenland). Thesis, Technische Universität, Braunschweig, 1980.

JANSEN, J. B. H.: Geological map of Greece, Island Naxos. Inst. for Geol. and Min. Res., Athens, 1973.

—: The geology of Naxos. Geol. Geophys. Res., vol. XIX, no. 1, Inst. for Geol. and Min. Res., Athens pp. 100, 1977.

JANSEN, J. B. H., SCHUILING, R. D.: Metamorphism on Naxos: petrology and geothermal gradients. Am. J. Sci., **276**, 1225—1253, 1976.

JANSEN, J. B. H., ANDRIESSEN, P. A. M., MAIJER, C., SCHUILING, R. D.: Changing conditions of the Alpine regional metamorphism on Naxos, with special reference to the Al-silicate phase diagram. In: Jansen, J. B. H., 1977, Metamorphism on Naxos (Greece) Ph. D. Thesis, State University of Utrecht, Chapter 7, 1977.

JOHANNES, W., PUHAN, D.: The calcite-aragonite transition, reinvistegated. Contr. Mineral. Petrol., **31**, 28—38: 1971.

KORNPROBST, J., KIENAST, J.-R., VILMINOT, J.-C.: The high-pressure assemblages at Milos, Greece: a constribution to the petrological study of the basement of the Cycladic archipelago. Contr. Mineral. Petrol., **69**, 49—63, 1979.

KREUTZER, H., HARRE, W., LENZ, H., WENDT, I., HENJES-KUNST, F.: K/Ar- und Rb/Sr-Daten von Mineralen aus dem polymetamorphen Kristallin der Kykladen-Insel Ios (Griechenland). Fortschr. Miner., **56**, Beiheft 1, 69—70, 1978.

MAAR, P. A. VAN DER: The geology and petrology of Ios, Cyclades, Greece. Ann. Geol. Pays Helléniques, XXX/1, 1980, p. 206—224.

MAAR, P. A. VAN DER, JANSEN, J. B. H.: Geological map of Greece, Ios island. Inst. .of Geol. and Min. Expl., Athens, 1981.

MAAR, P. A. van der, FEENSTRA, A., MANDERS, B. and JANSEN, J. B. H.: The petrology of the island of Sikinos, Cyclades, Greece, in comparison with that of the adjecent island of Ios. N. Jb. Miner. Mh., Heft 10, 459—469, 1981.

MARAKIS, G.: Datations des roches des zones internes de la Grèce, C. R. des Séances SPHN **7**, 52—58, 1972.

MARINOS, G.: Contribution à la pétrologie du système cristallophyllien du sud-est de la Grèce. L'île d'Ios. Ann. Géol. Pays Helléniques, Athens, **1**, 42 p. (French summary), 1942.

—: Geology and metallogeny of Seriphos island. Geol. and Geophys. Res., **1**, no. 4, 95—127 (in Greek with English summary), 1951.

—: Geology and mineral deposits of Andros island. Geol. Geophys. Res., **III**, 201—226 (in Greek with English summary), 1954.

—: On the polyphasic polymetamorphism in eastern Greece. Anm. Géol. Pays Helléniques, Athens, **29**, 427—439 (in Greek with English summary), 1978.

NITSCH, K. H.: Neue Erkenntnisse zur Stabilität von Lawsonit. Fortschr. Miner., **51**, Beiheft 1, 34—35, 1974.

OKRUSCH, M., SEIDEL, E., DAVIS, E. N.: The assemblage jadeite-quartz in the glaucophane rocks of Sifnos (Cyclades Archipelago, Greece). N. Jahrb. Mineral., Abh., **132**, 284—308, 1977.

PAPANIKOLAOU, D. J.: Contribution to the geology of the Aegean Sea: the island of Andros. Annales Géol. des Pays Helléniques, **29**, 477—553, 1977.

—: Contribution to the geology of the Aegean Sea: the island of Paros. Annales Géol. des Pays Helléniques, **30**, 65—96, 1979.

PAPASTAMATIOU, J. N.: Sur la présence des roches sédimentaires d'âges prétriassiques à Mykonos (archipel des Cyclades, Grèce). C. R. Acad. Sc., **256**, 5167—5169, 1963.

PAPAVASILIOU, S.: Ueber die vermeintlichen Urgneisse und die Metamorphose des kristallinen Grundgebirge der Kykladen. Zeitschr. Deutsch. Geol. Ges., **61**, 134—201, 1909.

—: Die Smirgellagerstätte von Naxos nebst denjenigen von Iraklia und Sikinos. Zeitschr. Deutsch. Geol. Ges., **65**, 1—123, 1913.

PHILLIPSON, A.: Beiträge zur Kenntnis der griechischen Inselwelt. Peterm. Mitt. Ergänzungsheft, **134**, 1—172. Gotha, 1901.

PSARIANOS, P. and CHARALAMBAKIS, S.: Geological investigation of the island of Yioura. Praktika Akademia Athinon, **26**, 237—258, 1951.

RICHARDSON, S. W.: Staurolite stability in part of the system Fe-Al-Si-O-H. Journ. Petrol., **9**, 467—488, 1968.

RICHARDSON, S. W., GILBERT, M. C., BELL, P. M.: Experimental determinations of kyanite-andalusite and andalusite-sillimanite equilibria, the aluminium silicate triple point. Am. J. Sci., **267**, 259—272, 1969.

SALEMINK, J.: Geological map of Greece, Serifos island. Nat. Inst. of Geol. and Min. Res., Athens, in press.

SMETH, J. B. de: Geological map of Greece, Kythnos island. Nat. Inst. of Geol. and Min. Res., Athens, 1975.

TATARIS, A.: The Eocene in the semi-metamorphosed basement of Thera island. Geol. Soc. Greece Bull., **6**, 232—238 (in Greek with English abstract), 1964.

WENDT, I., RASCHKA, H., LENZ, H., KREUTZER, H., HÖNDORF, A., HARRE, W., WAGNER, G. A., KELLER, J., ALTHERR, R., OKRUSCH, M., SCHLIESTEDT, M., SEIDEL, E.: Radiometric dating of crystalline rocks from the Cyclades (Aegean Sea, Greece). Fifth European Coll. of Geochron. Cosmochron. and Isotope Geol., Pisa, 1977.

ZWART, J. H., SOBOLEV, V. S.: Metamorphic map of Europe, sheet 15, Subcomm. for Carthography of the Metamorphic Belts of the World, Leiden and Unesco, Paris, 1973.