GEOLOGICA ULTRAIECTINA

Mededelingen van het Instituut
voor Aardwetenschappen
der Rijksuniversiteit te Utrecht

No. 28

METAMORPHISM ON IOS AND THE GEOLOGICAL HISTORY OF THE SOUTHERN CYCLADES, GREECE

P.A. VAN DER MAAR

Stellingen

1

De assemblage glaukofaan-granaat-albiet is kenmerkend voor glaukofaanschist facies kondities met een relatief hoge temperatuur.

2

De topologieën van Eh-pH diagrammen van een systeem zijn eenvoudig te bepalen door dat systeem te beschrijven met $-H^{+}$ en $-e^{-}$ als intensieve komponenten.

3

Het vereenvoudigde P-T diagram voor laaggradige metabasieten van Holland en Richardson (1979), waarin de relatieve stabiliteiten van de amfiboolkomponenten glaukofaan, tremoliet, edeniet en tschermakiet worden aangegeven, is in al zijn eenvoud fout.
(Holland, T.J.B., Richardson, S.W., 1979. Amphibole zonation in metabasites. Contrib. Miner. Petrol., 70, 143-148.)

4

Het door Kornprobst et al. (1979) beschreven Basement van het eiland Milos is gezien de geologische situatie op naburige eilanden zeker niet het Basement van de Cycladische Archipel.
(Kornprobst, J., Kienast, J-R., Vilminot, J-C., 1979. The High-Pressure Assemblages at Milos, Greece. A Contribution to the Petrological Study of the Basement of the Cyclades Archipelago. Contrib. Mineral. Petrol., 69, 49-63.)

5

De door Luckscheiter en Morteani (1980) bepaalde minimum drukken voor eklogietvormende reakties zijn waarschijnlijk veel te laag, mogelijk als gevolg van de "Tauernkristallisation".
(Luckscheiter, B., Morteani, G., 1980. The fluid phase in eclogites, glaucophane-bearing rocks and amphibolites from the Central Tauern Window as deduced from fluid inclusion studies. Tschermaks Min. Pet. Mitt., 27, 99-111.)

6

Kyaniet is in het Precambrium van Rogaland zowel makroskopisch als mikroskopisch niet gevonden hoewel het voorgestelde afkoelingstrajekt door het stabiliteitsveld van kyaniet loopt. Het is daarom aan te bevelen dit mineraal door een elektronenmikroskopisch onderzoek op te sporen.

7

Door het toenemende gebruik van de elektronenmikroskoop in de petrologie zal het begrip "sub-mikroskopisch" zijn betekenis gaan verliezen.

8

Het is raadzaam om bij het onderzoek naar de geschiedenis van een metamorf gebied de opeenvolgende metamorfe fasen met tientallen te nummeren.

9

Het valt niet te verwachten dat "glaucophanic enol" voorkomt in glaukofaan schist facies metamorfe gebieden.
(Crombie, L., Games, D.E., Knight, M.H., 1967. The constitution and chemistry of glaucophanic enol. J. Chem. Soc., (C), 8, 773-777.)

10

In geval van voortdurende bezuinigingen kunnen de geologische exkursies en veldwerken worden gehouden op een bij het Instituut voor Aardwetenschappen te plaatsen apenrots.

11

Op de Internationale Zeerecht Konferentie valt de Noord-Zuid dialoog weer in het water.

Utrecht, 26 mei 1981 P.A.van der Maar

Stellingen behorende bij het proefschrift: "Metamorphism on Ios and the geological history of the Southern Cyclades, Greece".

GEOLOGICA ULTRAJECTINA
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GEOLOGICAL HISTORY OF THE
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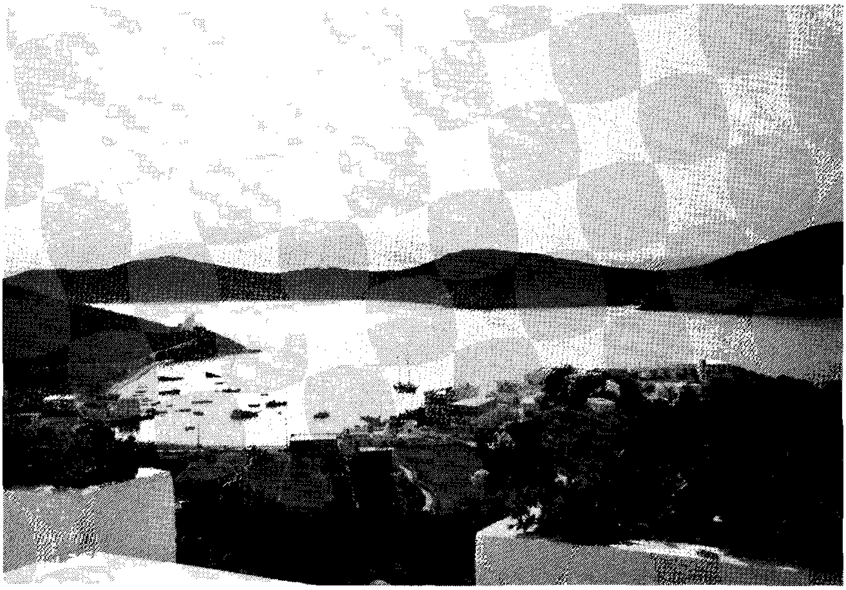

METAMORPHISM ON IOS AND THE GEOLOGICAL HISTORY OF THE SOUTHERN CYCLADES, GREECE

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR
IN DE WISKUNDE EN NATUURWETENSCHAPPEN
AAN DE RIJKSUNIVERSITEIT TE UTRECHT, OP
GEZAG VAN DE RECTOR MAGNIFICUS PROF.
DR. M.A.BOUMAN, VOLGENS BESLUIT VAN HET
COLLEGE VAN DECANEN IN HET OPENBAAR TE
VERDEDIGEN OP DINSDAG 26 MEI 1981 DES
NAMIDDAGS TE 2.45 UUR

door

PAUL AALDERT VAN DER MAAR
geboren op 16 augustus 1947 te hengelo(o)

PROMOTOR: PROF. DR. R.D. SCHUILING

Dit proefschrift kwam tot stand mede onder leiding van:

DR. J.B.H. JANSEN

aan Marianne,
Elsje en Finne

Voorwoord

Bij het gereedkomen van dit proefschrift wil ik graag iedereen bedanken die op enigerlei wijze heeft bijgedragen aan het totstandkomen ervan.
Mijn promotor Prof.Dr. R.D. Schuiling ben ik zeer erkentelijk voor zijn aandeel in mijn opleiding en voor de steun die hij gegeven heeft bij het verrichten van dit onderzoek en voor het feit dat hij me indertijd het eiland Ios heeft "toegewezen".
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Dr. Cees Maijer heeft voor veel van de petrologische problemen als vraagbak gefungeerd.
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Anne Feenstra, Henk van der Rijst, Jan Wijbrands en Mike Barton bedank ik voor hun aandeel in de gegevens en discussies die in dit proefschrift zijn verwerkt en voor de aangename tijd op de Huizingalaan en in het nieuwe Instituut in de Uithof.

Ineke Kalt bedank ik voor het typen van de vele manuskripten en de"gebedsrollen" met veranderingen en verbeteringen.

Jeanne Landers-Lücker heeft dit proefschrift getypt voor zover het haar mogelijk was. Ik ben Vino Kanhai en Mevr. Beringen-van Ettekoven dankbaar dat ze het laatste deel van deze type marathon op zich hebben willen nemen.

Het leeuwendeel van de illustraties werd vervaardigd door Izaak Santoe en Rene Meyer die samen met Frans Henzen altijd begrip hadden voor de promovendus die graag gisteren zij figuren klaar had gezien. Het resultaat heeft mij altijd verbluft.

Tenslotte bedank ik mijn ouders voor de steun die ze mij gegeven hebben tijdens mijn studie.

INDEX

Summary

The geology and petrology of the island of Ios, Greece are outlined in chapter I. The geology is determined by a mantled gneiss dome which forms the basement, on top of which a marble-schist series is emplaced. The various rocks of the island are described petrologically and their mineral contents are listed. The P-T conditions of a decreasing, polyphase regional metamorphism are inferred on the basis of relevant mineral assemblages. The emplacement of the series upon the basement predates the Alpine metamorphism.

The petrology of the adjacent island of Sikinos is concisely treated in chapter II. The geological constitution is similar with that of Ios, although the windows of the basement are relatively small. The rocktypes and their contents are also comparable with those of Ios.

In chapter III the metamorphic phases on Ios are better distinguished and also the pre-Alpine event in the basement are discussed. Additionally preliminary isotope dating of the Alpine metamorphic phases is summarized and it reveals 43 Ma and 25 Ma respectively. The metamorphic conditions are refined, and a review is given of the distribution of the metamorphic and magmatic events in the Cycladic area. A wider occurrence of basement, for example on Naxos is suggested.

A model for the Alpine metamorphic evolution in the southern Cyclades is developed in chapter IV. It is based on petrological data of mineral textures and mineral zonations in rocks from Pholegandros, Sikinos, Ios, Iraklia and SE Naxos and on chemical microprobe data of minerals mainly from Ios. The model is consistent with a rapid uplift of deep continental crust, which is supported by geophysical seismic and gravimetric data.

The geological map of Greece, sheet of the island of Ios is presented in a preliminary shape with an extended legend.

Samenvatting

De geologie van Ios wordt voornamelijk bepaald door een gneissdome, die bestaat uit ogengneiss en granaat-mica schisten, waarin relikten van intrusieve lichamen voorkomen. Samen vormen deze gesteenten het Basement, waarop een marmer-schist Serie ligt. Deze wordt geïnterpreteerd als een tektonisch samenraapsel van (isoklinaal) geplooide marmers, glaucofaanschisten, groenschisten en eclogieten. De geologie en petrologie van Ios wordt behandeld in hoofdstuk I, waar ook de verschillende gesteente types en hun mineralogiën worden beschreven. De invloeden van twee metamorfe stadia zijn te herkennen, te weten een M 1 hoge druk- lage temperatuur stadium in de glaucofaan facies metamorfose en een daaropvolgend M 2 stadium met wat lagere drukken en hogere temperaturen in de zogenaamde groenschist facies metamorfose. De grens tussen het Basement en de Serie markeert een grote overschuiving die aan het M 1 stadium voorafgaat.

In hoofdstuk II wordt de petrologie van het naburige eiland Sikinos beschreven. Het grootste deel van het eiland bestaat eveneens uit de Series en op enkele plaatsen verschijnt het onderligged Basement. De gesteente types, mineralogiën en het verloop van de metamorfose zijn vergelijkbaar met die van Ios.

In hoofdstuk III worden de metamorfe stadia op Ios nader gepreciseerd aan de hand van de geobserveerde mineraal assemblages. Tevens wordt ingegaan op de pre-Alpiene gebeurtenissen in het Basement. De beschikbare radiometrische ouderdoms gegevens zijn samengevat en zij onthullen voor het M 1 stadium ouderdommen rond 43 miljoen jaar, voor het M 2 stadium een ouderdom van 25 miljoen jaar en zij bevestigen de pre-Alpiene leeftijd van het Basement, hetgeen op grond van geologische waarnemingen vermoed werd. Tevens wordt een overzicht gegeven van de verspreiding van de metamorfe en magmatische gebeurtenissen in de Cycladische archipel en de geologische opbouw van Sikinos en Naxos wordt vergeleken met de Basement-Serie struktuur van Ios.

In hoofdstuk IV worden de petrologische, mineralogische en chemische gegevens van de eilanden Pholegandros, Sikinos, Ios, Iraklia en zuidoost Naxos samengevoegd tot een model van het verloop van de metamorfose in het zuidelijke deel van Attische-Cycladische Massief. Het model impliceert dat het gebied uit een stuk continentale korst bestaat dat sinds het M 1 stadium vanaf grote diepte relatief snel is opgeheven.

Hoofdstuk V wordt gevormd door de uitgebreide legenda van de geologische kaart van het eiland Ios. De kaart, die veel petrologische gegevens bevat is achterin toegevoegd in een voorlopige vorm.

CHAPTER I

The Geology and Petrology of Ios, Cyclades, Greece

by P.A. van der Maar

(in press, Annal. Geol. Pays Hell., Athens).

Abstract

The island of Ios is a dome consisting of an augengneiss core and a mantle of garnet-mica schists. The two rocktypes form the Basement which is overlain by a marble-schist Series. Bodies of metamorphosed intrusive rocks exclusively occur in the Basement and contribute to the petrological differences between the Basement and the Series. The Series is a sequence of marbles alternating with glaucophane schists, actinolite schists and chlorite schists. Metabauxite lenses are present in the marbles. Zones of eclogitic blocks and lenses of ultramafic composition occur in respectively the glaucophane schists and the chlorite schists. This implies that the Series as a whole is not a stratigraphic sequence but a tectonic pile, formed by thrusting.
Two metamorphic phases are inferred from the petrography e.g. a blueschistfacies phase (M 1) and a greenschistfacies phase (M 2). Estimates of the P-T conditions of metamorphism based upon the mineral assemblages suggest a pressure of 9-11 kb and a temperature range of 300°-400°C for the M 1 phase and 5-7 kb pressure and 380°-450°C for the M 2 phase. Preexisting high temperature assemblages in the Basement were nearly completely destroyed during the M 1 phase which explains the lack of a traceable temperature gradient in the dome structure. With regard to the origin of the Basement an intrusion model and an anatectic model are discussed. The Basement-Series boundary is interpreted as a major thrustplane along which thrusting took place prior to or during the M 1 phase.

Introduction

The island of Ios belongs to the Cycladic Archipelago in the Aegean sea, Greece and is situated about 200 km SE of Athens (fig.1). It measures a maximum of 17 x 20 km and the total area is about 110 km^2. The dominant topographic feature is a ridge running parallel to the NW-SE axis of the island.
The island is part of the Attic-Cycladic Massif, which is an intermediate part of the Alpine orogenic belts found on the Greek and Turkish mainland. The Massif mainly consists of regionally metamorphosed rocks of different metamorphic grades. Glaucophane schist facies rocks (blueschists) are found on the islands of Andros, Yioura, Tinos, Syros, Siphnos, Naxos, Milos, Pholegandros, Sikinos and Ios, fig.1 (Marinos, 1942; Dixon, 1968; Davies, 1966; Jansen, 1973b; Jansen en Schuiling, 1976; Fytikas et al., 1978;

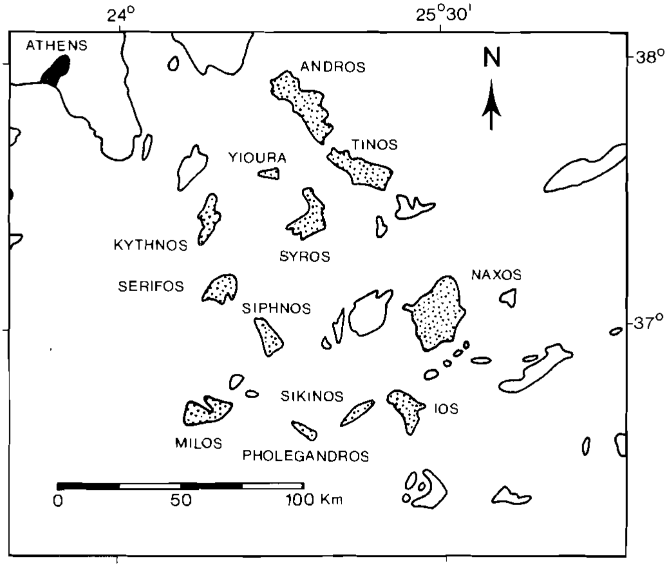

Fig. 1. Map of the Cyclades, Greece. The dotted islands are mentioned in the text.

v/d Maar and Jansen, in press).

The rocks on Syros and Siphnos exhibit the highest grade of glaucophaneschist facies metamorphism in the Massif (Dixon, 1976; Okrusch et al., 1977), and glaucophaneschist facies rocks on Syros, Ios, Naxos and Sikinos show an overprint of at least a greenschist facies metamorphic phase (Dixon, 1968; Henjes-Kunst and Okrusch, 1978; Jansen et al., in prep.).

Low and intermediate pressure greenschist facies rocks, without remnants of a high pressure metamorphic stage occur on the islands of Kythnos, Seriphos, Siphnos and Milos (Marinos, 1951; Davies, 1966; de Smeth, 1975; Fytikas et al., 1976; Salemink, in press).

Rocks of amphibolite facies metamorphism, locally with migmatite formation are found, for example, on Naxos and granodiorite intrusions with contact metamorphism and metasomatic phenomena occur on Naxos and Seriphos (Jansen and Schuiling, 1976; Salemink, in press).

Geology

The geology of Ios is determined by a mantled gneiss dome which forms the Basement, on top of which a marble-schist Series is found (fig.2; v/d Maar and Jansen, in press). The mantled gneiss dome consists of an augengneiss core which occupies nearly the whole southern half of the island and which is surrounded by garnet-mica schists. Separate lenses of garnet-mica schist are found within the augengneiss. The contact between the garnet-mica schist and the augengneiss shows no transition zone. Bodies of metamorphosed intrusive rocks occur in the garnet-mica schist and in the augengneiss but not in the marble-schist Series. Usually, the bodies are circular in shape (e.g. the metagranite on which the village has been built) but some (meta-lamprophyres) are of oblong

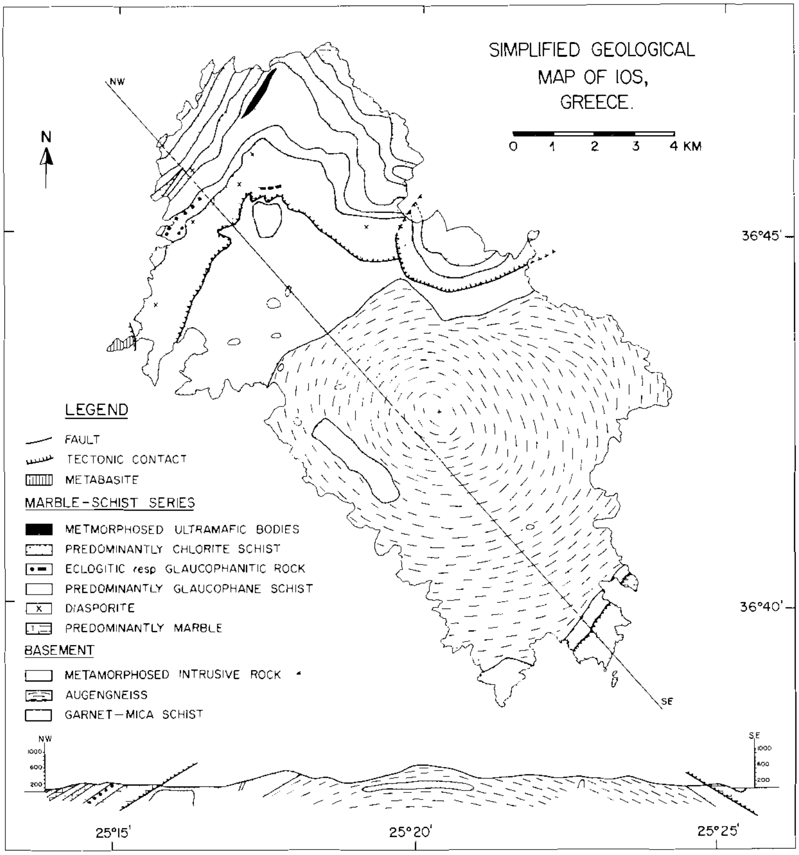

Fig. 2. Simplified geological map of Ios, with a schematic NW-SE cross section.

shape. They presumably belong to dike systems that only affected the Basement. Throughout the Basement milky quartz lenses occur that can reach considerable sizes. Along the boundary with the overlying Series the uppermost layers of the garnet-mica schists contain characteristic Fe-pods and an actinolite schist with megacrysts. The contact between the Basement and the Series is sharp and it possibly represents a time gap. The marble-schist Series consists of a sequence of limestones and rocks of pelitic and basaltic composition metamorphosed into mainly calcitic marbles and chlorite-, actinolite- and glaucophane-schists. Metabauxite lenses and Fe bodies, which are probably lateritic remnants, occur in the marbles. This is a rather common feature in the marbles of the Cycladic Islands and it indicates that the deposition of the limestone beds took place during periods of interrupted subsidence. Eclogitic and glaucophanitic blocks are found embedded respectively in the glaucophane schists proper and in glaucophane-bearing schists in the lower marble zone. In the chlorite schist a zone of nodules of ultramafic composition occurs. These horizons with eclogitic and ultramafic lenses indicate that the marble-schist Series as a whole consists of several units that were tectonically emplaced on top of each other. The same specific combination of these rock types is also described from other Cycladic Islands: Naxos, Siphnos, Syros (Jansen, 1973a,b, 1977; Dixon, 1976; Jansen en Schuiling, 1976; Okrusch et al., 1977; Dürr et al., 1978).

In contrast to the situation in the Basement, major quartz lenses seldom occur in the marble-schist Series.

In the extreme western part of the island a peculiar vulcanic rock has been thrusted against the Series. This rock is named metabasite and probably belongs to an ophiolite-suite which has been subjected to greenschist facies metamorphism.

The gneiss dome and the overlying Series have a somewhat anticlinal structure, the length-axis of which runs parallel to the length-axis of the island. In the eastern part of the island an out-lying block of the marble-schist Series has moved along a curved fault-plane, which dips about 40°NE, and in the north-western part of the island part of the Series is overturned. A striking general tectonic feature of practically all rock types on the island is a lineation pattern with a constant N-S direction which is not influenced by the dome structure.

Table I. Mineral assemblages in rock types from the Basement

Sample number	Coordinates Latitude	Coordinates Longtitude	Quartz	K-feldspar	Albite	Chlorite	Mica	Biotite 2)	Garnet	Actinolite	Amphibole	Epidote	Apatite	Sphene	Mag./Hem.	Calcite	Tourmaline
Garnet-mica schist in northern part																	
40	36°43'50"	25°17'00"	X		X		X						X				
57	36 43 50	25 16 04	X		X	+	X	0	X							X	
72	36 43 43	25 16 08	X		X	X	X	+	X	X		X					
89	36 43 09	25 17 26	X				X	+	X	Ctd					X		
90 B	36 43 13	25 17 26	X		X	X	X		X	Ctd		X			X		
25.5	36 41 18	25 17 11	X		X		X		X	X		Zo					
30.1	36 43 57	25 17 26				X		+	X	X		X					X
in southern part																	
34	36 40 10	25 23 04	X		X		X		X	X		X	X				
104	36 39 03	25 21 42	X		X		X				X			X			X
Io 85	36 39 03	25 21 42	X			X	X		X				X	X			X
in augengneiss dome																	
2	36 42 59	25 18 48			X	X			X	X		X	X	X			
26	36 42 30	25 18 25	0				X	+	X	X		X	X	X			
36	36 42 00	25 18 58	X		X		X		X	X		X	X	X			
67	36 42 14	25 18 50			X	X	X		X	X		X	X	X			
Io 73	36 41 20	25 19 25	X		X		X	+	X		X	X					
Augengneiss																	
3	36 43 09	25 19 58	X	X	X		X							X	X		
99	36 41 07	25 20 54	X	X	X		X	+									
79 B	36 41 23	25 19 23	X	X			X	+					X	X	X		
25 1)	36 42 40	25 18 08		X	X		X		0				X				
70 1)	36 42 36	25 18 38	X		X												
Metamorphosed intrusive rock																	
12	36 45 19	25 17 34	X	X	X		X	R	0				X		X		
84	36 44 13	25 17 47	X		X	X		R									
84 B	36 44 13	25 17 47	X		X		X	R	X		X	Zo				0	
85 C	36 43 57	25 17 26	X		X	X	X	R	+		X				X		
91	36 44 25	25 17 14	X	X	X	X	X								X	X	
100	36 41 09	25 21 42	X				X	R	+								
10.7 B	36 43 31	25 16 55	X		X		X	R	+								
Io 39	36 43 55	25 17 27	X		X	X	X		+		X		X	X			

X = major constituent; 0 = minor constituent; + = secondary mineral; R = relict mineral; Zo = zoisite; Ctd = chloritoid

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

Io: samples collected by B.W.Vink

Petrology

The Basement is formed by the garnet-mica schist mantle, the augengneiss core and the metamorphosed intrusive rocks (fig.2). In table I a selection of representative mineral assemblages is given for each distinctive rock type of the Basement.
The GARNET-MICA SCHIST occurs in a zone around the augengneiss and in some places within the augengneiss. It is mainly composed of the assemblages quartz-albite (An < 5%)-phengitic muscovite-garnet. Especially the mica can be very abundant over vast areas. Epidote and actinolite are common, but the latter is only found together with epidote and it seems to be more abundant in the schist lenses within the augengneiss than in the other garnet-mica schists surrounding the augengneiss core. The usual accessory minerals are apatite, sphene and opaques. The plagioclase is rarely twinned. Minute amounts of biotite are ubiquitous. The generally idioblastic garnet is almandine-rich in composition and usually measures several mm in diameter though crystals up to 3 cm in diameter can be found. The garnets normally contain numerous inclusions without showing any "snow-ball" structures or other rotation effects.
Chlorite is formed relatively late and it is often found in the pressure shadows of the garnet crystals. Chloritoid is found together with garnet, phengitic muscovite and chlorite in the northern part of the garnet-mica schist zone near the contact with the augengneiss (see fig.3a).
Tourmaline notably occurs in the southern part of the zone and in the lenses in the augengneiss. Milky quartz lenses, locally associated with tourmaline, are present and along these lenses rims of albite plus chlorite are found. In the uppermost beds of the northern part of the zone the schists become more chloritic and they occasionally contain calcite. In the same stratigraphic horizon

several hematitic and limonitic pods are exposed as well as an actinolite-garnet-mica-albite schist with actinolite megacrysts.

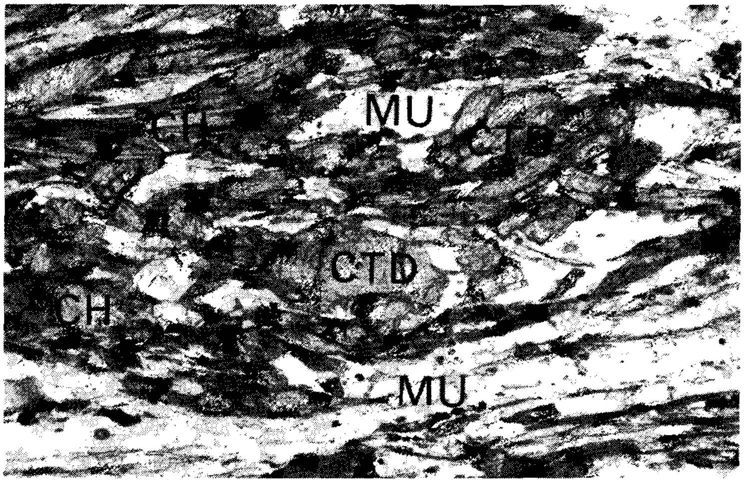

Fig. 3a. Chloritoid with muscovite and chlorite in garnet-mica schist near the augengneiss (50 x).

The AUGENGNEISS mainly consists of perthitic microcline augen, up to 3 cm in diameter, in a matrix of albite (An $< 5\%$)-quartz-muscovite.

Sphene, apatite and ore are accessory minerals. The microcline has locally reacted to produce muscovite. Near the center of the dome the augengneiss is very mica-rich and the characteristic augen are less pronounced. Minute flakes of biotite are observed in thin sections and they occur throughout the augengneiss core as late-formed minerals. The augengneiss can usually be distinguished from the garnet-mica schist by the presence of K-feldspar and the absence of primary garnet, but in some aplitic parts of the augengneiss K-feldspar is found together with newly formed garnet. An elongated lens of K-feldspar-albite-quartz-mica and accessories with fine-grained texture is situated west of the major garnet-mica schist lens in the augengneiss.

Several pure, milky quartz lenses occur in the augengneiss; they can reach a size of about 20 x 100 m. Albite and chlorite are abundant along the contacts of the lenses.

The METAMORPHOSED INTRUSIVE ROCKS occur in the augengneiss core and in the garnet-mica schist zone. They are clearly different from the surrounding rock types in mineral content and texture. One of the main characteristics of these rocks is their content of relictic biotite, often concentrated in lenses up to 10 cm long and somewhat affected by sericitization. On the basis of mineralogy, the rocks have been divided into metagranites and meta-lamprophyres. The largest metagranite body is found in the northern part of the garnet-mica schist zone. This body is remarkable for its content of K-feldspar (perthitic microcline) together with biotite, mica, albite, quartz, apatite, calcite and small amounts of newly formed, metamorphic garnets. The other metagranite bodies in the schist zone and in the augengneiss are of similar size and all show biotite lenses in a matrix of albite, quartz and mica with local zoisite and calcite. Apatite, sphene, magnetite and hematite are present as accessories. One metagranite body in the augengneiss can only be distinguished on account of its biotite content, massive structure and coarse grain size, while in other aspects it resembles the augengneiss. Around all of the bodies situated in the garnet-mica schist an aureole of a few meters wide exists in which the schist seems to be devoid of garnet.

Two bodies of the metamorphosed intrusive rocks in the northern part of the garnet-mica schist zone contain strongly sericitized, relictic, brown hornblende along with biotite, albite and some quartz. They are assumed to be meta-lamprophyres.

The marble-schist Series consists of an alternation of calcitic and dolomitic marbles with chlorite-, actinolite- and glaucophane-schists.

The glaucophane schist locally contains eclogites and the chlorite schist contains a zone of metamorphosed ultramafic rocks. In table II mineral assemblages are arranged for each rock type of the Series. Some chemical analyses of minerals from some of the rocks from the Series are given in table III.

The MARBLES are calcitic as well as, to a lesser extent, dolomitic. Micaceous parts in the marbles are common. Within the dolomitic marbles small quartz lenses are found without any neoformation of talc or tremolite. Hematite pseudomorphs after pyrite in pentagondodecahedras frequently occur. The marble beds contain metabauxites (diasporites) and several Fe-rich lenses. The Fe-rich bodies contain magnetite, hematite, goethite and limonite in considerable quantities. The association omphacite-riebeckite-garnet-calcite-epdiote-quartz is also observed. Muscovite, brown calcite and traces of malachite and azurite have been found.

The DIASPORITES are found in two different horizons of the marbles. They occur as lenses up to 2 m in diameter and they are intensely folded. The main mineral assemblage is: diaspore-calcite-epidote-margarite-chloritoid-hematite with accessory apatite and rutile. Some secondary kaolinite is found. In one case the assemblage kyanite-diaspore-chloritoid-calcite has been formed. The calcite is of columnar habit.

The GLAUCOPHANE SCHIST is only found in the northern part of the island. It contains the minerals glaucophane-crossite-albite-phengite-paragonite-chlorite-epidote-calcite-quartz with accessory minerals apatite, sphene, magnetite, hematite and, occasionally, rutile. Garnet is often present but not together with albite plus glaucophane. In some samples relicts of chloritoid are found as

Table II. Mineral assemblages in rock types from the marble-schist Series and the metabasite.

Sample number	Coordinates		Quartz	Albite	Chlorite	Muscovite[3]	Paragonite	Biotite	Garnet	Actinolite	Glaucophane	Crossite	Epidote	Calcite	Apatite	Sphene	Mag./Hem.
	Latitude	Longitude															
Marble [2]																	
7	36°44'58"	25°18'46"		X	X	0		0		0[5]	X	X	X		X		
17	36 45 50	25 17 26		X	X	0		0	X	FH[5]	X		X	X		X	X
73	36 44 03	25 16 02		0	X	X		X		0			X		X	X	X
81	36 44 37	25 16 18	X	X	X	X							X	X			X
92	36 45 29	25 17 17		X	X	X			X				ZE	X		X	X
93	36 45 42	25 17 20	X	X	X	X		X	X				X		X	X	X
22.4-16	36 45 43	25 17 50		X	X	X			X	0[5]	X	X	X		X	X	
Io 8	36 45 20	25 18 17	0	X						0[5]	X		X	X			X
Glaucophane schist																	
29	36 44 29	25 20 34	X		X	X	X	0	X	Ctd[4]	X						X
31	36 44 48	25 15 42	X	X	0	X		0	X	X			X		X	X	
38	36 45 57	25 18 36		X	X	X		0		X			ZE			X	
39	36 45 41	25 18 31		X				X			X						X
45 E	35 45 00	25 16 09	X		X	X		X			X	X		X		X	X
83	36 45 03	25 16 04	X	X	X	X		0		X[5]	X	X	X		X	X	X
95	36 45 57	25 17 03	X	X	X	X		0		X[5]	X	X	X		X	X	X
Io 11	36 45 35	25 18 40	X	X	X			0	X	Ctd[4]	X[5]		X			X	X[6]
Io 57	36 45 36	25 18 40	0	0	X	X	X				X	X	X	X		X	X
Io 80[1]	36 45 04	25 15 51	X	X	X	+	X		0	Ctd[4]	X		ZE	X	X	X	X
Io 81	36 45 04	25 15 51	X	X	+	X		0			X		X	X	X	X	X
Chlorite schist																	
18	36 45 52	25 16 18		X	X								X	X	X	X	
19	36 45 52	25 16 18	X	X	X	X					X		X	X	X	X	X
42	36 45 46	25 18 49	X	X	X	X		0	X				X	X	X		X
63	36 45 47	25 16 24	X		X	X			X	X					X	X	
66	36 46 38	25 16 38			Ta	Fu				X							
96	36 46 10	25 16 30				X		X									X
Io 53	36 45 15	25 19 10	X	X		X			X	Cu			X		X	X	X[6]
Io 63	36 45 39	25 18 10	0	0	X	X				X							X[6]

Table II continued

Sample number	Coordinates Latitude	Coordinates Longitude	Quartz	Albite	Chlorite	Mica	Garnet	Actinolite	Glaucophane	Crossite	Epidote	Apatite	Sphene	Mag./Hem.	Calcite	Other Minerals
Diasporite																
22.1	36°44'05"	25°15'33"				Ma		Ctd				X	Di	X	X	
76	36 44 05	25 15 39				Ma		Ctd			X	Ka	Di	X	X	Ky
Io 82	36 44 05	25 15 39				Ma					X		Di	X	X	Ky
Io 83	36 44 05	25 15 39				Ma		Ctd				Ru	Di	X	X	Ky
Eclogitic rock																
32	36 44 58	25 15 48	0				X		Ri					X	X	Ky
108 A	36 45 02	25 16 03		X		X	X	+	Ri		X			X		Om
108 C	36 45 02	25 16 03	X	X	St		X		Ri		X		X	X		Om
108-97	36 45 25	25 16 17	X	R		X	X		Ri		X		X	X		Om
Glaucophanitic rock																
15	36 45 42	25 17 32		0	+		X	X 5)	X	X	X	0	X	X	X	
16-17	36 45 44	25 18 30		X					X	X	X	X	0	X		
Io 9	36 45 40	25 17 42	X	0	X	X	X		X	X	X	X	0	X		
Metamorphosed ultramafic bodies																
68 A	36 46 45	25 17 05			X	X		X	Fu		X					Ta
68 C 1)	36 46 45	25 17 05				X	X	X	Fu		X					
48	36 46 45	25 17 10														An
Metabasite																
5 B	36 43 30	25 15 10	X	X	X	X									X	
5 D	36 43 30	25 15 10		X	X	X		X			Zo	0	X	X	X	Bi

X= major constituent; 0= minor constituent; += secondary mineral; R= relict mineral; An= antigorite; Bi= biotite; Ctd= chloritoid; Cu= cummingtonite; Di= diaspore; FH= ferro-hastingite; Fu= fuchsite; Ka= secondary kaolinite; Ky= kyanite; Ma= margarite; Om= omphacite; Ri= riebeckite; Ru= rutile; St= stilpnomelane; Ta= talc; Zo= zoisite; ZE= zoisite-epidote.

1) pseudomorph after lawsonite
2) samples are mainly 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) with rutile

Io : samples collected by B.W.Vink

inclusions in garnet and glaucophane crystals. Glaucophane and crossite occur side by side and both can have actinolitic rims when epidote and/or zoisite are present. The amphiboles normally show a zonal pleochroism with more deeply pleochroic rims. In some cases this pleochroic pattern is also found in the coexisting epidote and zoisite. The plagioclase is nearly pure albite with a maximum of 5% An (cf. the Basement). Biotite is found in minute amounts around the garnet while chlorite is common in pressure shadows of this mineral. The stratigraphic base of the predominantly glaucophane schist is a white-pinkish coloured phengite-paragonite-calcite-quartz schist with well-developed idiomorphic glaucophane crystals. In the marble-schist Series glaucophane-bearing chlorite schists are found in a few horizons.

The ECLOGITIC AND GLAUCOPHANITIC ROCKS occur as more or less rounded blocks which are embedded respectively in the glaucophane schists proper and in the glaucophane-bearing schists within the marble (fig.2). The blocks have a distinctive more massive character than the surrounding country rock. The minerals in these blocks trend to be concentrated in monomineralic layers probably as a result of metasomatism. These layers look like boudinaged schlieren because the blocks were intensely folded.

The eclogites mainly consist of the assemblage omphacite-riebeckite-garnet-epidote. The other minerals present are calcite, magnetite, pyrite, apatite, sphene and locally quartz, albite and mica. The omphacite is pleochroic from light green to dark green and is always fine-grained. The riebeckite is pleochroic from dark blue to practically opaque. The blocks often show a zonation from omphacite-riebeckite in the center, via omphacite-riebeckite-garnet and garnet-epidote to epidote-calcite along the margins with the country-rock. In garnet-epidote-magnetite-albite rich parts of the blocks the mineral stilpnomelane has been found (see fig.3b).

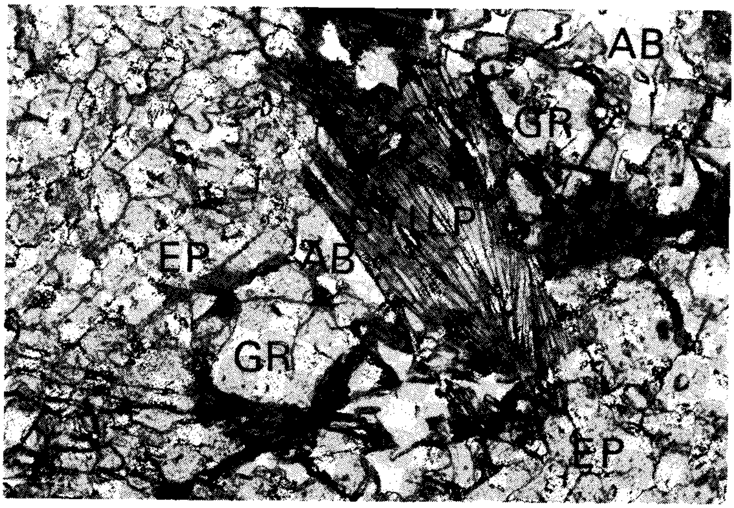

Fig. 3b. Stilpnomelane in a garnet-epidote-albite-rich part of the eclogite 108c. (see table II)(100 x).

The glaucophanitic rocks are found as a small zone of blocks in one of the glaucophane-bearing schists, located in the lower marble zone. They consist almost entirely of glaucophane and crossite with schlieren of the assemblage epidote-garnet-calcite. Magnetite, sphene and apatite are present in moderate amounts. The glaucophane and crossite display zonal pleochroism and they occasionally become actinolitic towards the rim. Chlorite is locally found around the garnet. The calcite in the eclogitic and glaucophanitic rocks has a typical columnar habit which is thought to be pseudomorphic after aragonite.

The CHLORITE SCHIST occurs in several zones in the marble-schist Series. It consists of chlorite-albite (An $\leq$ 5%)-mica-epidote/zoisite with minor carbonate, apatite, sphene and hematitic

Table 111. Microprobe analyses of minerals from the marble-schist Series.

mineral	stilpnomelane	stilpnomelane	epidote	garnet	glaucophane	glaucophane	chloritoid	riebeckite	garnet
Sample no.	108 C	108 C	108 C	108 C	108 C	29	29	32	Io 64
Coordinates Lat.	36°45'02"	36°45'02"	36°45'02"	36°45'02"	36°45'02"	36°44'29"	36°45'29"	36°44'58"	36°45'38"
Long.	25 16 02	25 16 02	25 16 02	25 16 02	25 16 02	25 20 34	25 20 34	25 18 48	25 18 48
SiO_2	45,75	45,46	38,00	38,86	54,45	55,81	24,15	51,14	36,99
Al_2O_3	6,59	6,66	23,18	19,77	8,40	10,15	37,49	3,21	17,71
TiO_2	-	-	0,08	0,10	0,06	-	-	-	-
FeO_{tot}	27,39	28,36	11,57	28,51	21,89	15,28	26,37	29,27	16,82
MgO	5,07	4,83	0,08	0,52	4,83	7,11	1,86	2,84	0,41
MnO	4,46	2,49	0,08	1,70	0,03	0,15	0,42	0,32	17,10
CaO	0,29	0,41	22,76	12,24	0,69	0,32	0,18	1,93	7,66
Na_2O	0,33	0,18	0,05	-	6,48	7,18	-	6,31	-
K_2O	0,93	0,59	-	-	0,02	0,02	-	0,04	-
Anhydrous total	90,81	88,98	95,80	99,70	96,85	96,02	90,47	95,05	96,69
Number of ions on basis of oxygen	48	48	13	12	23	23	6	23	12
Si	15,84	15,96	3,26	2,99	8,01	8,00	1,04	8,10	3,11
Al	2,69	2,75	2,35	1,89	1,46	1,72	1,90	0,60	1,76
Ti	-	-	0,01	0,01	0,01	-	-	-	-
Fe	7,93	8,33	0,83	1,93	2,69	1,83	0,95	3,88	1,18
Mg	2,61	2,53	0,01	0,06	1,06	1,52	0,12	0,67	0,05
Mn	1,31	0,74	0,01	0,12	-	0,02	0,02	0,04	1,22
Ca	0,11	0,15	2,09	1,06	0,11	0,05	0,01	0,33	0,69
Na	0,22	0,12	0,01	-	1,85	2,00	-	1,94	-
K	0,41	0,26	-	-	-	-	-	0,01	-

pseudomorphs after pyrite. Some of the chlorite schists contain glaucophane or actinolite. The mineral assemblages in the glaucophane-bearing chlorite schists are essentially the same as those in the glaucophane schists. The actinolite-bearing chlorite schists mainly show the assemblage actinolite-muscovite-albite-quartz sometimes with epidote or garnet. Lenses of brown calcite with fuchsite are randomly distributed in the chlorite schists.

A zone of METAMORPHOSED ULTRAMAFIC BODIES and some isolated talc-bearing lenses are found in the chlorite schists. The bodies are about 1 m in diameter and they often have a radial pattern due to the orientation of the Mg-rich minerals. Some bodies are more or less monomineralic and consist either of chlorite, talc, actinolite or antigorite. Most of the bodies contain the association actinolite-mica-fuchsite-chlorite-zoisite/epidote-garnet-calcite. Pseudomorphs of about 5 mm in size after lawsonite, which is replaced by the assemblage phengite-fuchsite-zoisite-calcite, have been found in the actinolite- and chlorite-rich bodies. Brown calcite lenses, containing bright green fuchsite, are fairly abundant in this zone.

A METABASITE which was thrust against the marble-schist Series is located on the extreme western peninsula of the island. This rock consists of chlorite, sericite, heavily altered green amphibole and plagioclase. The amphibole is replaced by chlorite and hematite while the plagioclase is altered to an assemblage of epidote-calcite-albite. The metabasite is brecciated and cross-cut by quartz and calcite veins.

ESTIMATION OF THE P-T CONDITIONS

The petrographical description given above leads to the conclusion that the rocks of Ios were subjected to several metamorphic phases. The geology and petrology of the Basement indicate that it at least underwent a period of magmatic activity, but P-T conditions of this

phase are unknown because the associated mineralogies were largely destroyed. The most obvious metamorphic phase is a blueschist facies phase which was apparently followed by a greenschist facies metamorphic phase. Other islands in the Cycladic area also show the evidence of a blueschist metamorphism followed by a greenschist metamorphism (Syros, Naxos, Siphnos, Sikinos). The blueschist metamorphic phase and the greenschist metamorphic phase have been named M 1 and M 2 respectively in order to correlate the terminology for Ios with that used for Naxos (Jansen et al., in prep.).
The metamorphic conditions of the M 1 phase can be estimated from the preserved relictic and partly pseudomorphic mineralogies. Relevant metamorphic reactions are shown in fig. 4. Aragonite was not found on Ios but the calcite in some rock types of the Series is persistently of columnar habit which is interpreted as a pseudomorphic form after aragonite. The minimum conditions must consequently lie to the high pressure side of the experimentally derived curve (2) of the aragonite-calcite transition (Johannes and Puhan, 1971). The pseudomorphs after lawsonite support this conclusion. The M 1 conditions are thus confined to the low temperature side of the lawsonite breakdown reaction (4) determined by Nitsch (1974). The reaction jadeite + quartz to albite was not demonstrated on Ios. The evidence could easily have been destroyed. Based upon the present mineral assemblage data the range of the M 1 conditions is limited to the low pressure side of the reaction curve (1) (Boettcher and Wyllie, 1969).
Diaspore is the main Al-mineral in the diasporites. Only in one case the association diaspore-kyanite was found, possibly an effect of the M 2 phase. Haas (1971) determined the conditions for the reaction diaspore + pyrophyllite = kyanite + H_2O (5). The M 1 conditions probably lie on the low temperature side of this curve.
With the described restrictions a rough estimate of the P-T conditions of the M 1 phase can be made. The upper temperature

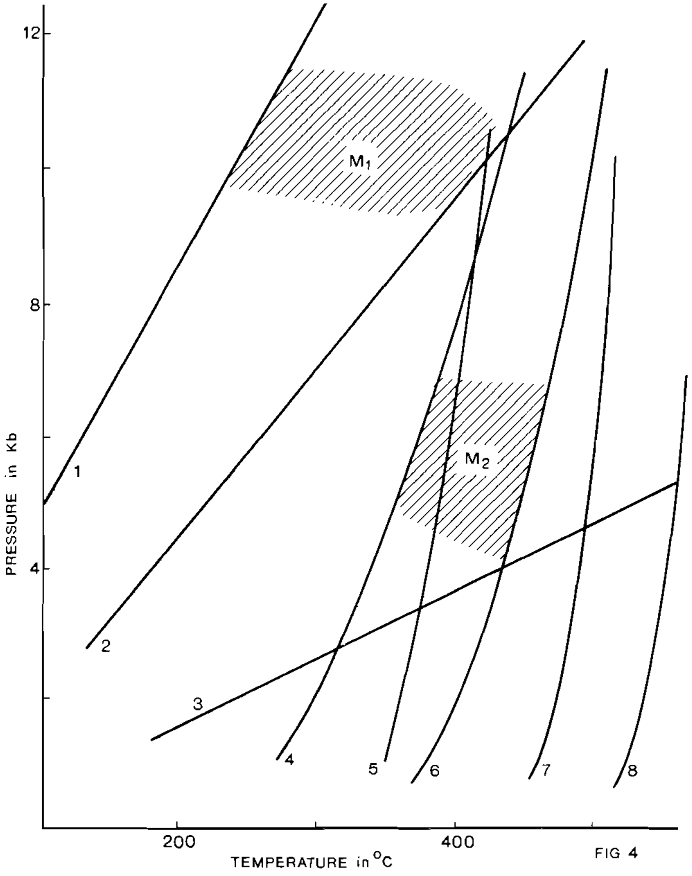

FIG 4

Fig. 4. P-T curves of mineral equilibria relevant to the mineralogies observed on Ios. Dotted arrow: estimated change in P-T conditions since M 1 metamorphic phase. Note the rise in temperature connected with the M2 phase. 1, jadeite + quartz = albite (Boettcher and Wyllie, 1969); 2, aragonite = calcite (Johannes and Puhan, 1971); 3, kyanite = andalusite (average value using Althaus, 1967 and Richardson et al., 1969; see Jansen and Schuiling, 1976); 4, lawsonite = margarite + zoisite + quartz + H_2O (Nitsch, 1974); 5, diaspore + pyrophyllite = kyanite + H_2O (Haas, 1971); 6,diaspore = corundum + H_2O (Haas, 1971); 7, appeanrance of biotite in pelitic rocks (Winkler, 1974; Jansen and Schuiling, 1976); 8, breakdown of chloritoid (Richardson, 1968).

limit is set either by curve (4) or (5) at 400°C. The lower temperature limit lies between 200° and 300°C. Blueschists notably are thought to originate under relatively high pressure and low temperature conditions. Taylor and Coleman (1968) calculated the metamorphic temperatures of several blueschists complexes in the world using the O^{18}/O^{16} ratios of mineral pairs. They found temperatures around 300°C for "medium grade" blueschists (glaucophane-quartz-mica-garnet-chlorite- occasionally aragonite and lawsonite) and between 400°-550°C for "high grade" glaucophane schists (glaucophane-garnet associations without aragonite and lawsonite) and eclogites. A reasonable estimate of P-T conditions during the M 1 phase would be between 300°-400°C with a pressure range of 9-11 kb. The upper pressure limit for the same temperature range would be about 15 kb. The P-T conditions of the M 2 phase can be estimated based on the occurrences of the following minerals and mineral assemblages. Aragonite has been replaced by calcite and lawsonite was replaced by the assemblage zoisite-mica-calcite. The M 2 conditions are thus confined to the low pressure side of reaction (2) and to the high temperature side of reaction curve (4). 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 (6): diaspore to corundum, determined by Haas (1971). Kyanite occurs in the metabauxites in association with diaspore. Reaction (5) 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, curve (3) (average value using Althaus, 1967 and Richardson et al., 1969; see Jansen and Schuiling, 1976). Moreover chloritoid occurs in the metabauxites as well as in the garnet-mica schist near the augengneiss dome (fig.3a). This indicates that M 2 conditions were below those of the -chloritoid curve (8) (Richardson 1978). Late formed biotite is regularly found in minute amounts in the rocks of the island. M 2 conditions apparently were just above a biotite isograd. The temperature conditions for biotite-forming reactions on Ios probably were some 40^{o} below those for the +biotite isograds for rocks of pelitic composition shown in fig.4 (7) (Winkler, 1974). Nowhere in the rocks exposed on Ios does the plagioclase contain more than 5% An.

The mineralogy indicates an adaptation of the M 1 blueschist assemblage to greenschist facies conditions. Therefore the range of P-T values of the M 2 phase is estimated to be restricted to 5-7 kb pressure and 380^{o}-450^{o}C. The greenschist facies overprint of the blueschist assemblages is the result of a small rise in temperature as well as a decrease in pressure (fig.4). Elsewhere in the Cyclades the M 2 phase is also characterized by a period of rising temperature that affected the M 1 blueschist mineralogies (e.g. Siphnos, Dixon, 1968; Okrusch et al., 1977). Occasionally the M1 mineralogies were completely destroyed by the M2 metamorphic phase (e.g. Naxos, Jansen et al., in prep.).

Discussion

The geological and petrological constitution of the Basement gives no definite indication about the nature of a pre-M 1 metamorphic phase. Two models for the pre-M 1 history of the Basement are possible:

1- An intrusion model assumes the augengneiss to be a metamorphosed granitic intrusion. In this model the garnet-mica schist is the oldest formation of the Basement and the garnet-mica schist lense in the augengneiss are interpreted as metamorphosed roof-pendants The intrusion caused H-T contact metamorphism in the country rock and in the roof-pendants. A phase of updoming is also assumed to be associated with the intrusion.

2- An anatectic model assumes the Basement to be the remnant of a mantled gneissdome. The augengneiss represents the migmatite core and the garnet-mica schist is the equivalent of the innermost schist envelope. Mantled gneissdomes are thought to be the result of high grade regional metamorphism with anatexis. The mobilized rock generates a dome structure with a migmatite core and a schist mantle characterized by an outward decreasing metamorphic grade (Thompson et al., 1968; Fletcher, 1972). Examples are known from many older and younger orogenies such as the Finnish Caledonides (Eskola, 1949), the Appalachians (Thompson et al., 1968) and the east Mediterranean where similar dome structures were found in the Menderes Massif and on the island of Naxos (Schuiling, 1962; Jansen and Schuiling, 1976; Dürr et al., 1978).

The main difference between the two models actually lies in the sizes of the metamorphosed areas and in the physical conditions during the formation. In the intrusion model a relatively small zone of contact metamorphism was generated in the country rock close to the intrusion and in the roof-pendants. In the anatexis model a zone of upper amphibolite facies metamorphic rock of several kilometers wide must have been present around the migmatite core and one should expect to find the remnants of a temperature gradient towards the center of the dome. In the domestructure of Ios, however, the total lack of a metamorphic zonation and the absence of relicts or pseudomorphs of typically high-temperature minerals are remarkable phenomena. The existence of postkinematic dike systems in the Basement (metamorphosed intrusive rocks) favours the intrusion model. Dikes of aplitic-, lamprophyric- and granitic-composition are not unlikely to develop after a major intrusion. The sharp boundary between the augengneiss and the garnet-mica schists also suggests the intrusion model. Nevertheless the widespread occurence of especially garnet in the garnet-mica schists could be an indication of the former high grade regional metamorphic

phase. Attempts to solve some questions about the history of the Basement through chemical investigation are in progress.
The distinct lithological differences between the Basement and the Series point to different geological histories. Augengneiss and bodies of metamorphosed intrusive rocks occur only in the Basement whereas marble, glaucophane schist, eclogites and ultramafic lenses are restricted to the Series. The geological constitution of the Series itself suggests that it is a sequence that was tectonically assembled by thrusting rather than formed in situ.

The thickness of the garnet-mica schists decreases eastward and the major metagranite body in the garnet-mica schist is situated just below the marble-schist Series which bears no marks at all of magmatic activity.

The Basement-Series boundary is sharp and in the uppermost layers of the garnet-mica schists an actinolite schist with megacrysts is found which probably is the remnant of an ophiolite sheet. Because of these arguments the Basement-Series boundary is interpreted as a major thrustplane along which at some time the Series were thrust on top of the Basement. The boundary, however, can be an old erosion surface that acted as a zone of structural weakness along which major thrust processes were favoured. The occurences of Fe-pods, possibly lateritic remnants, in the uppermost layers of the garnet-mica schists support the existence of such an erosion surface but along the basis of the Series no indication of a metamorphosed basal conglomerate was found.

The lineation in the Basement is parallel to the N-S directed lineation pattern in the Series where it can be observed, for example, in the orientation of the glaucophane crystals. This indicates that the lineation is associated with the M 1 metamorphic phase. Furthermore the schistosity pattern in the augengneiss is in accordance with the strikes and dips in the Series and the thrustplane is folded. The Basement and the Series were apparently together subjected to the M 1 metamorphic phase. This could imply that the major phase of overthrusting took place prior to or during the M 1 phase. In this respect it is important to notice that the megacrysts in the actinolite schist in the uppermost layers of the garnet-mica schists are also N-S orientated. If the Basement and the Series, however, were subjected to the M 1 phase separately before the major overthrust took place, the directions of the imposed M 1 lineation and of the thrust movement must have been identical because the N-S lineation is the only one observed. The petrological effects of the M 1 phase on the Basement and on the Series were different because the Basement was a high grade metamorphic complex. In the Series the M 1 generated the characteristic blueschist facies mineralogies whereas in the Basement it merely erased the preexisting high-temperature mineralogies apparently without generating typical high-pressure minerals. It also transformed either the granitic intrusion or the migmatite core into the present augengneiss.

Folding associated with the M 1 phase also initiated the present dome structure probably aided by the buoyancy of the augengneiss due to its lower overal density as compared with the overlying schist and marble-schist Series (c.q. Thompson et al., 1968; p. 216).

There is no noticeable influence of the updoming on the lineation direction therefore the main doming phase must have been prior to or during the M1 metamorphic phase in which the lineation originated. The M 2 caused a distinct greenschist facies type overprint of the blueschists in the Series which partly destroyed the high pressure mineralogy. Its influence on the Basement is noticeable by the occurence of minute amounts of late formed biotite, which is found in nearly all the rock types of the island.

Lineation generated by the M 2 phase is, if present at all, subparallel to the M 1 lineation.

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CHAPTER II

The petrology of the island of Sikinos, Cyclades, Greece in comparison with that of the adjacent island of Ios.

by P.A. van der Maar, A. Feenstra, B. Manders and
J.B.H. Jansen.

(submitted for publication)

Abstract

The rocks exposed on Sikinos are divided into two units. The stratigraphically lower unit consists of quartz-chlorite-mica-garnet schists in which several bodies of metamorphosed intrusive rock occur. The upper unit is a marble-schist series that consists of marbles alternating with glaucophane schists, greenschists and chlorite schists. Metabauxites, eclogitic lenses and rocks of ultramafic composition are locally present in the series. Both units contain the records of two metamorphic phases: a glaucophaneschist facies metamorphism (M1) and a subsequent greenschist facies metamorphism (M2) that partly erased the M 1 mineralogies. Similarities in geology with the adjacent island of Ios are evident. On account of the mineralogies and textures the lower unit is interpreted as a part of the Pre-Alpine Basement of the Cycladic Massif and the Basement-Series boundary is thought to represent a pre M1 thrustplane.

Introduction

Sikinos is a small island in the Cycladic Archipelago and it is located about 200 km SE of Athens (fig. 1). Its topography is dominated by a single mountain chain that runs parallel to its SW-NE length axis. The island is part of the Attic-Cycladic Massif, which mainly consists of regionally metamorphosed rock of various metamorphic facies (DIXON, 1968; JANSEN and SCHUILING, 1976; DÜRR et al., 1978; v.d. MAAR and JANSEN, in press). On the adjacent island of Ios the rocks indicate glaucophane schist facies metamorphism with an overprint in the greenschist facies (HENJES-KUNST, 1980; v.d. MAAR, in press).

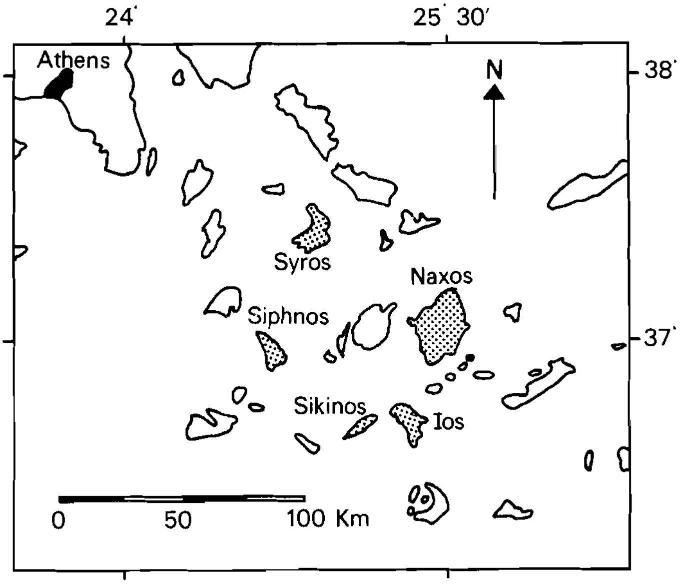
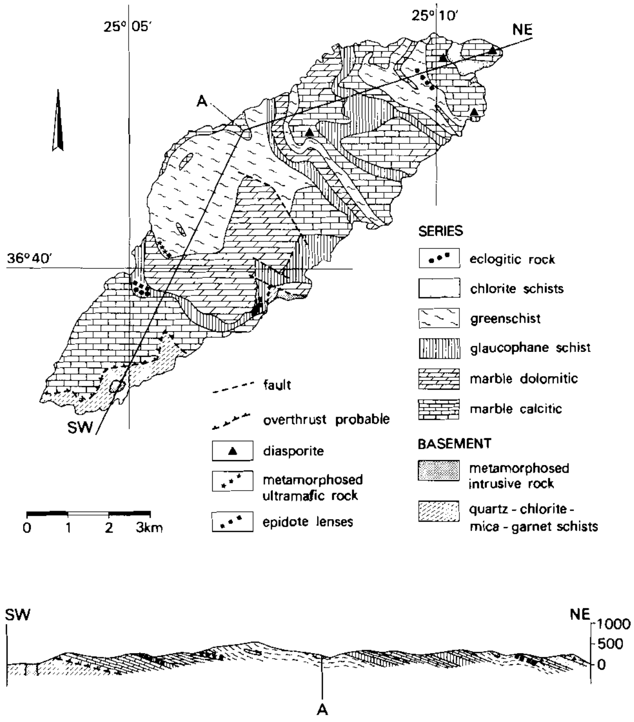


Fig. 1. Map of the Cyclades, Greece. The dotted islands are mentioned in the text.

In general the rocks exposed on Sikinos show a NE dip. The apparently lower rock unit in the SE part of the island is a quartz-chlorite-mica-garnet schist that contains bodies of metamorphosed intrusive rocks of dioritic composition. On top of it a marble-schist series occurs of which the section exposed is about 4 km thick. The schists of the series are subdivided in glaucophane schists, greenschists and chlorite schists (fig. 2). Layers of isolated bodies of eclogitic rock and epidote lenses occur in the glaucophane schists and the greenschists. Lenses of metamorphosed ultramafic rock are also observed. Metabauxites are found in marbles in the north-eastern part of the island.



SIMPLIFIED GEOLOGICAL MAP OF SIKINOS, GREECE

Fig. 2. Simplified geological map of Sikinos with a schematic SW-NE cross section

Petrology

A selection of representative mineral parageneses of the lower unit and of the marble-schist series is given in Table I.
The quartz-chlorite-mica-garnet schist of the lower unit is a banded rock in which chlorite-rich, albite-rich and garnet-rich layers alternate. Berginis (1973) reported this schist to be glaucophane-bearing. The metamorphosed intrusive rocks have a dioritic composition and they originally consisted of brown hornblende, biotite, plagioclase and quartz with allanite and opaques. Relicts of the brown hornblende react to a bluish-green amphibole, while the crystals remain optically continuous with strictly delimitated brown and bluish-green pleochroic domains (fig. 3).

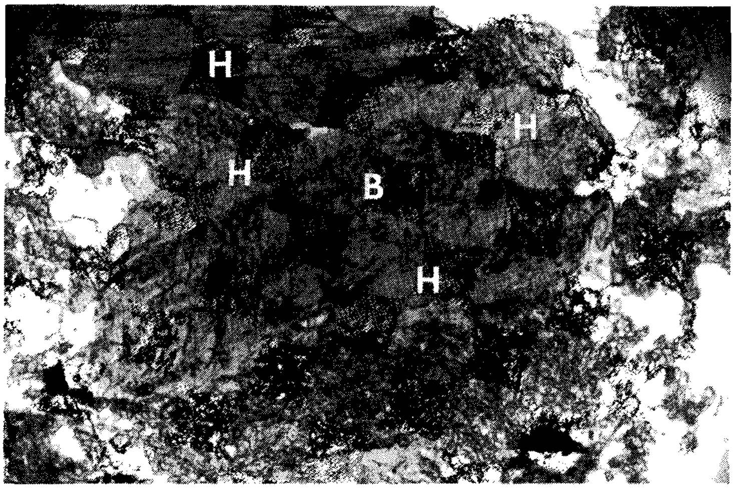


Fig. 3. Metamorphosed intrusive rock S 132. Relicts of brown hornblende (H) with a central area of blue green pleochroic amphibole (B) characterized by a sagenitic pattern of sphene and ilmenite inclusions. The amphibole as a whole is optically continuous. 120 X.

Sample	Coordinates		Quartz	Albite	Chlorite	White mica	Biotite	Garnet	Actinolite	Glaucophane	Pyroxene	Epidote	Calcite	Apatite	Sphene	Mag./Hem.	Other mineral
number	Latitude	Longtitude															
Metamorphosed intrusive rock																	
S132	36^{o}39'40''	25^{o}07'35''			+	+	R			HB$^{1)}$		AL			x	IL	RU
Glaucophane schist																	
S14	36 41 15	25 08 10	x			x	+	x	+	x		x	o	o	x	x	RU
S14B	36 41 15	25 08 10	x	x	+	x						o	o		x		G
S35	36 41 25	25 08 50	x		+	x			+	x$^{3)}$		x	x		x	x	
S36	36 41 37	25 08 25	o	x	+	x			+	x		x	o	o	o	x	
S37	36 41 55	25 07 30	x		+	x		x		x		x	x		x		
S99	36 40 00	25 07 40	o	x	o	x			+	x		x	o		x	x	
S104A	36 41 40	25 07 25				x		x		x$^{3)}$		x					
S104B	36 41 40	25 07 25	x	R	+	x	+	o		x		o			o		
S106B	36 41 15	25 08 05	x			x						x			x		TM
S106C	36 41 15	25 08 05	x		+	x	+	o				x		x	x		
S136A	36 42 00	25 08 40	x	x	+	x		o				x		x	x		TM
S136B	36 42 00	25 08 40	x			x		CTD							x		TM
S137	36 42 00	25 09 00	x		+	x	+	x	+	x		x	x		x		
S141A	36 41 15	25 09 20		x	+	x		x		x$^{3)}$		x	x		RU	x	
S141B	36 41 15	25 09 20		x	+	x		CTD		x		x				x	
S145A	36 41 40	25 10 00	x	x		o		x	+	x$^{3)}$		x		x	x	x	
S148A	36 39 35	25 05 10	x		o	x				x		x	x	o	x		
Greenschist																	
S25A	36 41 30	25 06 33	x	x		x						ZO$^{2)}$	x	x	x		
S28D	36 40 18	25 05 40		x	+	o			x			CL			x		
S42B	36 41 45	25 07 38	x		+	x	+	x	+	x		x	o	o	x		
S52C	36 42 20	25 09 20	o	x	+	x		x	+	R		x		o	o		
S98	36 40 58	25 06 00	x	x	+	x	+	R		R		x		x	x		
S130	36 41 15	25 08 20	x	x		x						PM	x	x	x	x	
S162	36 42 30	25 09 15	x		+	x	+	x		R$^{3)}$				x			
E6	36 40 10	25 05 40	x		+				x	R				x	RU	x	
Chlorite schist																	
S41C	36 42 50	25 10 20		o	o	x			+	R		CL	x				
Eclogitic rock/Epidote lenses																	
S53	36 42 25	25 09 50		x	+						x	x			x		PU
S140B	36 39 35	25 05 20		x						x	x	x				x	
S152B	36 39 35	25 05 25		o	+				x			x			x	x	

Table I. Minerals in rocktypes from Sikinos.

Table I (cont.)

Sample number	Coordinates Latitude	Coordinates Longitude	Diaspore	Kyanite	Chloritoid	Chlorite	Muscovite/Paragonite	Margarite	Clinozoisite	Calcite	Rutile	Hematite	Apatite	Tourmaline
Metabauxite														
S41A	36°42'50"	25°10'20"	R$^{4)}$	x				x			o	x	o	o
S41B	36 42 50	25 10 20	x		x		o	x			o	x		o
S63n	36 42 50	25 10 55	x		x			x	x	o	o	x	o	
S125A	36 42 50	25 10 55	x		x	+		x	x	o	o	x	o	
S125B	36 42 50	25 10 55	R$^{5)}$		x		x	x	x		o	o		
S135A	36 42 50	25 10 20			x		x		x		o	o		
S140F	36 42 05	25 10 35	R$^{4)}$	x	x			o			o	x		

x= major constituent; o= minor constituent; R= relict mineral; += secondary mineral; AL= allanite; CL= clinozoisite; CTD= chloritoid; G= graphite; IL= ilmenite; PM= piemontite; PU= pumpellyite; RU= rutile; TM= tourmaline; ZO= zoisite.

1) initial brown hornblende (see text)
2) zoisite or clinozoisite cores and epidote rims
3) darker crossite rims around glaucophane cores
4) inclusions in kyanite
5) inclusions in chloritoid and clinozoisite

The bluish-green amphibole is speckled with ilmenite and sphene inclusions. The brown hornblende shows exsolution lamellae of cummingtonite that are absent in the bluish-green amphibole. Biotite relicts are rimmed with coronas of garnet (fig. 4). The original plagioclase has been transformed into a mixture of albite-zoisite and mica. The zonal distribution of the zoisite inclusions indicates the normal zoning of the initial magmatic mineral.

In nearly all the schists of the series glaucophane can be observed, in various stages of desintegration. In the glaucophane schists the glaucophanes are relatively unaltered. The glaucophane crystals show distinct dark pleochroïc rims (fig. 5). The zonality possibly indicates different stages of growth in the glaucophaneschist facies. Garnet and albite are regular constituents and chloritoid is rare. Garnet generally appears to have been formed earlier than the zoned glaucophanes. The albite is speckled with zoisite and mica inclusions suggesting that the initial plagioclase contained more calcium. Secondary growth of chlorite, mica, actinolite and of green biotite is obvious in most of the glaucophane schists. The actinolite notably occurs as rims around the glaucophane. The glaucophane schists also contain chloritoid-rich lenses. The chloritoid and tourmaline blasts in these lenses contain much rutile and sphene. The primary constituents of the greenschists are plagioclase, epidote, white mica, chlorite and occasionally garnet. The common amphibole is actinolite. The greenschists may contain some

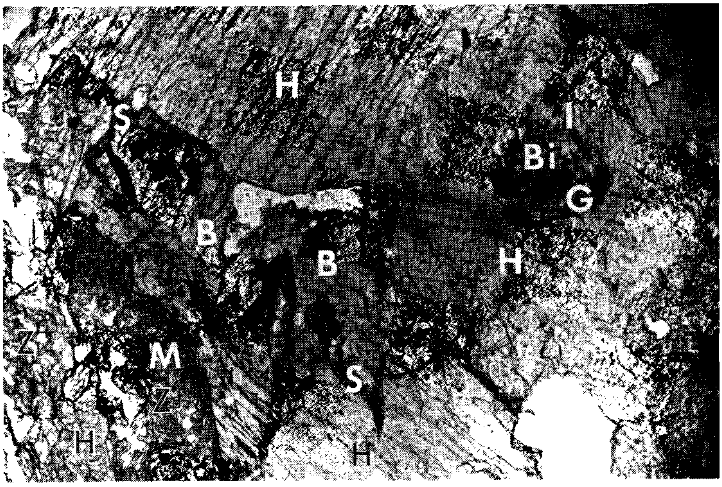


Fig. 4. Metamorphosed intrusive rock S 132. The biotite (Bi) inclusions in brown hornblende (H) are rimmed by ilmenite (I) and garnet (G). Aggregates of muscovite (M) and zoisite (Z) replace the original Ca-rich plagioclase. The brown hornblende reacted to blue green amphibole (B) and sphene (S) along its margins. 120 X

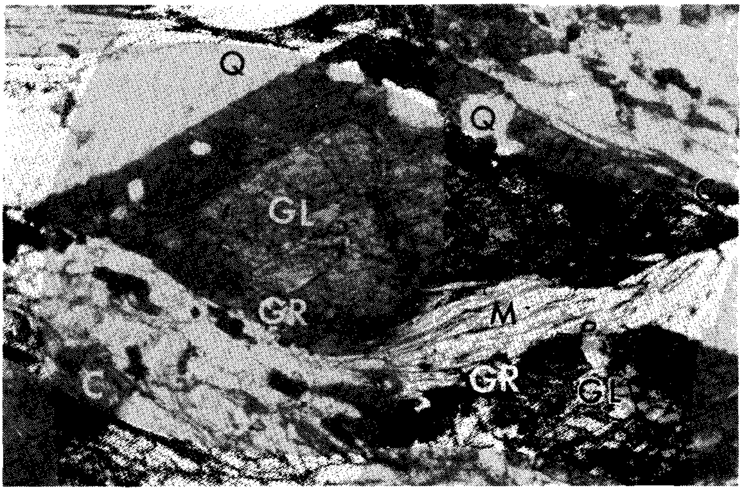


Fig. 5. Glaucophane schist S 162. Two generations of glaucophane (GL). The light coloured core contains less inclusions whereas in the darker crossitic rim many inclusions of quartz (Q) and garnet (GR) are observed. The matrix mainly consists of white mica (M), quartz (Q) and some chlorite (C). The glaucophane is surrounded by a minute rime of chlorite. 100 X.

glaucophane, which is either intensely affected by actinolitization and chloritization (fig. 6) or present as small relicts in albite and epidote crystals.

The extreme form of actinolization is demonstrated by the existence of small blue-violet pleochroic domains in the actinolitic amphibole. Two generations of chlorite are observed. The M 1 generation consists of large green pleochroic crystals, whereas the M2 generation is finegrained and brownish-yellow pleochroic. The epidote crystals are zonally developed with zoisite cores and epidote rims. The Mn-rich epidote piemontite is found in lenses in the greenschists. Albite has typical zoisite and mica inclusions. The chlorite schist that occurs in the northern part of Sikinos is mainly composed of chlorite, albite and white mica. The marble beds of the series are generally thin. Massive parts without schist intercalations occur notably in the southern part of Sikinos. Locally the marbles contain the association glaucophane-quartz-

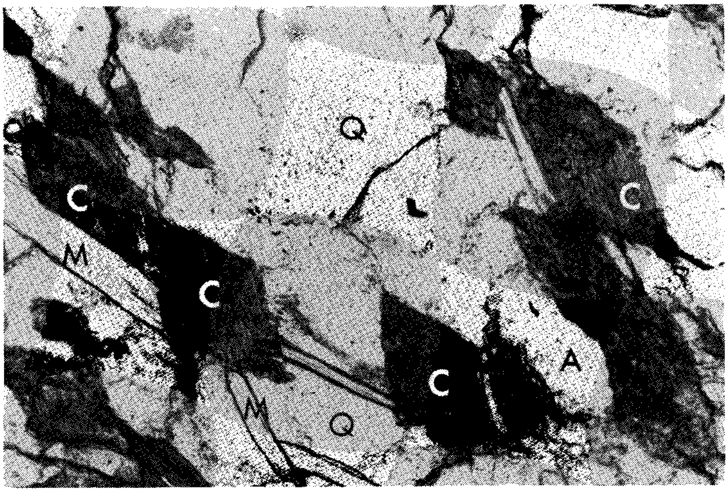


Fig. 6. Greenschist S 154. Quartz (Q) - albite (A) - chlorite (C) - mica (M) schist with chlorite pseudomorphs after glaucophane. 50 X.

garnet-epidote-white mica. Lenses of eclogitic rock occur in some parts of the glaucophane schists and greenschists. It is a dense rock that consists of omphacite, Fe-rich glaucophane, garnet and magnetite. Epidote, calcite, sphene and albite also occur. The lenses show monomineralic zones probably due to metasomatism interaction with the country rock. The omphacite is locally coarsegrained. Along the crystalboundaries the omphacite reacts to form large idiomorphic glaucophanes. These glaucophanes show a distinctive zonation with dark cores and lighter rims. This zonation is the reverse of the one observed in the glaucophanes from the schists. The glaucophanes are subsequently rimmed by actinolite.

Epidote lenses are spatially associated with the eclogitic rock. Epidote is finegrained and the associated minerals are clinopyroxene, albite, chlorite and sphene. Actinolite is sometimes present. The clinopyroxene occasionally reacts to form pumpellyite, chlorite and epidote (fig. 7). At the basis of the greenschists some lenses of metamorphosed ultramafic rock occur. They consist of antigorite, talc, actinolite, chlorite and magnetite. The metabauxites are conformably enclosed in the marbles. The typical mineral assemblage is diaspore-chloritoid-margarite-hematite-rutile. The diaspore occurs as finegrained crystals and it is usually intergrown with chloritoid poikiloblasts.

The chloritoid contains rutile, hematite and diaspore as inclusions. Polysynthetic twins of chloritoid are ubiquitous (fig. 8). Pisolitic textures are common in the finegrained parts of the deposits (c.f. VALETON, 1972). In the numerous veinlets coarse grained diaspore,

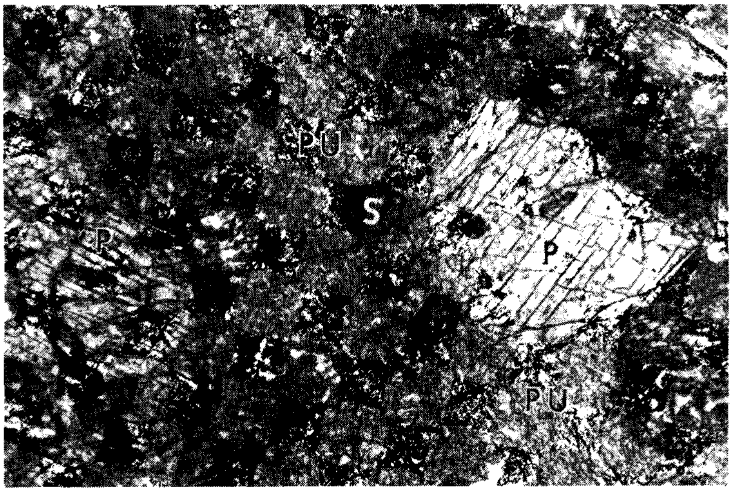


Fig. 7. Epidote lense S 53. Clinopyroxene-rich part of an epidote lens. The pyroxene (P) reacts to a fine grained mixture of chlorite and pumpellyite (PU). 100 X

euhedral chlorotoid, massive green chlorite and flaky margarite can be found. The massive margarite often contains small cubes filled with chlorite or limonitic hematite. They probably are pseudomorphs after pyrite. The deposits become rich in SiO_2 towards the margins where kyanite and clinozoisite occur as additional minerals. The kyanite contains inclusions of diaspore (fig. 9).

Margarite is formed relatively late in these SiO_2-rich parts as it partly replaces kyanite, clinozoisite and chloritoid (fig. 8 and 9).

Conclusions

The assemblages and textures observed in the rocks of the lower unit demonstrate the presence of metamorphosed diorites. The mineralogical textures show that the metadiorites were metamorphosed first under glaucophaneschist facies conditions (M1) and later under greenschist facies conditions (M2). The marbles are absent in the lowest unit. The contacts that exist between the meta-intrusives and the marbles of the marble-schist series are due to post-metamorphic faults (see fig. 2). The geological setting, the specific mineral contents and the replacement textures of the metadiorites strikingly resemble those of the meta-intrusive bodies in the Pre-Alpine Basement of Ios (HENJES-KUNST, 1980; v.d. MAAR, in press). Because of these parallels the quartz-chlorite-mica-garnet schists and the metamorphosed intrusive rock on Sikinos are also interpreted as a part of the Pre-Alpine Basement of the Cycladic Massif.

The marble-schist series on Sikinos shows all the typical properties of the Series as it is exposed on a number of other Cycladic islands like Ios, Naxos, Siphnos and Syros (DIXON, 1968; JANSEN and SCHUILING, 1976; OKRUSCH et al., 1977; DÜRR et al., v.d. MAAR and JANSEN, in

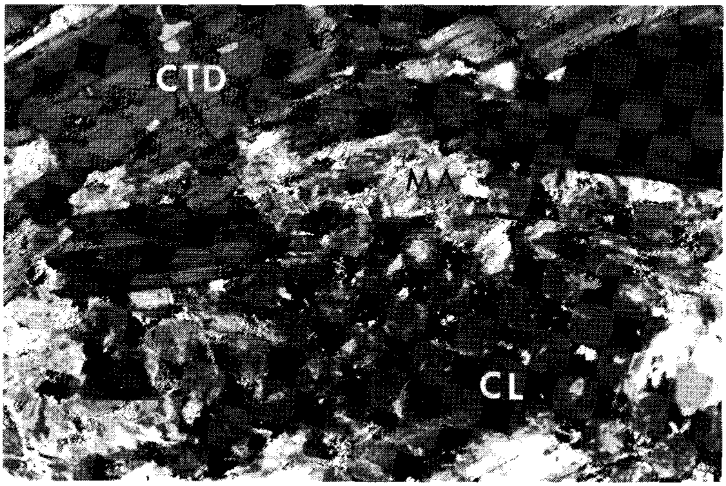


Fig. 8. Metabauxite S 135A. Clinozoisite (CL) and chloritoid (CTD) react to margarite (MA) and rutile (not indicated). The chloritoid shows polysynthetic twinning. 50 X

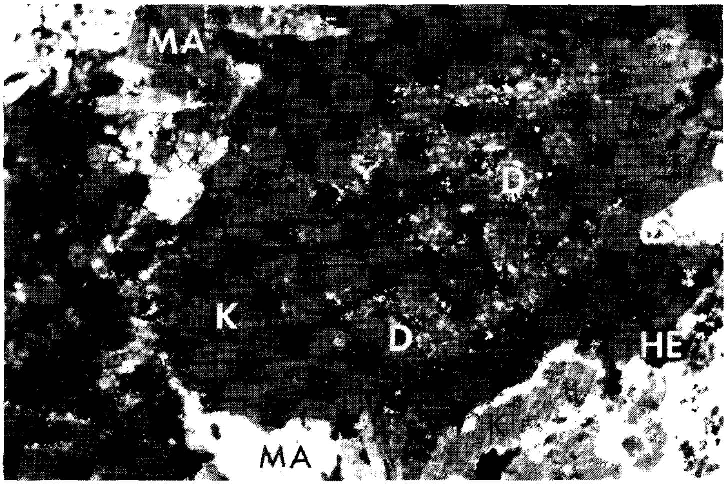


Fig. 9. Metabauxites S 41A. SiO_2-rich part of diasporite. Kyanite (K) contains numerous diaspore inclusions (D). The matrix mainly consists of margarite (MA), hematite (HE) and small rutile crystals. 50 X

press). This Series is interpreted as a metamorphosed, tectonically composed pile of sediments and volcanics, both of probably Mesozoic age (c.f. DÜRR et al., 1978).
On Sikinos the rocks of the marble-schist series also contain the records of at least two major metamorphic phases. The oldest metamorphic phase (M1) is characterized by glaucophaneschist facies conditions. Its influence can be traced back in nearly all the rocktypes of Sikinos. The zonality observed in several M1 minerals points to a polyphasic metamorphism. The M1 metamorphism has affected most of the Cycladic islands and it was dated at about 45 Ma. (WENDT et al., 1977; ALTHERR et al., 1979; ANDRIESSEN et al., 1979; HENJES-KUNST, 1980). On Ios the high pressure metamorphism (M1) was followed by a greenschist facies metamorphism phase (M2) that partly erased the blueschist mineralogy. The M2 was also recognized on Sikinos as a greenschist facies overprint. On several islands the M2 was dated at about 25 Ma (WENDT et al., 1977; ALTHERR et al., 1979; ANDRIESSEN, 1978; HENJES-KUNST, 1980). The boundary between the Basement and the marble-schist series on Sikinos is interpreted as a thrustplane along which the Series were emplaced on top of the Basement prior to the M1 phase (c.f. Ios, v.d. MAAR, in press).

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CHAPTER III

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

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(submitted for publication)

Abstract

The geological structure of the island of Ios, Cyclades, Greece, is a dome consisting of an augegneiss 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 350-400 °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.

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 of 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, in press). 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, in press).

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 metabauxites (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 stratigraphic 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, in press).

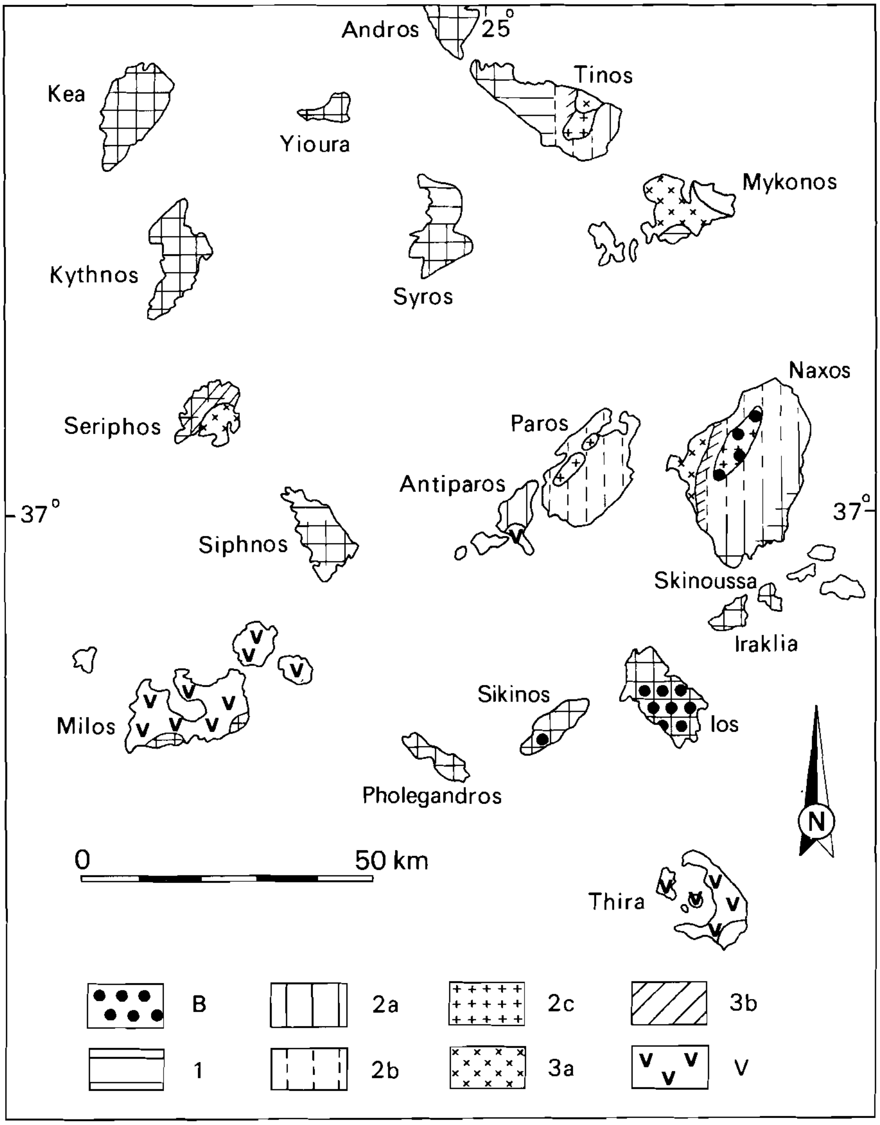

Fig. 1. Map of the Cyclades, Greece with the distribution of metamorphic rocks. B: Pre-Alpine Basement; 1: M 1 Glaucophane-schist facies to glaucophanitic greenschist facies metamorphism; 2a: M 2 greenschist facies metamorphism; 2b: M 2 amphibolite facies metamorphism; 2c: M 2 migmatite; 3a: M 3 Late Alpine granodiorite; 3b: M 3 contact metamorphism; V: Pliocene to Recent volcanism. For references: see table III.

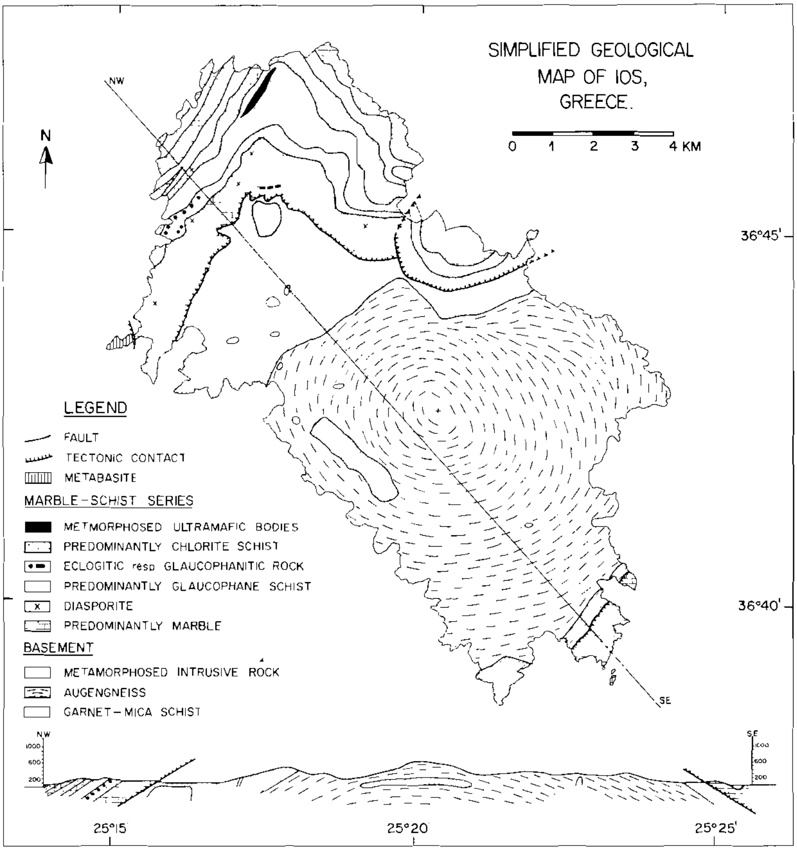

Fig. 2. Simplified geological map of Ios, with a schematic NW-SE cross-section.

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.

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 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 preliminarily dated with the K-Ar method on phengite and paragonite of glaucophane schists from the northern part of Ios. The minerals 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.

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 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.

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		+	X6)	+	X	Ctd4)	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	+		X5)	X	X	X		X	X	X	
Eclogitic rock																	
32	36 44 58	25 15 48	0					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		0	+			X	X5)	X	X	X	X	0	X	X	
16-17	36 45 44	25 18 30		X						X	X	X	X	X	0	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	0	X	X	

X= major constituent; 0= 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.

Table II. Minerals in rock types from the Basement

Sample number	Coordinates Latitude	Coordinates 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							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

An extensive petrological description is given in an earlier paper (v.d. Maar, in press.).

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.

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 finegrained 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 occurence 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-muscovite 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 hornblende and biotites from metamorphosed intrusive rocks show model ages of 1576, 784, 173 and 166 Ma (Kreutzer et al., 1978). The first two ages were interpreted as "excess argon" results and the other two as "mixed age" results. An additional Rb-Sr dating on the same biotite, that gave 173 Ma with the K-Ar method, showed 217 Ma. This age was also interpreted as a "mixed age" result. The few 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 metamorfic 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 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 actinolite 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 occurences of the following minerals and mineral assemblages. Aragonite has been replaced by calcite and sodic-pyroxene has reacted to produce riebeckite and actinolite 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 schist. 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 neoformation 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 S-E 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 rock-pile of 18 km thickness and the corresponding average rate of uplift must have been .7 mm/a.

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

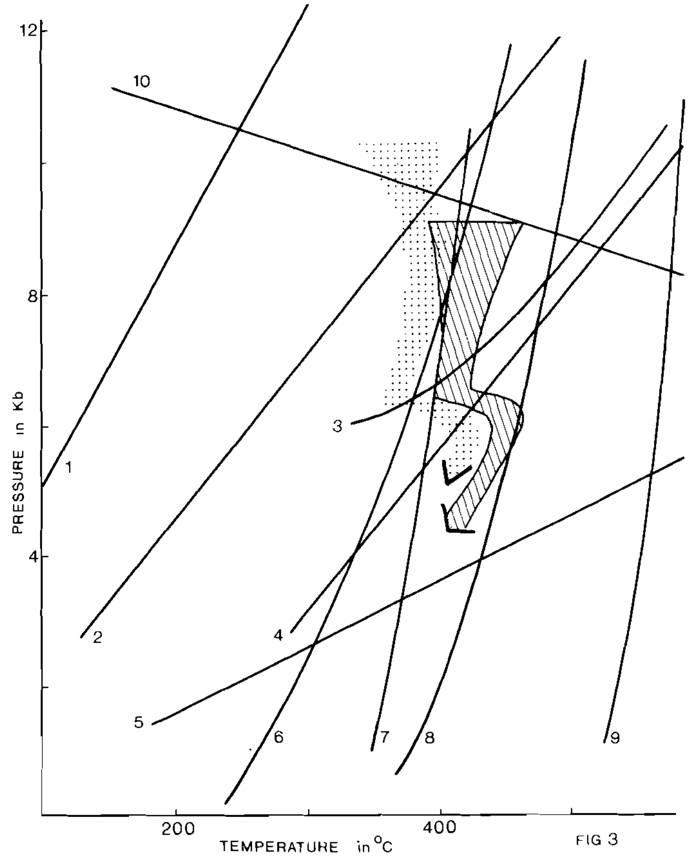

Fig. 3. P-T curves relevant to the mineralogies observed on Ios. 1, jadeite + quartz = albite (Boettcher and Wyllie, 1969); 2, aragonite = calcite (Johannes and Puhan, 1971); 3, crossite + epidote = albite + actinolite + chlorite + magnetite/hematite (Brown, 1978); 4, actinolite + muscovite + stilpnomelane = 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 for SE Naxos.

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, Antiparos, Iraklia, Kea, Kythnos, Milos, Naxos, Paros, Pholegandros, Seriphos, Sikinos, Siphnos, Skinoussa, Syros, Tinos and Yioura; for the references see Table III. The occurences of a few horizons of metamorphosed bauxites and Fe-rich bodies in the marbles and of lenses of eclogitic, metavolcanic, ultramafic and gabbroic rocks in the schists provide markers for lithological correlation among the islands. On Ios, Iraklia, Kythnos, Naxos, Paros, Sikinos and Siphnos metamorphosed bauxites and Fe-bodies are found in the marbles. 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, in press.). 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, Paros and Kea, rocks on all other mentioned islands locally show convincing remnants of glaucophane schist facies and glaucophanitic greenschist facies metamorphism of the M 1 phase (fig. 1 and Table III). On Antiparos and Paros the M 2 and M 3 phases were intensive and probably all remnants of the M 1 phase were obliterated. The available data for

Kea are too scarce to be definite about the presence of M 1 relicts but because of similarities with Attica and the adjacent island Kythnos we assume that Kea was also subjected to the M 1 phase. On Mykonos and Thira, that largely consists of recent volcanic rocks, glaucophane schist is reported by Marinos (1978). In schists on Kythnos and in the extreme nothern part of Seriphos glaucophane 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-Alpine 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 on Seriphos and Kythnos the barely noticeable M 1 influence is of glaucophanitic greenschist facies character and to the south-east 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 could be interpreted as an original compression zone. 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^{o}C. In practically the entire Massif the M 2 phase induced a relatively small temperature rise to at least 400^{o}C. But in the central part of Naxos, on Paros and locally on Tinos the M 2 phase was an amphibolitefacies 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) and Seriphos (9,8 Ma). As a rule these intrusions caused

Table III. Distribution of the metamorphic and magmatic phases in the Cyclades (fig. 1).

Island	Phase	Type	Pressure in Kb	Temperature in °C	Age in Ma	References (no. see below)
Andros	M 1	glauc.sch.	HP	LT		17,27
	M 2	green sch.	MP	MT		
Antiparos	M 2	green sch.	MP	MT		2,27
	M	volcan.	LP	HT		
Ios	M 0	Basement			Pre-Alpine	3,12,13,15,27
	M 1	glauc.sch.	9-11	350-400	43	
	M 2	green sch.	5-7	380-420	25	
Iraklia	M 1	glauc.sch.	HP-MP	LT		21,27
	M 2	green sch.	MP	LT		
Kea	M 1 ?	gl-gr sch.	HP-MP	LT		22,27
	M 2 ?	green sch.	MP	LT		
Kythnos	M 1	gl-gr sch.	HP-MT	LT		22,24,27
	M 2	green sch.	MP	LT		
Milos	M 1	eclog.and glauc.sch.	15	MT-LT	64-33+)	7,11,27
	M 2	green.sch.	MP	MT		
	M	volcan.	LP	HT	2.5-.95	
Mykonos	M 1	glauc.sch.	HP	LT		6,18,25
	M 3	contact ? (granod.)	LP	HT	10	
Naxos	M 0	Basement			Pre-Alpine	3,8,9,10,20
	M 1	glauc.sch.	8	400-500	45	
	M 2	green sch.-amphibolite	5-7	380-700	25	
	M 3	contact (granod.)	2	200-600	11	
	M 4	retrograde	.5-1	350	10	
Paros	M 2	amphibolite	MP	500-600		27
Pholegandros	M 1	glauc.sch.	HP-MP	LT		22,27
	M 2	green sch.	MP	LT		
Serifos	M 1	glauc.sch.	HP-MP	LT		6,16,23,25,27
	M 2	green sch.	MP	LT		
	M 3	contact (granod.)	.5-1	200-600	9.8	
Sikinos	M 0	Basement	MP	HT	Pre-Alpine	21,22,27
	M 1	glauc.sch.	HP-MP	LT		
	M 2	green sch.	MP	LT		
Siphnos	M 1	eclog.and glauc.sch.	15	450	48-41	1,4,19
	M 2	green sch.	MP	LT	24-21	

Table III.continued

Island	Phase	Type	Pressure in Kb	Temperature in ^{o}C	Age in Ma	References (no. see below)
Skinoussa	M 1	glauc.sch.	HP	LT		6,18
	M 2	green sch.	MP	LT		
Syros	M 1	eclog. and glauc.sch.	14	450	46-35$^{+)}$	5,25,27
	M 2	green sch.	MP	LT		
Thira	M 1	glauc.sch	HP	LT		18,27
	M	volcan.	LP	HT		
Tinos	M 1	glauc.sch.	HP	LT	33$^{+)}$	6,14,25
	M 2	green sch.-amphibolite	MP	MT-HT	27	
	M 3	contact (granod.)	LP	LT-HT	15-13	
Yioura	M 1	eclog. and glauc.sch.	HP	LT		22,26
	M 2 ?	green sch.	LP	LT		

$^{+)}$presumably a mixed age of M 1 with later events

References: a. Altherr et al. (1979); 2. Anastopoulos (1963); 3. Andriessen et al. (1979); 4. Davis (1966); 5. Dixon (1968); 6. Dürr et al. (1978); 7. Fytikas et al. (1976); 8. Jansen (1973a); 9. Jansen and Schuiling (1976); 10. Jansen et al. (1977); 11. Kornprobst et al. (1979); 12. Kreutzer et al. (1978); 13. v.d. Maar (in press); 14. Marakis (1972); 15. Marinos (1942); 16. Marinos (1951); 17. Marinos (1954); 18. Marinos (1978); 19. Okrusch et al. (1977); 20.Papavasiliou (1909); 21. Papavasiliou (1913); 22. Phillipson (1901); 23. Salemink (in press); 24. de Smeth (1975); 25. Wendt et al. (1977); 26. Zwart and Sobelev (1973); 27. Unpublished data, Vening Meinesz Laboratorium.

eclog.: eclogite facies; glauc.sch.: glaucophaneschist facies; gl-gr sch.: glaucophanitic greenschist facies; green sch.: greenschist facies; contact: contact metamorphism; granod.: granodiorite intrusion; volcan.: volcanism; Basement: high grade Pre-Alpine Basement (see text).

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, 1978); 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, in press). 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 thought 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

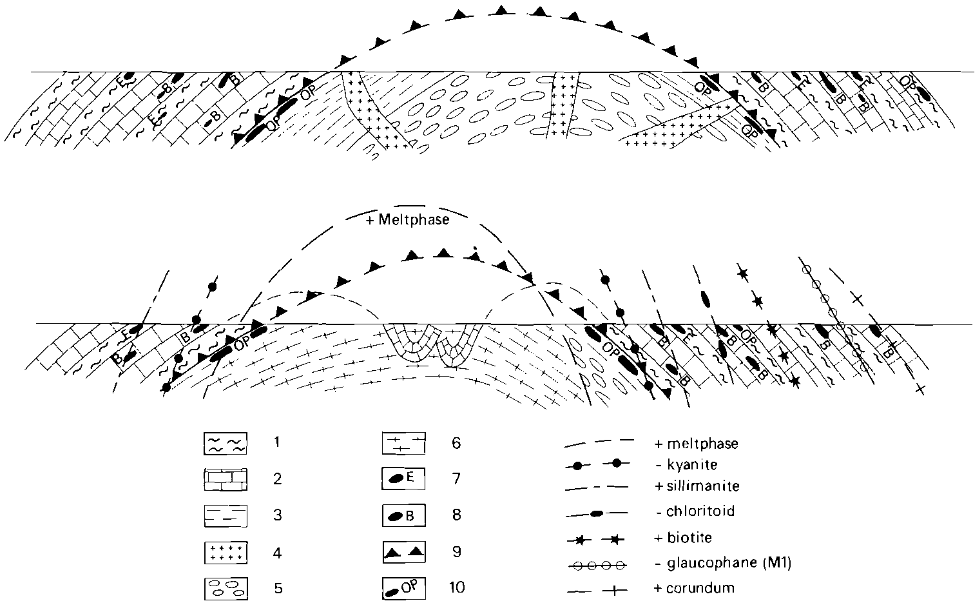

Fig. 4. Schematic profiles of Ios (a) and of Naxos (b).
1: schist; 2: marble; 3: massive schist and gneisses; 4: metamorphosed intrusive rock; 5: augengneiss; 6: migmatite (M 2); 7: eclogitic rock; 8: meta-bauxite; 9: thrustplane; 10: remmants of ophiolite sheet.

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.

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. 4a, 4b).

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 not withstanding 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 pressume 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 determination of the very low K-content these data were regarded 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 Mediterranean 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. 4b). The M 2 phase apparently imposed a metamorphic overprint on a configuration that probably resembled the present-day situation on Ios (fig. 4a).

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, 1973a). 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. 4b); 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 occurence of this Basement in the Attic-Cycladic Massif.

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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 P.A.M. Andriessen, M. Barton, A. Feenstra and R.D. Schuiling.

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CHAPTER IV

The metamorphic evolution of the Southern Cyclades, with special emphasis on the island of Ios.

by P.A. van der Maar
(manuscript)

Abstract

The metamorphic rocks of the southern Cycladic islands of Pholegandros, Sikinos, Ios, Iraklia and Naxos represent a polymetamorphic part of the Attic-Cycladic Massif. The pre-Alpine Basement, recognized on Ios, Sikinos and presumably in the central part of Naxos, is overthrust by a tectonically assembled Series of marbles, schists and eclogitic rocks. This emplacement predates the Alpine metamorphism in which two main phases M 1 and M 2 can be distinguished. The M 1 phase, marked by high-pressure and low-temperature conditions induced eclogite- to blueschist facies metamorphism that was subsequently overprinted by the Paro-Naxotic greenschist- to amphibolite facies metamorphic phase (M 2).

The pre-Alpine rocks were affected by both Alpine phases. On Naxos the pre-Alpine records are practically erased, but on Ios and Sikinos some relicts are still recognizable.

The Alpine metamorphic history is recorded in replacement textures of minerals and in chemical compositions of the minerals involved. Especially zoned minerals and minerals that occur in several generations with different chemical compositions are the clues in an attempt to resolve the metamorphic evolution. The tentative model of the metamorphic evolution is mainly derived from the amphiboles, pyroxenes, garnets and white micas. This model calls for a period of rapid uplift of deep crust after the HP-LT metamorphic phase (M 1) and it is consistent with available geophysical data. A preliminary comparison is made between the southern part of the Attic-Cycladic Massif and the Sesia-Lanzo zone in the western Italian Alps.

Introduction

The island of Ios and the adjacent islands of Sikinos, Pholegandros, Iraklia and Naxos, situated about 200 km SE of Athens, represent a part of the Attic-Cycladic Massif, which mainly consists of regionally metamorphosed rocks (fig. 1).

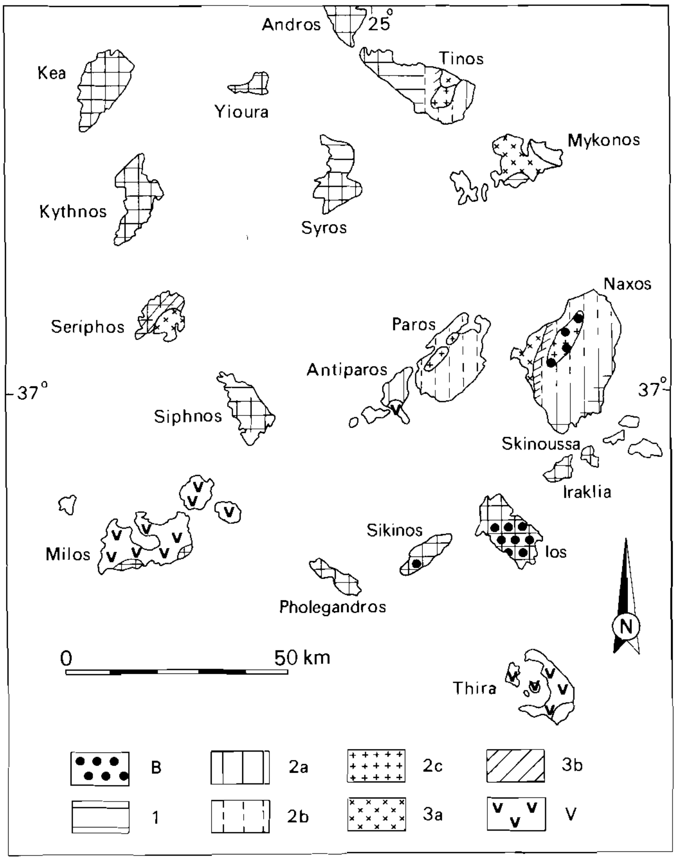


Fig. 1. Map of Cyclades, Greece, with the distribution of metamorphic rocks. B: Pre-Alpine Basement; 1: M 1 glaucophaneschist facies to glaucophanitic greenschist facies metamorphism; 2a: M 2 greenschist facies metamorphism; 2b: M 2 amphibolitefacies metamorphism; 2c: M 2 migmatite; 3a: M 3 Late Alpine granodiorite; 3b: M 3 contact metamorphism; V: Pliocene to Recent volcanism.

The rocks of Ios and, although less pronounced, on Sikinos, can be divided in a Basement and an overlying marble-schist Series (v.d. Maar, in press; v.d. Maar et al., in prep.). The boundary between these units is interpreted as a metamorphosed thrustplane (fig. 2). The Basement consists of orthogneisses, mantled by garnet-bearing schists. Bodies of metamorphosed intrusive rocks only occur in the Basement. The Series is a tectonically assembled pile of marbles, chlorite schists, actinolite schists and glaucophane schists. Metabauxites occur in some marble beds. Zones of eclogitic rocks are embedded in glaucophane-bearing schists. The rocks on Pholegandros, Iraklia and in the southeastern part of Naxos all belong to the marble-schist Series (v.d. Maar and Jansen, in prep.).

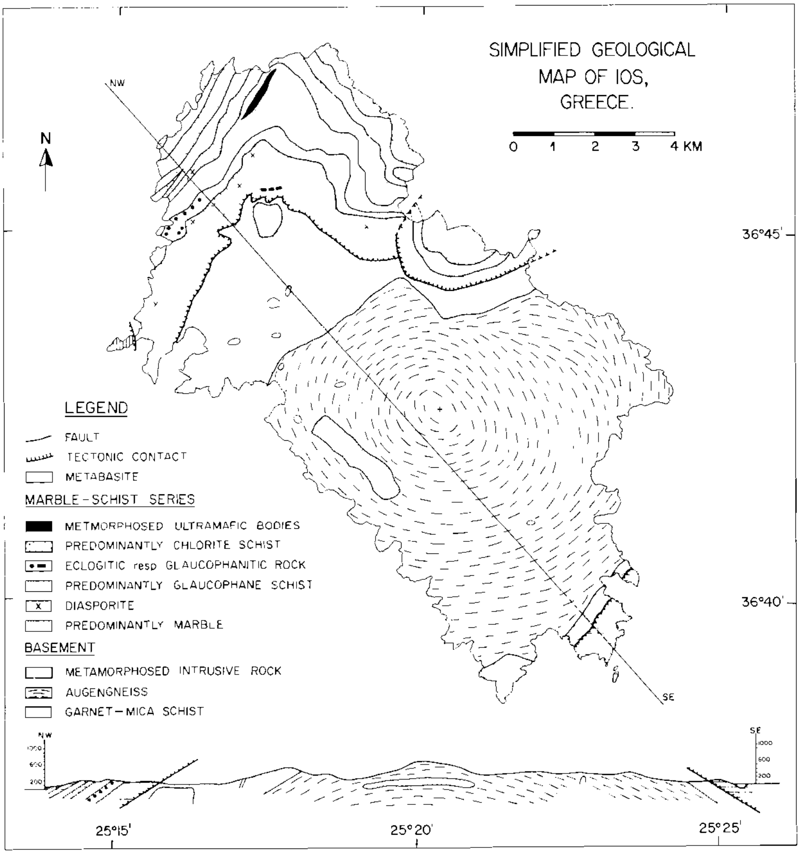


Fig. 2. Simplified geological map of Ios, with a schematic NW-SE cross section.

On these southeastern Cycladic islands two different Alpine metamorphic phases were recognized both geochronologically and petrologically. The first phase, M1 is characterized by high pressure - low temperature assemblages. Minerals of this phase have given radiometric dates ranging from 48 to 40 Ma for Naxos (Andriessen et al., 1979) and from 46 to 35 Ma for Ios (Kreuzer et al., 1978). The M 1 phase has been locally overprinted by a metamorphic phase M 2 of at least greenschist facies grade, whose climax has been dated around 25 Ma (Andriessen et al., 1979). The M2-phase reached the amphibolite facies in the central part of Naxos, where the M1 phase mineralogy has been totally erased.

In the Basement a pre-Alpine, presumably amphibolite facies mineralogy is exhibited whereas in the Series records of pre-Alpine events are extremely scarce. It is the purpose of the present paper to illustrate the mineral records of the several metamorphic phases, to evaluate the records with microprobe analyses of especially zoned minerals and to develop a metamorphic evolution for the rocks of the southeastern Cyclades.

The mineral records of the metamorphic phases

AMPHIBOLES

Blue amphiboles are ubiquitous in the Series of Ios, Sikinos, Pholegandros, Iraklia and common in the Series of SE Naxos.

In the Basement they are present but extremely rare. There the occurrences of glaucophane are restricted to metabasitic relicts in in the garnet-mica schist and roof-pendants of this schist in the augengneiss on Ios. The microprobe analyses of the sodic-amphiboles from schists of Ios and Naxos are given in the appendix (p. A1-A2). They mainly plot in the glaucophane and ferroglaucophane field as defined by Miyashiro (1957). The analysed glaucophanes of Naxos are slightly more crossitic than the glaucophanes of Ios (fig. 3). The sodic-amphiboles from eclogitic rocks of Ios plot in the crossite and magnesio-riebeckite field. The agreement between the blue-amphibole analyses of Ios and Naxos and the analyses given by Henjes-Kunst (1980) is striking except for some of the crossites and riebeckites.

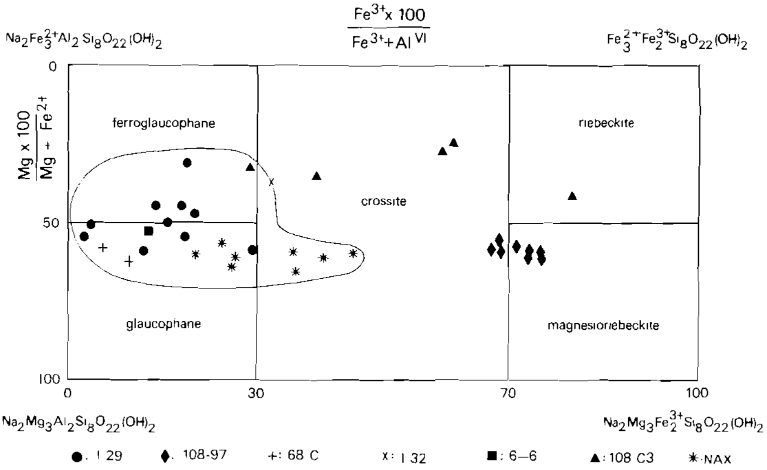


Fig. 3. Diagram of sodic amphiboles after Miyashiro (1957). Sample 6-6 was taken from rocks of the Basement. The enclosed area marks the range in composition of the sodic amphiboles analyzed by Henjes-Kunst (1980).

Microtextures and discontinuous zoning-patterns indicate the existence of several generations of the sodic-amphiboles during the M1 phase of the Alpine metamorphism in the southeastern Cyclades. On all of the islands the normal zoning of these sodic-amphiboles is most common and it is often developed in two ways. Many glaucophane crystals show a pale-coloured core and a distinct, slightly deeper coloured rim. This zoning corresponds to a weak increase in Fe and a decrease in Mg and Al (fig. 3). Especially in the eclogitic rocks the crystals exhibits a zoning with coloured cores and deeply coloured rims with very small 2V and optical orientation of crossite (C. Maijer; pers.comm.)(fig. 4). These rims are enriched in iron during the middle M 1 stage. In some metabasic rocks on Naxos large crystals of deeply-coloured sodic-amphiboles have replaced presumably hornblende, which can be dated as a pre-M 1 phase, as indicated by the presence of well delineated, rhombic patterns, clouded

Fig. 4. Glaucophane schist, Sikinos (S 162). Two generations of glaucophane: a light coloured glaucophane core with a dark coloured crossite rim that contains quartz inclusions. The amphibole is enveloped by a tiny rim of chlorite. Plane polarized. 50 x.

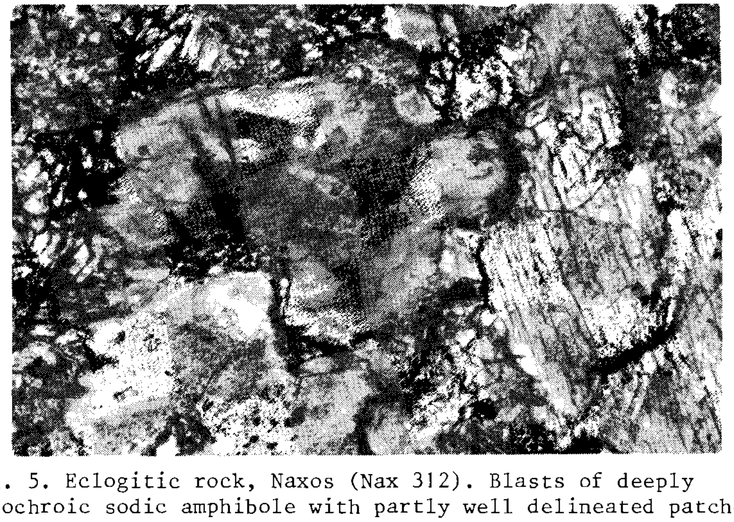


Fig. 5. Eclogitic rock, Naxos (Nax 312). Blasts of deeply pleochroic sodic amphibole with partly well delineated patches filled with sphene and ilmenite. The blue amphibole presumably originated from pre M 1 titaniferous hornblende. Plane polarized light. 100 x.

by sphene and ilmenite inclusions (fig. 5). These deep coloured ferro glaucophanes are supposed to represent the oldest sodic-amphibole generation. In eclogitic rocks on Sikinos some blue-amphiboles are developed with an inverse zonation with a deep-coloured core and a lighter rim. Occasionally these rims have a superimposed normal zoning with a deep-coloured outer rim. Both zonations are rather abrupt (fig. 6). The normal zoning corresponds with an iron enrichment at the end of the M1 phase, whereas the inversed zoning is supposed to have formed early during the M1 phase.

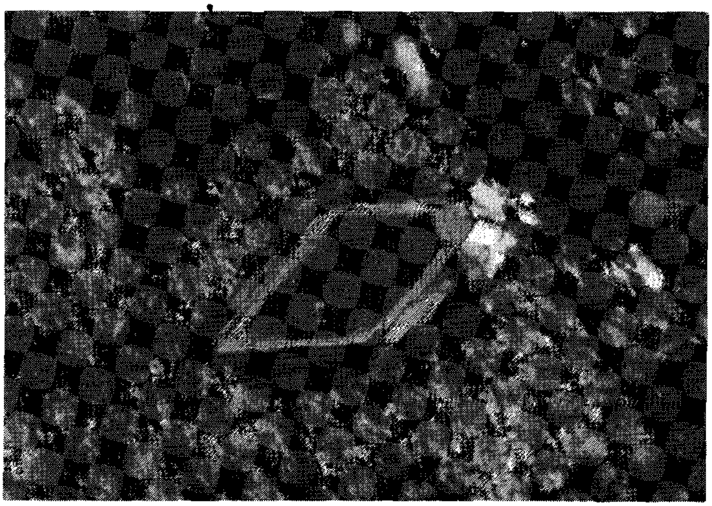


Fig. 6. Eclogitic rock, Sikinos (S 140 B), Idiomorphous crystals of sodic amphibole in a finegrained groundmass of omphacite, garnet, zoisite and magnetite. The amphibole shows a zonation with dark coloured cores, lighter rims and again dark coloured outer rims. The latter consists of a crossitic amphibole. Plane polarized light. 100 x.

In resuming it can be stated that these zoning patterns suggest the existence of three blue amphibole generations. The oldest one is deeply coloured and formed at the onset of the M 1 phase, the second generation is pale to light coloured and crystallized during the early M 1 phase, while the third crossitic generation is again deeply coloured and formed at the end of the M 1 phase.

This first generation of glaucophane occurs in various associations with the minerals omphacite, zoisite, phengite, rutile, ilmenite and magnetite. The second generation with garnet, actinolite, epidote, phengite, rutile, calcite, quartz, chlorite and paragonite. The third generation with epidote, actinolite, chlorite, albite, sphene, chloromelanite, phengite or muscovite and paragonite. Alterations of the blue-amphiboles are usually observed. During the last stage of the M1 and the first stage of the M2 metamorphic phase they are altered along rims and fractures into albite with a green pleochroic calcic-amphibole, often actinolite and occasionally barroisite or winchite. In a final stage of the M2 phase the amphiboles are converted in brown-green biotite (fig. 7). In one occasion crossite reacts to form stilpnomelane (v.d. Maar, in press). On Naxos and Sikinos the crossites alter during the final M2 stage directly into albite and magnetite (fig. 8).

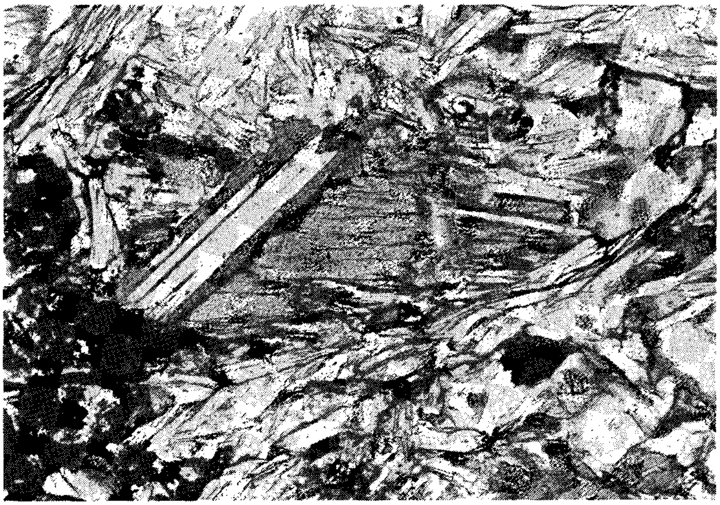


Fig. 7. Glaucophane-bearing roof-pendant of a garnet-mica schist, Ios (I 6-6). Relicts of glaucophane and primary phengite crystals in a matrix of albite, secondary finegrained phengitic muscovite, paragonite, quartz and ore. The glaucophane has actinolitic rims that, like the micas, are finally rimmed by biotite. Plane polarized light. 100 x.

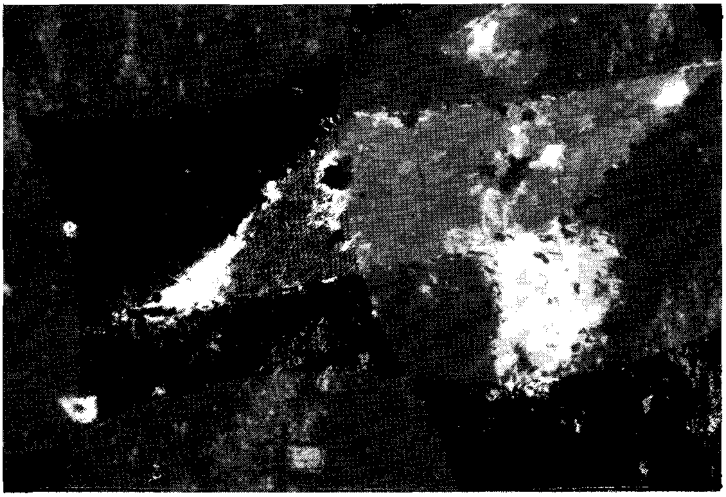


Fig. 8. Glaucophane schist, Naxos (Nax 321 D). Altered glaucophane schist consisting of glaucophane, actinolite, epidote, chlorite and paragonite. The glaucophane crystals are rimmed with opaques and albite and they are partly replaced by fine-grained white mica aggregates. Plane polarized light. 100 x.

Brown amphiboles are only observed in the metamorphosed intrusive bodies in the Basement of Ios and Sikinos. They are common magnesiohornblendes and they clearly are of magmatic origin. The subhedral hornblendes occured together with calcic plagioclase, quartz, orthoclase, reddish-brown biotite and allanite. This pre-Alpine mineralogy was nearly completely obliterated by the M1 phase of the Alpine metamorphism. The calcic plagioclase is altered into aggregates of zoisite and white micas: the orthoclase was converted into microcline; the quartz is totally recrystallized and the biotite is partially transformed into a blue-green hornblende with garnet and rutile.

The brown magnesio-hornblende often has submicroscopic lamellae of cummingtonite. The subsolidus immiscibility of Ca-poor amphibole in a Ca-rich hornblende is commonly observed in magmatic rocks, especially when they have undergone a metamorphic overprint (Robinson and Jaffe, 1969). Relevant chemical analyses are tabulated in the appendix (see number A3 and A4). In figure 9 the analyses of brown hornblendes plot in the center of the magnesio-hornblende field as defined by Leake (1978).

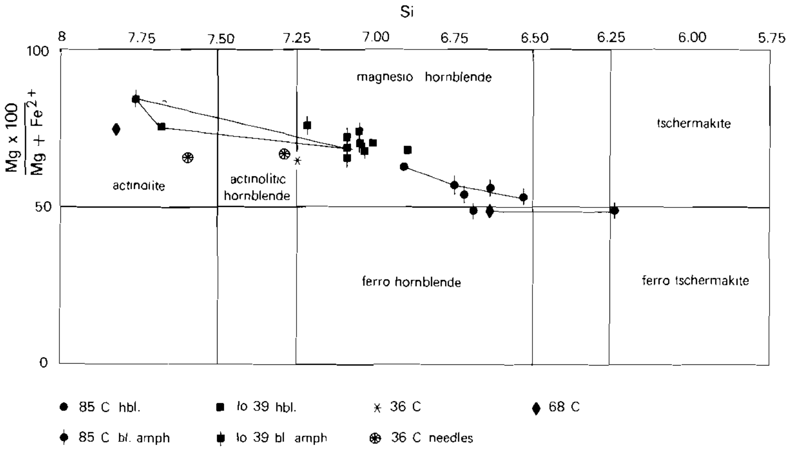


Fig. 9. Composition diagram of the brown and greenblue amphiboles after Leake (1978). Sample 68 C is taken from a metagabbroic lens of the Series. The other samples were all taken from rock types within the Basement.

Alterations of the brown hornblende took place in two steps, probably both initiated by the M1 phase. In the first step the brown hornblende is transformed into green-blue hornblende rich in sphene inclusions, which are parallel orientated (fig. 10). This secondary hornblende is free of lamellae and optically continuous with the original brown hornblende. The phase boundary between the two amphiboles is sharply defined by a string of small garnet and sphene crystals (fig. 10 and 11). In the second step a pale bluish-green actinolite is derived from both amphiboles discussed above. This actinolite is free of inclusions and along its phase boundaries no garnet and sphene crystals are observed (fig. 11). This last alteration is probably a result of the M1 phase, but a M2 origin cannot be excluded. The chemistry of these alteration products are also plotted in figure 9. The green-blue hornblende turns out to be also a magnesio-hornblende but slightly more actinolitic than the

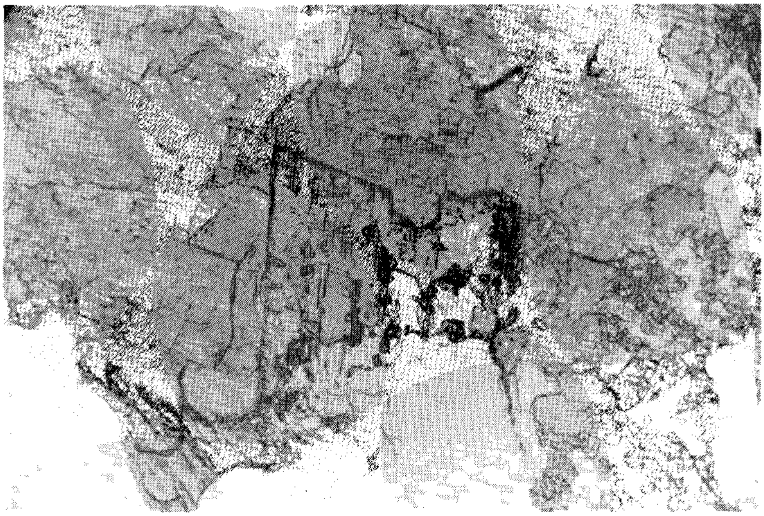


Fig. 10. Metamorphosed intrusive rock, Sikinos (S 132). Well delineated patches of a greenblue hornblende developed at expense of pre M 1 brown hornblende. The secondary amphibole is characterized by orientated sphene inclusions. The amphiboles are optically continuous. Plane polarized light. 50 x.

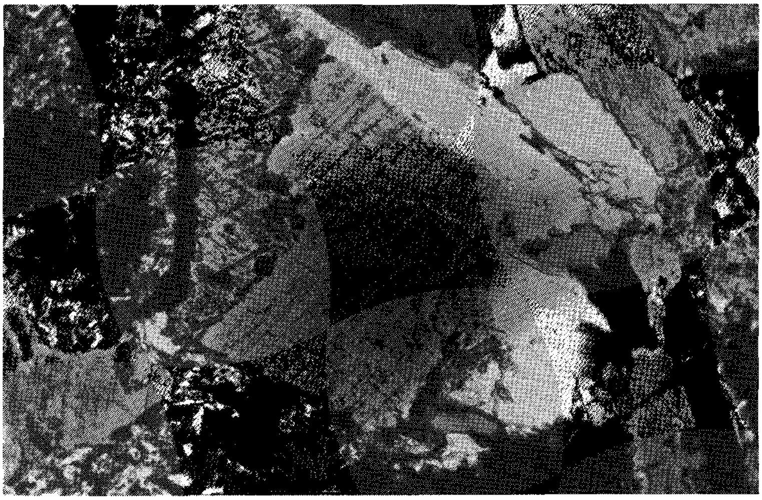


Fig. 11. Metamorphosed intrusive rock, Ios (Io 39). Crystal of magnesio-hornblende showing exsolution lamellae of cummingtonite. The hornblende first transformed into a greenblue, lamellae-free hornblende that is characterized by orientated sphene and ilmenite inclusions. The boundary between the two hornblendes is marked by a string of small sphene and garnet crystals. Both hornblende varieties later became a pale bluish green actinolite, devoid of inclusions and lamellae. Plane polarized light. 50 x.

original phase. The bluish-green actinolite is chemically less homogeneous and it ranges in composition from the actinolite to magnesio-hornblende.

In the <u>green actinolitic amphiboles</u> three Alpine generations can be recognized in the rocks of the islands in the SE Cyclades.

The first generation consists of actinolite that is formed as idiomorphic crystals in the Basements and possibly also in the Series. This generation presumably developed during the early M1-phase, whereas relicts of pre-Alpine actinolitic amphibole could have possibly survived in the Basement. In the garnet-mica schist actinolite is common. The crystals are normally large and idiomorphic. They occasionally contain inclusions of garnet and zoisite (fig. 12). The core of the actinolite of sample I 36 C from the garnet-mica schist might represent this first generation. In the Series the first generation of actinolite locally crystallized in ad-

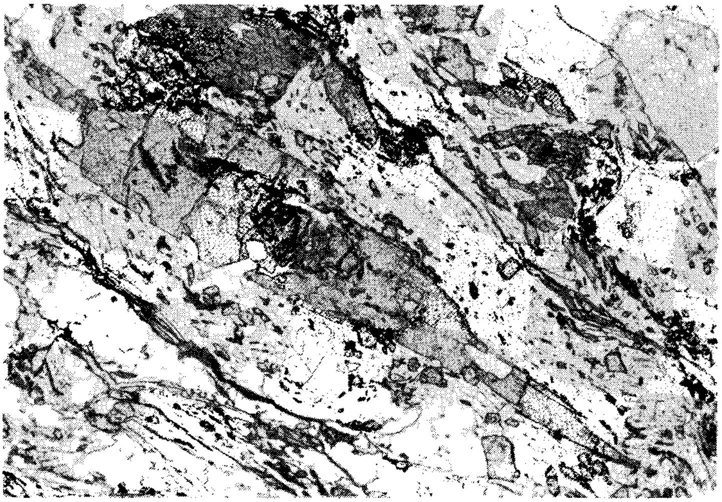


Fig. 12. Roof-pendant of garnet-mica schist, Ios (I 36 C). Blasts of actinolite with garnet and zoisite inclusions in an albite, phengite, epidote, garnet, actinolite matrix. The large actinolite blasts presumably formed during the early stage of the M1 phase. Plane polarized light. 50 x.

dition to the glaucophane. Henjes-Kunst (1980) argued on the basis of elementdistribution, that two glaucophane-actinolite pairs from the Series were in equilibrium during an early stage of the metamorphism. Similar coexisting amphibole pairs are described on Siphnos, where the rocks apparently were less intense retrogressively metamorphosed (Schliestedt, 1979).

The second generation consists of the actinolitic amphibole, that was derived by the breakdown of sodic-amphibole. This alteration generation is observed as relatively broad rims around glaucophane and crossite crystals. The rims are composed of deeply coloured blue-green barroisite or green actinolite. Second generation type actinolites sometimes contain only small blue-violet coloured domains indicating that the alteration process was nearly completed. This phenomenon is restricted to rocks of the Series, and it means that many actinolite-rich rocks apparently were glaucophane-rich in origin.

The chemical compositions of the blue amphiboles and their barroisite and actinolite rims are plotted in figure 13. Some cores are zoned with barroisite and some directly with actinolite. On its turn the barroisite may be rimmed by actinolite. Actinolite crystals of the first generation in the Basement probably also have actinolite rims of the second generation. The Mg/Mg + Fe ratios usually are somewhat lower in the rims than in the cores. The second generation of actinolite is produced during the late stage of the M1 and probably also during the early stage of the M2 phase.

The third generation of actinolite is very pale green, nearly colourless and it is normally associated with chlorite. It occurs as small crystals in replacement textures. The pale green rims around sodic-amphiboles, barroisites and deeply green coloured actinolites of both other generations seem to belong to this generation. The transition between the second and the third generation is difficult to indicate. Up till now the only arguements are the colour intensity, the outer rim position or the tiny crystallinity and the way of occurrence in aggregates with chlorite. This third generation is supposed to have originated during the M2 phase.

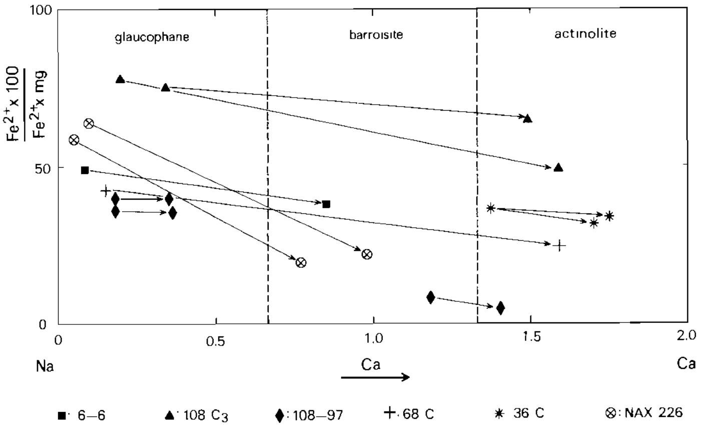


Fig. 13. Diagram of core-rim compositions of zoned sodic-calcic amphiboles. The arrows point to the rim compositions. Sample 6-6 and 36 C were taken from rock types from the Basement.

PYROXENES

The alkali-pyroxenes are rather distinctive minerals for the metamorphism in eclogitic and meta-gabbroic rocks and in metamorphosed iron-rich lenses in the Series. Several generations of pyroxenes can be recognized on microtextural grounds. The composition of the pyroxenes are plotted in the jadeite-acmite-augite diagram after Essene and Fyfe (1967). The composition of the pyroxenes in the eclogitic rocks of Ios ranges from chloromelanite to aegirine-augite (jd = 23 to 5%). The acmite-content never exceeds 40% in these pyroxenes. The meta-gabbroic rocks occuring within the metamorphosed ultramafic bodies contain omphacites with a jadeite-content of about 30%. (Analyses in appendix p. A5)

A compositional zonation is analyzed in some of the aegirine-augites (fig. 14). The rims contain less jadeite. Chloromelanites and aegirine-augites are green pleochroic and generally granoblastic (fig. 15). Jadeite-rich pyroxenes were reported by Henjes-Kunst (1980) and contain up to 75% jadeite (fig. 14). These pyroxenes were described as relicts of an early stage of the M1 phase metamorphism. The jadeite-rich pyroxenes are in assemblage with ferroglaucophane. The omphacites coexist with normal glaucophanes. The chloromelanites and aegerine-augites are in association with crossitic glaucophanes, crossites and riebeckites.

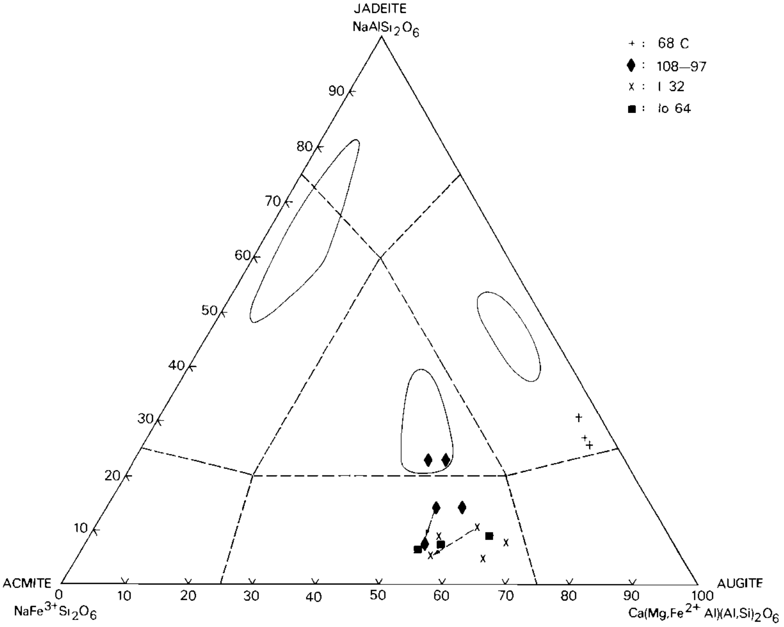


Fig. 14. Diagram of the sodic pyroxenes after Essene and Fyfe (1967). The enclosed areas show the compositional variation of pyroxenes from Ios reported by Henjes-Kunst (1980).

Similar trends in the chemistry of coexisting sodic pyroxene and amphibole are reported by Onuki and Ernst (1969) from the Californian Coastal Range and the Sanbagawa Belt, Japan.
Analyses of the alkali-pyroxenes of Sikinos and Pholegandros are not yet available and it is not known if alkali-pyroxenes occur on Iraklia. Analyses of relictic augites of meta-gabbroic rocks of Naxos are also given in the appendix (p. A5-A6). The augites occur with relictic quartz in a matrix of albite and pargasite. In the Basement of Ios the occurrence of probably pre-Alpine diopside relicts is reported by Henjes-Kunst (1980).

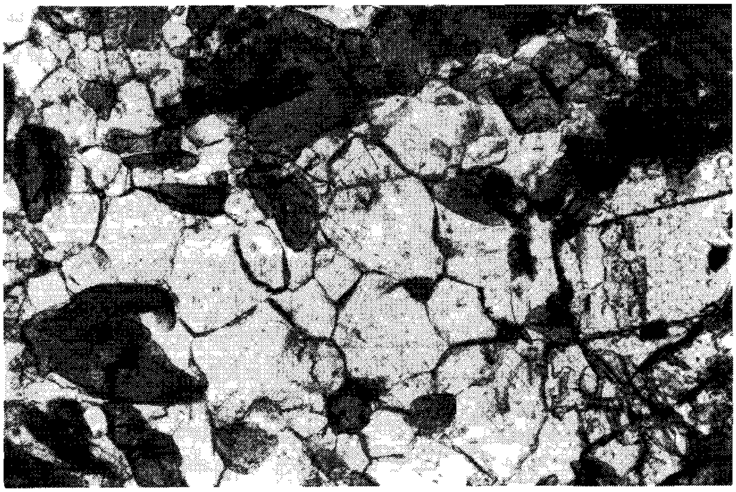


Fig. 15. Eclogitic rock, Ios (I 32). Characteristic granoblastic appearance of aegirine-augite with calcite and garnet. Plane polarized light. 80 x.

Pyroxene alteration is common. The pyroxenes are partially or completely transformed in the late stages of the M1 phase and in the M2 phase. The omphacites alter into a finegrained mixture of albite and actinolitic amphibole. A replacement of omphacite by albite is also described by Henjes-Kunst (1980). The aegirine-augites react to amphiboles of riebeckitic composition and albite. Some pyroxenes of Sikinos are replaced by aggregates of pumpellyite and chlorite. The augite and quartz relicts on Naxos seem to be endproducts of a reaction of the jadeite component with quartz to pargasite plus albite. This reaction took place under high grade greenschist facies conditions during the M2 event.

GARNETS

Except in marbles and metagranitoids the garnets are common in all lithologies on the islands involved. They occur as red to red-brown crystals, usually idioblastic in the rocks of the Series and porphyroblastic in the schists and gneisses of the Basement.
In the metamorphosed intrusive rocks of Ios and Sikinos the garnet typically forms at the expense of primary biotite and hornblende. It forms coronas around the original crystals of the pre-Alpine mi-

nerals (fig. 11). This garnet most probably formed during the M1 phase of the Alpine metamorphism.

Microprobe analyses of the garnet coronas on Ios may characterize the compositional range of the Alpine garnets (Appendix p. A6-A8). The spessartine-content never exceeds the 4 mole % and the pyrope-content is never more than 6 mole %. Some garnets are relatively high in grossular content, up to about 50% and one is rather low with 13% (fig. 16). According to Henjes-Kunst (1980) some cores of garnets in metabasic rocks in the Basement are somewhat higher in spessartine. Their rims show a tendency towards higher grossular-content than the cores, while the average spessartine-content becomes lower. In the garnet-mica schist on Ios the garnet is developed as large porphyroblasts up to 3 cm in diameter, as fine-grained aggregates along the foliation or as small, dusty coronas, especially around older garnet blasts (fig. 17). The first variety is supposed to represent in most cases a pre-Alpine garnet generation, while the other two varieties evidently are of M1 origin. In case of suitable bulk composition of the schist a part of the porphyroblasts are totally recrystallized during the M1 phase as it is indicated by the distribution of typically M1 inclusions all over the garnet blast. The minerals phengite, chloritoid, zoisite and paragonite occur as such inclusions. Henjes-Kunst (1980) described even pseudomorphs of white mica after lawsonite as inclusions in garnet from the Basement.

Microprobe analyses of the presumably pre-Alpine garnet cores show grossular-poor compositions, less than 6 mole %, whereas the abruptly grown, dusty rims and the fine-grained crystals fall in the M1 compositional range and they contain 19 to 42 mole % grossular (fig. 16). The spessartine-content in this Alpine garnet generation does not exceed 5 mole %, whereas it is somewhat higher in the cores. Moreover the cores with a low grossular-content have twice as much pyrope than the high grossular garnet generation. Analyses of garnet in similar rock compositions, reported by Henjes-Kunst (1980), follow these chemical trends. The spessartine-content in the alleged pre-Alpine cores even increases to about 20 mole%. The average

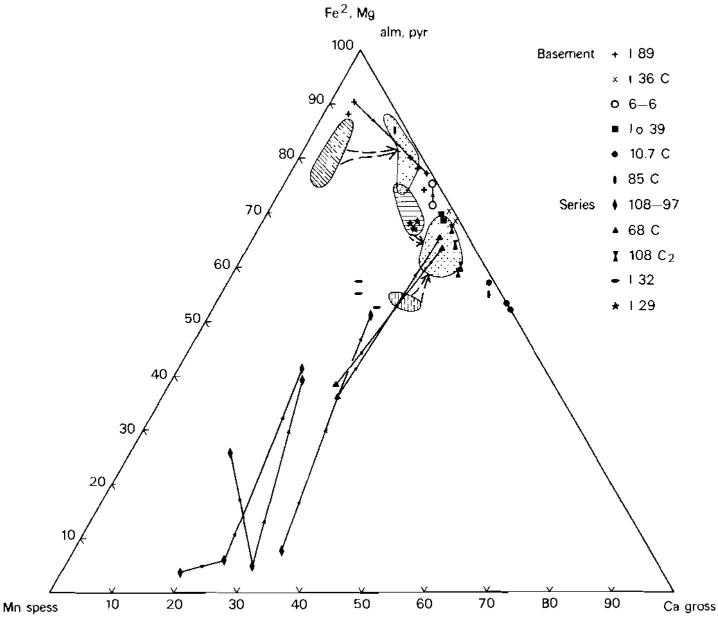


Fig. 16. Compositional diagram of garnets from Ios. Both types of arrows point to rim compositions of zoned garnets. The marked areas indicate the compositional variation of garnets analyzed by Henjes-Kunst (1980). The diagonal hatched area represents the compositions of pre-Alpine garnet cores. The connected stippled area indicates the compositions of the corresponding rims that developed during the M1 phase. The horizontal hatched area represents the compositions of garnet cores in metabasites from the Basement. The vertical broken hatched area marks the compositional variation of garnet cores in several rocktypes from the Series. The stippled area in between indicates the compositions of the rims grown during the M1 phase.

grossular-content of his analyses of the rims is relatively small and it goes down to 9 mole %.

The assumption made on textural grounds that some cores of garnets could be pre-Alpine seems to be supported by these chemical differences between the cores and the rest of the garnets.

In the glaucophane schist hypidiomorphic garnets frequently occur with glaucophane, phengite, paragonite, epidote, quartz, sphene and ore minerals (fig. 18). Some garnet crystals contain small inclusions of glaucophane, phengite, actinolite, zoisite and chlori-

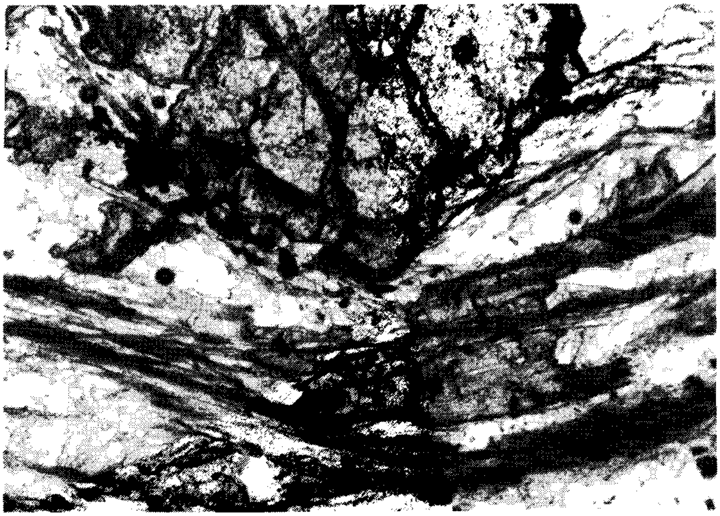


Fig. 17. Chloritoid-bearing garnet-mica schist, Ios (I 89). Pre-Alpine garnet overgrown by a rim of M1 garnet that contains small rutile inclusions, probably as the result of the breakdown of pre-Alpine biotite. Plane polarized light. 100 x.

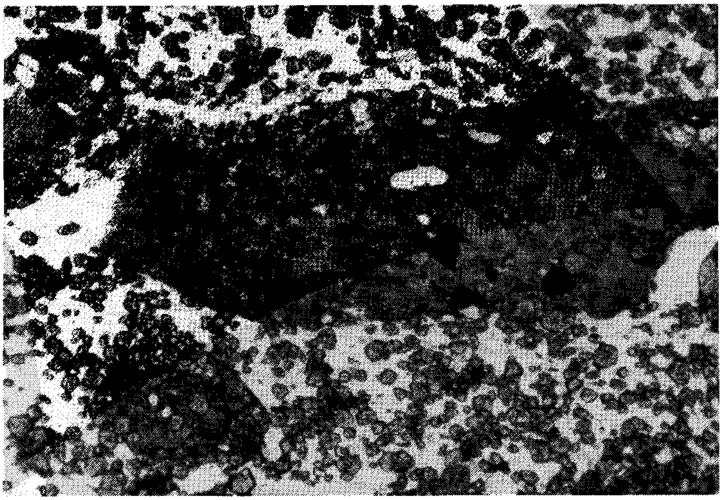


Fig. 18. Glaucophanitic rock, Ios (Io 9). Glaucophane crystals in a quartz-rich groundmass speckled with small early M1 idiomorphic garnet crystals that have dusty cores. The glaucophane was partly chloritized during the M2 phase. Plane polarized light. 80 x.

toid. The latter mineral is totally absent in the matrix of the glaucophane schists. This generation of garnet apparently belongs to the M1 phase metamorphism. A few microprobe analyses show that the garnet has a composition of about Almandine_{60} Pyrope_{7} Grossuslar_{25} Spessartine_{8}.

The garnet of the eclogitic rocks is generally idiomorphic and optically zoned. In that case it exhibites sharply delineated, dusty cores. The garnets are in association with aegirine-augite, epidote, quartz, magnetite and calcite together with crossite or riebeckite. Late recrystallisation causes monomineralic "schlieren" of irregularly shaped garnet without visible zonation.

The chemistry of the garnets of the eclogitic and gabbroic rocks mainly varies in spessartine- and almandine-content. The pyrope-content remains low, less than 4 mole % and the grossular-content ranges from 15 to 35 mole %. The dusty cores of the garnets in the eclogitic rock are exceptionally rich in spessartine-content ranging from 55 to 80 mole %. Their almandine-content does generally not exceed the 10 mole %. The rims around these cores become richer in almandine up to 52 mole %, while the spessartine component decreases down to 23 mole %. The unzoned garnet crystals of the eclogitic rock sample I 32 have a compostition similar to these last rims. The recrystallized garnet of the "schlieren", derived from eclogitc rock has a composition, that approaches the range of the Alpine garnets as described for the Basement. The general trend of the extremely large variation in the garnet composition, within the eclogitic rock, as it is shown in figure 16, is in agreement with the core-rim variation of garnets from the gabbroic rock (I 68 C) that occurs in the metamorphosed ultramafic lenses and of the garnets from the eclogites, which were investigated by Henjes-Kunst (1980). The observed total, chemical variation of the garnet in the Series on Ios, as is discussed above, resembles the chemical behaviour of garnets in a normal prograde metamorphic cycle. Reinsch (1980) observed a similar chemical trend in garnets from blueschists of the Sezia-Lanzo zone. On the basis of elementdistribution an increasing temperature traject during a continued crystallization of zoned garnet-clinopyroxene pairs is calculated by Reinsch. If the comparison with Ios is valid the spessartine-rich garnets represent a generation that was formed at the onset of the M1 phase of Alpine metamorphism or they are remnants of pre-M1 phase low grade metamorphism. The anomalously spessartine-rich garnet cores may also be interpreted as the result of the presence of primary igneous garnets rich in mangenese, which occur originally in volcanics that are non-metamorphic equivalents of the eclogitic rocks.

The third interpretation of this exceptionally strong garnet zonation is based on the petrological observation that the garnet, or at least the rim, seems to be in assemblage with aegirine-augite, riebeckite and Pb-rich epidote. All minerals are more or less zoned so they presumably grew together. Because of the fact that the associated minerals are restricted to the late stage of the M1 phase the development of the zonal garnet is also attributed to this stage.

Alteration of garnet is recognized in all metamorphic rock types on the mentioned islands. The garnets are partially or completely replaced by chlorite aggregates with locally some green biotite and hematite (fig. 19). This chloritization was effected by the M2 phase overprint.

Fig.19. Metapelitic schist . Naxos (Nax 463). Pseudomorphs of M2 chlorite after M1 garnet. Small newly grown biotite is observed along the margins of the pseudomorphs. Plane polarized light. 50x.

WHITE MICAS AND BIOTITES

On the SE Cyclades white micas are ubiquitous. They occur at least as three generations.

Within the Basement of Ios and Sikinos they are observed in the augengneiss, in the garnet-mica schist and in the metamorphosed intrusive rocks. Especially in the latter rock type large relict crystals of muscovite are associated with brown biotite and they are often surrounded by rims of garnet (fig. 20). These relicts are assumed to belong to the magmatic paragenesis of the pre-Alpine intrusive rock. They are low in phengite with a Si-content in the range of 3.05-3.08 . The TiO_2-content is relatively high. from 0.75 to 1.45 wt. % (Tabel 1). This pre-Alpine muscovite generation yielded with Rb-Sr dating method an age of about 295 Ma and coexisting brown biotites gave ages of about 220 Ma (Henjes-Kunst, pers. comm.).

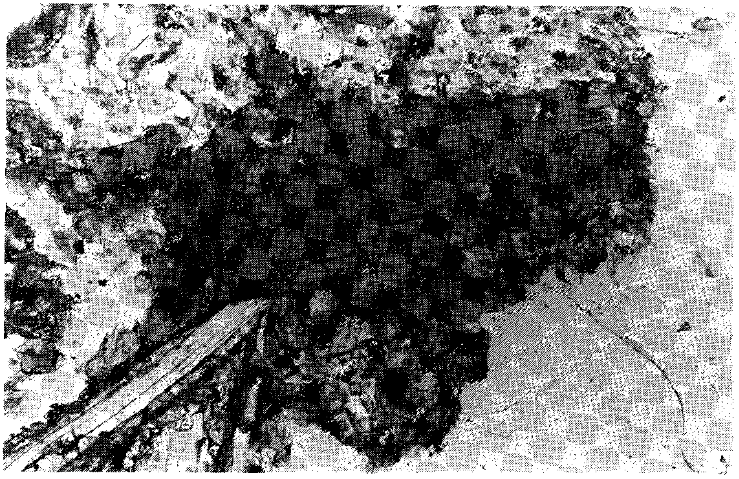


Fig. 20. Metamorphosed intrusive rock, Ios (Io 39). A pre-Alpine magmatic biotite has been nearly completely altered during the M1 phase into a magnesio hornblende surrounded by a rim of garnet. Also primary muscovite is rimmed by garnet. Plane polarized light. 50 x.

	sample no	rocktype	Si^{4+} content	TiO$_2$ wt.%	textural data
Pre-Alpine Basement	Ios 11	metagranite	3.05 - 3.08	0.75 - 1.10	intergrown with red biotite no sagenitic pattern
	Ios 10.7	metadiorite	3.07 - 3.08	∿ 1.45	relicts with garnet rim no sagenitic pattern
M1-phase Basement	Ios 89	garnet-mica schist Ctd - bearing	3.45 - 3.46	∿ 0.20	sagenitic pattern
	Ios 36	garnet-mica schist lens in augengneiss	∿ 3.35	∿ 0.35	intergrown with glaucophane
	Ios 6.6	garnet-mica schist glauc - bearing	3.34 - 3.36	0.15 - 0.45	intergrown with glaucophane
	H.K. 204	metabasic	3.31	0.32	
	H.K. 316	albitegneiss	3.35	0.20	
	H.K. 192/147	micaschist	3.28 - 3.30	0.31 - 0.33	
Series	Ios 68	metagabbro	∿ 3.49	0.10 - 0.15	intergrown with glaucophane
	Ios 29	glauc schist	3.39 - 3.44	-	intergrown with glaucophane
	H.K. a few samples	glauc-bearing rocks	3.31 - 3.45	0.09 - 0.16	
	SE Naxos a few samples 1)	glauc-bearing rocks	3.36 - 3.45	∿ 0.20	intergrown with glaucophane
M2-phase Basement	Ios 89	garnet-mica schist Ctd - bearing	3.22 - 3.28	∿ 0.20	intergrown with chlorite no sagenitic pattern
	H.K. 154	pelitic schist xenolith	3.21	0.28	see text
Series	SE Naxos a few samples 1+2)	glauc-bearing greenschists	3.02 - 3.20	0.1 - 0.43	related to chlorite and green biotite
	Center Naxos a few samples 2)	sillimanite schist	3.05 - 3.18	0.94 - 2.38	amphibolite facies conditions
Questionable Basement	H.K. 147/154	mica schist pelitic schist	3.13 - 3.14	0.70 - 0.76	see text

1) Andriessen (1978); 2) Wijbrans (pers. comm.)

Table I. Si^{4+} content and TiO$_2$ wt.% of muscovites, phengites and phengitic muscovites from Ios and Naxos.

The white mica in the metamorphosed intrusive rocks that is intergrown with garnet, magnesio hornblende and various titanium-rich minerals is evidently a M1-phase mineral. It occurs as finegrained crystals in the matrix and along the biotite relicts (fig. 21). This type of white mica was not analyzed. Only the large crystals of the same generation in the garnet-mica schist are investigated and they are phengites with Si-contents in the range from 3.34 to 3.46, while their TiO_2-content is low and varies from 0.15 to 0.45 wt. %. Henjes-Kunst (1980) reported phengites from the Basement with Si-contents varying from 3.28 to 3.35. This range is only a little bit lower and it may be caused by later recrystallization. Henjes-Kunst also mentioned some analyses of postkinematic white micas with Si-contents of about 3.13 to 3.14. These latter data could be explained in two ways. While they occur together with relictic red-brown biotite, these micas may represent partly recrystallized pre-Alpine muscovites. The relatively high TiO_2-

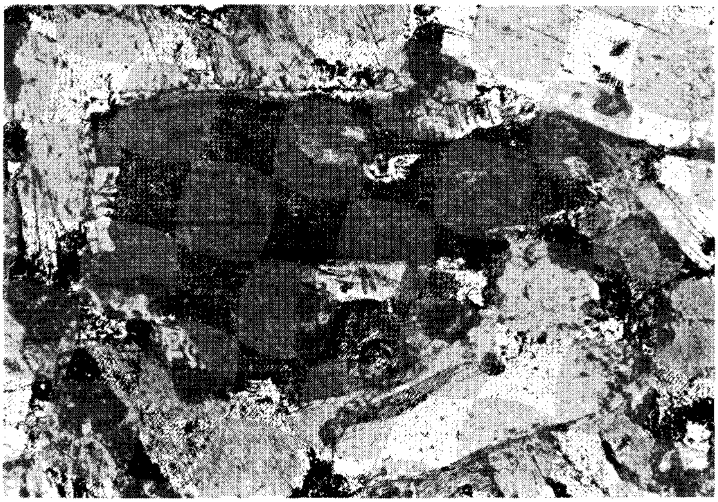


Fig. 21. Metamorphosed intrusive rock, Ios (I 10.7 B). Pre-Alpine biotite with a rim of phengite and ilmenite that formed during the M1 phase. Locally idiomorphic garnet crystals developed along the biotite. Plane polarized light. 50 x.

content of about 0.75 wt. % is in support of this interpretation. Postkinematic texture of these micas however and the presence of chlorite, oxychlorite and secondary biotite, next to the relictic biotite in these samples, as described by Henjes-Kunst (1980), could mean that the micas are partly produced as effect of the M2 phase greenschist facies metamorphism.

The phengites in the rocks of the Series crystallized without any doubt during the M1 phase. They are found as inclusions in glaucophanes, omphacites, garnets and zoisites as well as in crossites, barroisites, epidotes and actinolites. The chemistry of phengites from the Series of Ios and SE Naxos is rather uniform. They all have a Si-content in the range of 3.36-3.49 and their TiO_2-contents are low. Analyses of phengites, reported by Henjes-Kunst (1980), show a similar chemistry (see tabel I).
In total the range of Si-contents of the phengites of Ios and Naxos, that apparently grew during the M1 phase of metamorphism, varies from 3.28 to 3.49 while their TiO_2-content never exceeds the 0.45 wt. %. The phengite generation of the M1 phase in the Series on Ios is dated with the K-Ar method. Andriessen (1978) reported ages of about 43 Ma and Henjes-Kunst (1980) gave dates of 33 to 39 Ma for phengites as well as for coexisting paragonites. The white mica of the Series from SE Naxos gave K-Ar ages in the range from 40 to 48 Ma. These ages are supported by a corresponding Rb-Sr age of 42.3 Ma for mica-wholerock systems (Andriessen et al, 1979).

The third generation of the white micas is observed in the Basement of Sikinos and Ios and in the Series of Ios and Naxos. It developed as finegrained crystals together with albite, chlorite, oxychlorite, pale green actinolite and green-brown biotite. On Naxos the crystals are evidently postkinematically grown after a deformation phase (D 3), that is locally characterized by open folds (Wijbrans, pers. comm.). This is in agreement with the observations by Henjes-Kunst (1980), who proposed that a white mica generation (M 3) of Ios is synkinematic with a deformation phase (D 3). Presumably these deformation phases are identical.

Chemical analyses of this generation of white mica from the SE Cyclades are scarce. Some micas in sample I 89 from the Basement of Ios occur together with chlorite and they show no sagenetic pattern, like adjacent phengites of M1 phase age do. These micas are relatively poor in TiO_2 and their Si-contents are intermediate, ranging from 3.22 to 3.28. A comparable phengitic muscovite is also mentioned by Henjes-Kunst (1980). His sample contains relictic pre-Alpine minerals as well as apparently M2 minerals, so the anlysis can hardly be connected with a metamorphic phase. The low TiO_2-content suggests a M2 origin.

Phengitic muscovites are also known from Naxos. In the SE-part of the island these micas have Si-contents ranging from 3.02 to 3.20 with low TiO_2-contents. In this area the M2 phase was a low-grade greenschist facies type of metamorphism.

In the central part of Naxos where the metamorphic grade of the M2 phase reached amphibolite facies conditions, the micas near the +sillimanite isograd show Si-contents from 3.05 to 3.18, while the TiO_2-contents are high, varying from 0.94 to 2.38. These values correspond with the values of the pre-Alpine muscovite from the Basement of Ios. This suggests that the metamorphic conditions of that pre-Alpine Basement were of the amphibolite facies. This assumption was already expressed by Henjes-Kunst (1980) on the basis of the occurrences of minerals like hornblende, garnet, pseudomorphs after sillimanite and alleged pseudomorphs of staurolite.

The M2 phengites and muscovites in rocks from Ios that developed as sericite are poorly dated. Only one K-Ar model age of 25.7 Ma is given by Kreuzer et al (1978). This age is in full agreement with the conclusion that on Naxos the M2 phase reached its culmination 25 ± 5 Ma ago (Andriessen et al, 1979).

Paragonites have been identified on all islands, mainly in the glaucophane-bearing schists. It occurs either as separated crystals or as interlayered flakes with phengite and phengitic muscovite. The muscovite-content in the paragonite is relatively low and never exceeds the 10 mole %. The paragonite has developed during the whole period of Alpine metamorphism and it is not indicative for a specific stage.

The paragonite-content in the phengites and muscovites of the rocks on Ios generally ranges between 4 and 12 mole %; even when the paragonite-component is chemically buffered by free paragonite crystals. Due to late Na-K exchange the geothermometry with the paragonite-muscovite solid solution gives too low metamorphic temperature conditions (Chatterjee and Froese, 1975).

For SE Naxos the muscovite-contents expressed as the X_K-values of the white micas after the method by Guidotti and Sassi (1976) give metamorphic temperatures for the M2-phase in the range of 450 to $550^{\circ}C$ and a total pressure of about 5 Kb (Wijbrans, pers. comm.).

Margarite is a regular constituent in the meta-bauxites, where it occurs as intermixed layers with muscovites and paragonites and as massive deposits that resulted of late hydrothermal-metasomatic activity. The occurrence of margarite seems to be restricted to the M2-phase. Its major scource of development was the breakdown of kyanite.

Pre-Alpine biotite that probably occurred in many rock types of the Basement was not stable during the high pressure-low temperature conditions of the M1 phase. The reddish brown biotite only occurs as relicts in the metamorphosed intrusive bodies in the Basement. The biotite is partly replaced by phengite, ilmenite and garnet, or by magnesio hornblende, garnet, rutile and sphene. (fig. 20 and 21). Sagenitic patterns in the phengite and the hornblende are often the only indications of the complete replacement of pre M1 biotite (fig. 20 and 22). The chemical analyses show that the biotites are Ti-bearing up to 2.65 wt % TiO_2 and that their Mg/Mg + Fe ratio is about .38.

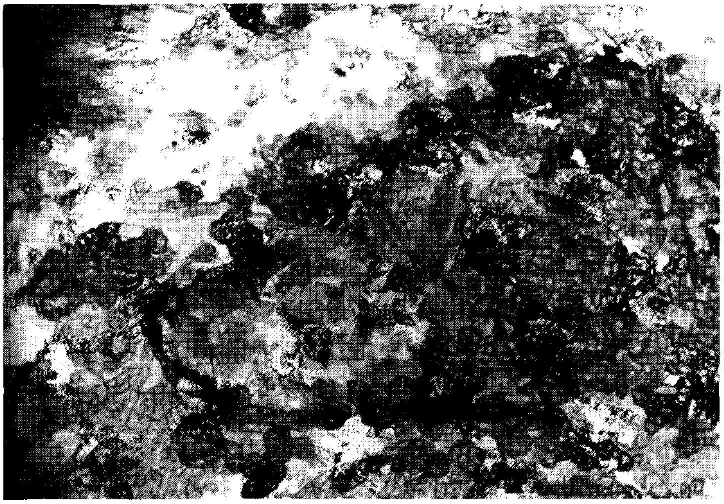


Fig. 22. Metamorphosed intrusive rock, Ios (Io 39). Pre-Alpine biotite is completely replaced by a mixture of phengite, garnet and feldspar. The crystal shape of the original biotite is marked by a garnet rim. Sagenitic pattern is preserved in the phengite. Plane polarized light. 50 x.

Green brown biotite is often observed in the rock from Ios, Sikinos, Naxos and Pholegandros. It evidently is a late formed M2 mineral as it occurs around pale green actinolites and around M2 chlorites (fig. 7 and 19). The chemistry of M2 biotites on Ios is only known for one sample which shows a TiO_2 content of 1.15 % wt. % and a Mg/Mg + Fe ratio of about .58.

On Naxos M2 biotites from rocks of pelitic composition from the high grade part of the greenschist facies contain 1.3-1.6 wt. % TiO_2 and show Mg/Mg + Fe ratios of .48 to .51. Although the variation in these data is mainly influenced by the bulk chemistry of the rock rather that by temperature and pressure, it incidentically may refer to a prograde metamorphic trend with increasing wt. % TiO_2 and decreasing Mg/Fe ratios.

Fig. 23. Augengneiss, Ios (I 99). Potassic feldspars (microcline) and crystals of primary muscovite are surrounded by albite, secondary phengite and quartz. The albite is randomly speckled with zoisite and mica inclusions, suggesting its origin from primary Ca-rich plagioclase. Plane polarized light. 50 x.

Fig. 24. Metamorphosed intrusive rock, Ios (Io 10.7 A). Pseudomorph of zoisite and white mica after pre-Alpine magmatic plagioclase. The core of the plagioclase was An-richer than the rim, as can be concluded from the distribution of the zoisite in the pseudomorph. Plane polarized light. 50 x.

FELDSPARS

Potassic feldspar occurs in large amounts in the rocktypes of the Basement. Microcline forms the characteristic "augen" in the augengneiss complex and it is furthermore found in some of the metamorphosed intrusive bodies.
It also occurs in parts of the garnet-mica schist, including the roof-pendants. The microcline is marked by cross-hatching and occasionally contains patches of albite and besides that it has a moderately zoned extinction pattern (fig. 23). For these reasons the microcline is believed to be a product from orthoclase.
The albite in the Basement contains numerous inclusions of zoisite and mica, that tend to be concentrated in the cores of the crystals. Also groups of adjacent albites are linked together by a circular pattern of inclusions. Both features result from replacement of a pre Alpine Ca-rich plagioclase. The albite itself is rarely twinned and never contains more than 5% An.
In the metamorphosed intrusive rocks pseudomorphs after euhedral plagioclase are observed that are completely transformed into a finegrained mixture of zoisite, mica and albite (fig. 24).
Henjes-Kunst (1980) reported the existence of plagioclase with up to 54% An in some less affected metagranites in the garnet-mica schist. The feldspar that is found in the Series is always nearly pure albite. It is in contrast with the albite in the Basement more free of inclusions but also rarely twinned and the An-content never exceeds 5%. Part of the albite in the Series is of M2 age because it was produced together with chlorite and pale green actinolite during the breakdown of sodic amphiboles and pyroxenes.

In the metabasite on the western peninsula of the island idiomorphic plagioclase crystals are found that are not completely transformed into zoisite, mica and albite. However the still remaining feldspar that shows a closely spaced twinning pattern is nearly pure albite in composition. The pseudomorphs are surrounded by a rim of chlorite.

EPIDOTES, LAWSONITES and PUMPELLYITES

Pre-Alpine allanite is observed in metadiorites and metalamprophyres of the Basement from Ios and Sikinos. These allanite crystals are not of metamorphic origin. They occur with brown hornblende, plagioclase pseudomorphs and red-brown biotite. Some allanite is also found in potassium-feldspar-rich parts of the garnet-mica schist. These parts seem to represent completely reworked pre-Alpine intrusive rocks. Allanite is a notably resistent mineral in metamorphic processes and it is only occasionally rimmed by epidote (fig. 25). Similar magmatic allanites rimmed with clinozoisite are described by Compagnoni (1977) in the eclogitic micaschist complex of the Sesia-Lanzo zone. A few microprobe analyses of allanites from Ios show that especially the CaO-content is about 4 wt% too low with respect to epidotes. Qualitative analyses reveal the presence of Ce, La, Nd, Th, U, and presumably of Sm, Eu and Gd. The microprobe analysis of the allanites and their epidote rims are given in the Appendix (p. A11)

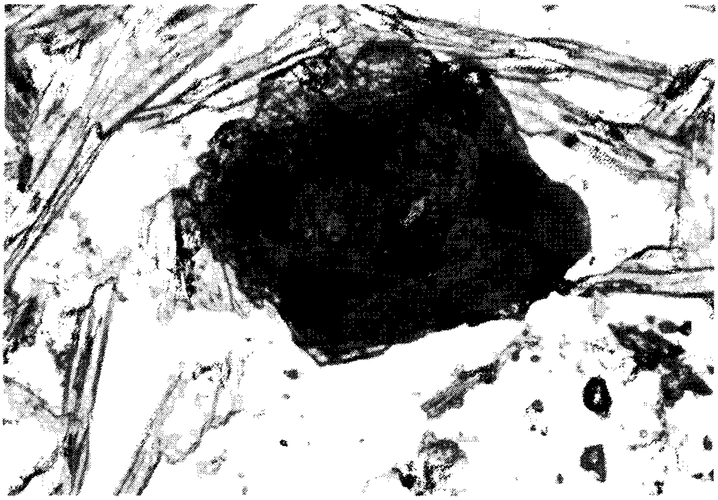


Fig. 25. Actinolite-bearing garnet-mica schist roof-pendant, Ios (I 79). Pre-Alpine allanite is overgrown with a rim of Alpine epidote (M1, M2). The specimen also contains some crystals of dark brown biotite. Plane polarized light. 100 x.

In the rocks of the Basement and the Series epidote is the most common mineral of the epidote-group. Zoisite occasionally occurs in the metamorphosed intrusive rocks and it coexists with phengite and albite in pseudomorphs after Ca-rich plagioclase. Clinozoisite is found together with chloritoid and kyanite in the metabauxites on Ios, Sikinos, Iraklia and SE Naxos. Analyses of epidote minerals from the islands involved are scarce. Some analyses of clinozoisite, zoisite and epidote are reported by Henjes-Kunst (1980). The mutual relationships are not yet fully understood, because of the complicate patterns of prograde and retrograde zonations, as for example illustrated by Enami and Banno (1980) for the metamorphic belt in Japan. Two pale green epidotes from eclogitic rocks, where they occur with aegirine-augite, riebeckite and spessartine-rich garnet, are marked by an exceptionally high lead-content up to about 35 wt% PbO. The lead preferentially replaces the Ca and the Al in the epidote-structure. Epidotes with a comparable amount of lead are known under the mineral name Hancockite. The Mn-epidote, piemontite is frequently observed on Sikinos. It is also known from SE Naxos (Jansen, 1977).

The mineral lawsonite itself is extremely scarce. Only one occurrence of lawsonite was reported in the Series by Henjes-Kunst (1980). It is a small armoured idiomorphous relict with the typical rectangular shape within a garnet crystal. Pseudomorphs after lawsonites are more common and are found in various rock types of the Basement on Ios and of the Series on Pholegandros and Ios. In the metagabbroic rock on Ios the pseudomorphs consist of aggregates of zoisite, phengite, paragonite, calcite and some chlorite (fig. 26). Pseudomorphs consisting of aggregates of white mica, allegedly after lawsonite, are described as inclusions in M1 phase garnets from the Basement of Ios (Henjes-Kunst, 1980). This type of pseudomorph is also observed in the garnets of the metagabbroic rock of the Series on Ios. Locally on Pholegandros lawsonite is completely replaced by finegrained aggregates of pale green coloured pumpellyite (fig. 27).

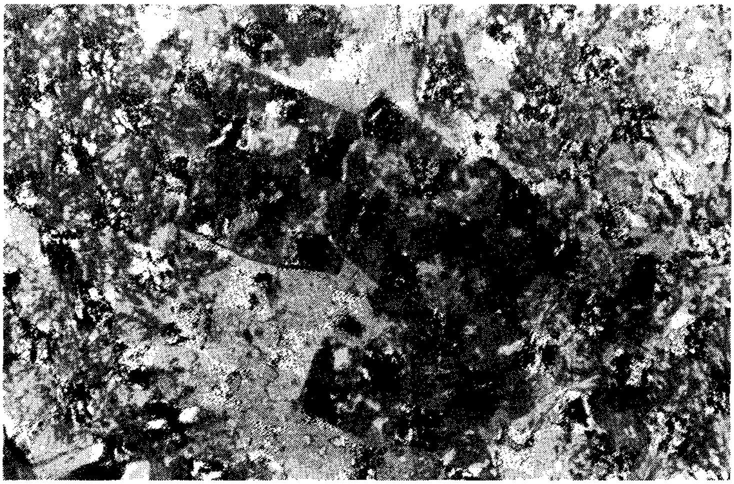


Fig. 26. Meta-gabbroic rock, Ios (I 68). Pseudomorphs after lawsonite in a rock mainly consisting of epidote, garnet, phengite and calcite. The pseudomorphs consist of zoisite, white mica, calcite and some chlorite. Crossed nicols. 100 x.

Fig. 27. Metabasic rock, Pholegandros (F 13). Pseudomorphs after lawsonite consisting of pumpellyite. The matrix is composed of chlorite, epidote, actinolite, albite and quartz. Plane polarized light. 50 x.

Apart from its occurrence in these pseudomorphs pumpellyite is found as idiomorphic crystals in a quartz-epidote vein, cross-cutting metabasic rocks on Pholegandros (fig. 28). It was also reported from Sikinos (Van der Maar et al, in prep.), where it occurs associated with chlorite and epidote as an alteration product of omphacitic clinopyroxene. Because of these replacement textures the pumpellyite is produced relatively late during the Alpine metamorphism.

Fig. 28. Epidote lens, Pholegandros (F 21 B). Pumpellyite crystals developed in a quartz-rich part of an epidote-pumpellyite-sphene matrix. Plane polarized light. 100 x.

KYANITES and CHLORITOIDS

Of the Al-silicates only kyanite is observed. It normally occurs in the metabauxites of SE Naxos, Iraklia, Ios and Sikinos. On Sikinos, Iraklia and Ios the kyanite is in assemblage with diaspore, chloritoid, clinozoisite and calcite. It is locally replaced by margarite. The diasporites of SE Naxos occasionally contain the assemblage kyanite, diaspore and pyrophyllite. Kyanite could not be demonstrated in eclogitic rocks of the Southeastern Cyclades. In a xenolith of pelitic composition in the augengneiss of the Basement of Ios, kyanite is identified in pseudomorphs after sillimanite (Henjes-Kunst, 1980).

The occurrences of chloritoid on the SE Cyclades are scarce and scattered. Medium size crystals of about 2 mm in diameter are observed in the lower part of the garnet-mica schist of the Basement of Ios. In the same rock it occurs as small inclusions in garnet porphyroblasts, which were particularly formed during the M1 phase. In the Series on Sikinos, Ios, Iraklia and SE Naxos chloritoid is a regular constituent of the metabauxites. In glaucophane schists on Pholegandros, Ios and SE Naxos it occurs as small inclusion in the M1 phase minerals garnet, glaucophane and zoisite. This mode of occurrence defines chloritoid as a relatively early M1 mineral.

The compositions of a few chloritoids are given in the appendix (p. A11) and they show that the mineral is Mn-poor. The Mg/Fe^{2+} ratio of about 0.20 of chloritoid of the metabauxites from Ios falls in the range of most of the natural chloritoids from 0.05 to 0.24 as given by Hoschek (1967).

The Mg/Fe^{2+} ratios of the chloritoids of the garnet-mica schists are relatively high. The range varies from 0.25 to 0.35. These ratios are comparable with the ratios of chloritoids from Ile de Groix and from the environments of Zermatt where they are respectively 0.27 and 0.30 (Velde, 1967; Bearth, 1963). They are held to be typically for glaucophane schist facies areas. The Mg/Fe^{2+} ratios of chloritoids of rocks from the Basement of Ios as described by Henjes-Kunst (1980), vary from 0.20 to 0.28. Only the highest part of this range is comparable with those of typical high pressure metamorphism.

CHLORITES and STILPNOMELANE

Chlorite was apparently generated in two metamorphic episodes. It exists as large crystals in glaucophane-bearing rocks and as secondary, finegrained aggregates and stacks. The large crystals are up to 4 mm in diameter and can be attributed to the M1 phase.
The secondary generation probably developed during a late stage of the M1 or during the M2 phase of metamorphism. However, the

primary chlorites are never observed as inclusions in the typical M1 phase minerals like garnet, glaucophane and zoisite. One analyses of a green primary chlorite, from a glaucophane-bearing part of the garnet-mica schist in the Basement gives a $Fe^{2+}/Fe^{2+} + Mg$ ratio of 0.42, whereas pale brown coloured chlorite from chloritoid-bearing garnet-mica schist, yielded ratios of about 0.50. This chlorite was certainly generated during the M2 phase, because of the coexistence with pale green actinolite and green brown biotite. Henjes-Kunst (1980) mentioned ratios of about 0.50 for chlorite associated with oxychlorite and secondary biotite in rock from the Basement. Probably these chlorites can be interpreted as secondary minerals attributed to the M2 phase. He gave also an analysis of chlorite of the Series with a ratio of 0.49. This chlorite is tentatively supposed to be secondary. The rest of his analyses of chlorites fall in a range of 0.36 to 0.45. Presumably these chlorites are real M1 phase minerals.

Only at one locality the mineral stilpnomelane was recognized. It occurs in a garnet-epidote-rich part of an eclogitic rock on Ios. The stilpnomelane seems to be associated with riebeckite, epidote and albite. Some analyses of this stilpnomelane occurrence was given by Van der Maar (in press).

CARBONATES

Additionally it may be mentioned that the carbonate in generally is calcite, while also dolomite, magnesite and ankerite are observed. In some dense parts of the eclogitic-, glaucophanitic- and metabauxitic lenses the carbonate has a columnar habit. It is optically bi-axial but its X-ray pattern shows it to be calcite. This type of occurrence of calcite is interpreted as pseudomorphic after aragonite.

Evolution model of the regional metamorphism in the southern Cyclades

The Alpine metamorphic evolution of the rocks in the Southern Cyclades is summarized in Table II. It is a rather complex polyphase picture, that is inferred from field observations, microscopical studies of about 1000 thin sections and chemical mineral analyses. The evolution is marked by the two main events of Alpine metamorphism, which are labeled M1- and M2- phase. Three stages have been recognized in the M1 phase and two in the M2 phase. The pre-Alpine assemblages, which are distinguished from the Alpine parageneses, are not considered within this evolution.

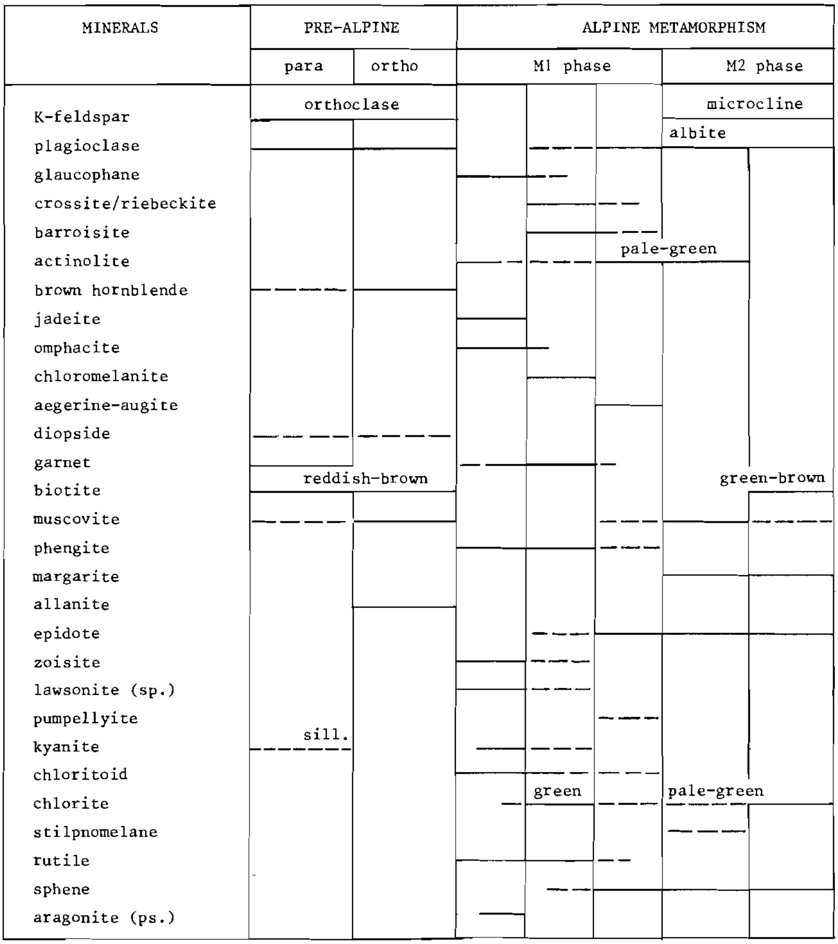
In the first stage of the M1 phase the highest pressure conditions existed. Relicts are expecially preserved in eclogitic rocks. The minerals jadeite, lawsonite, kyanite and aragonite can be attributed to this stage and the following mineral assemblages originated during this stage: omphacite-garnet-glaucophane-zoisite; garnet-phengite-rutile; garnet-glaucophane-chloritoid and garnet-phengite-zoisite-actinolite.

The second stage is characterized by the development of crossite, barroisite, chloromelanite, albite, epidote and chlorite in eclogitic and metabasic rocks. Glaucophane gradually gives way to crossite and barroisite. Lawsonite is replaced by zoisite-phengite aggregates.

In the third stage of the M1 phase the crossite is replaced by the riebeckite, while the riebeckite itself together with barroisite gradually alters to actinolite and albite. The clino-pyroxene is developed as aegirine-augite. The white mica becomes less phengitic. The titanium-rich mineral sphene is more common than rutile. The pumpellyite presumably belongs to this stage.

In resuming it may be supposed that the M1 phase of Alpine metamorphism evolved from an initial eclogite facies through a blueschist facies to a glaucophanitic greenschist facies metamorphism. This trend is indicated by a subsequent recrystallization and progressive growth of the following amphiboles: ferroglaucophane --

Table II. Tentative diagram of the mineral evolution of the SE Cyclades.



glaucophane -- crossite -- riebeckite or barroisite -- actinolite. The actinolites, which were formed during the early stage of the M1 phase (see fig. 29), is mainly formed in the Basement of Ios and Sikinos, whereas in the Series on all islands glaucophane is the most common amphibole in the same stage. Most probably the reason for the occurrence of actinolite instead of glaucophane must be sought in the difference in chemical composition of the

bulk rock of the Basement with that of the Series.
Parallel to this amphibole trend the development of the clinopyroxenes is as follows: jadeite + omphacite -- omphacite + chloromelanite -- chloromelanite -- aegirine-augite -- augite.

The M2 phase of the Alpine metamorphism is a greenschist facies overprint with two separate stages. The first stage started with the development of microcline, phengite-poor muscovite, stilpnomelane and margarite. The typical M1 phase minerals barroisite, aegirine-augite,chloritoid, phengite and pumpellyite were no longer produced. It is mainly this absence that marks the transition between the two Alpine phases.
The second stage of the M2 phase is characterized by the growth of green-brown biotite together with pale-green chlorite, epidote, albite, paragonite and muscovite, whereas actinolite and stilpnomelane do not seem to grow in this stage.
As can be observed on Naxos the M2 overprint is directly related in space and time to the Paro-Naxotic amphibolite facies metamrophism which erased the preceeding M1 phase and formed high grade migmatite domes in the center of both islands (see fig. 1). On Naxos the grade of the amphibolite facies metamorphism is decreasing towards the South-East and where it becomes about 450°C in temperature at about 5 Kb total pressure, the glaucophane-out isograd can be recognized (Jansen et al., 1977). The metamorphic conditions on the other islands involved were below this isograd as is indicated by the regular occurrence of glaucophane.

Discussion and conclusions

The islands of Pholegandros, Sikinos, Ios and Iraklia and the SE part of Naxos belong to the Attic-Cycladic Massif which forms the southernmost crystalline, mainly metamorphic part, of the internal Pelagonian zone. The petrological study of the rocks from the islands yield a consistent picture of the Alpine metamorphic history of the area. An eclogite- to blueschist-facies metamorphic phase M 1 is overprinted by the metamorphic Paro-Naxotic phase

M 2, which in the area discussed generally reached greenschist facies conditions. Both phases affected the rocks of the Series and of the Basement. This implies that the emplacement of the Series upon the pre-Alpine Basement predates the M 1 phase. The HP-LT M1 phase took place in continental crust and overprinted pre-Alpine metamorphics and granitoids. The M1 phase of metamorphism is supposed to have occurred at about 30 to 40 km deep in the crust and consequently a rockpile of the same thickness must have been eroded since the Eocene M1 phase (45 Ma). During Miocene and Pliocene Crete knew a period of subsidence and great amounts of sediments apparently derived from a north situated landmass were deposited. In the Pleistocene the vertical movement changed its direction and Crete started to rise again. In the same time the Cyclades started a period of subsidence that still continues.

These facts are supported by geophysical data of which a compilation is given by Makris (1977). The central Aegean area is not seismically active and therefore it is assumed to be a continental miniplate involved in a collison with crustal blocks. In the Southern part of the Aegean mini-plate the positive gravity anomalies (Bouguer anomalies) reach high values up to +110 mgal and the heat flow data are also extremely high, ranging from 85 mW/m^2 in SE Naxos to 93 mW/m^2 on Ios. The Moho discontinuity is estimated at about 26-30 km depth on the basis of refractional and gravimetric data. The 550^{o}C-isotherm is computed to be 20 km below the Aegean islands. It is proposed that a very sharp uplift of isotherms and of rock material took place, so that these islands probably represent deeply buried, metamorphosed crust, which is equivalent with deep parts under the Pelagonian zone. The tectonic position of the islands is also comparable with the internal position of the Pelagonian zone within the Alpine orogeny of the Hellenides.

Compagnoni (1977) and Compagnoni et al. (1977) described the metamorphic evolution of the Sezia-Lanzo zone the Western Alps. There are some striking similarities between this area and the southern Cyclades. Both areas were subjected to a blueschist facies metamorphism and afterwards to a greenschist facies type of metamorphism. The pressure indications for the HP-LT metamorphism in the Cyclades were about 10 to 15 Kb, being lower than for the equivalent metamorphism in the Sesia-Lanzo zone, where they were inferred to be between the 15 and 17 Kb. Parallel to this the temperature estimate were about 50-100°C lower for the Cyclades.

A similarity between the two zones is the presence of pre-Alpine continental basement in the Sesia-Lanzo zone, that is like in the Cyclades affected by an Alpine HP-LT metamorphism. Pre-Alpine rocks are widespread in the Sesia-Lanzo zone and they are contineously exposed whereas the Cyclades the pre-Alpine basement crops out only in a few windows.

The preliminary ages of the pre-Alpine basement of the island of Ios yielded about 300 Ma (Henjes-Kunst, pers. comm.). This age is much older than the one obtained for the pre-Alpine rocks in the Sesia-Lanzo zone and corresponding units. The latter ages are dated to be 240-140 Ma. However the Alpine metamorphic phases in the Cyclades are much younger than those in the Sesia-Lanzo zone. The HP-LT metamorphic phase is dated as early Alpine in the Sesia-Lanzo zone with ages in the range of 60-90 Ma and the Lepontine phase is 38 Ma old, while the HP-LT metamorphic M1 phase in the Cyclades is about 40 to 45 Ma and the Paro-Naxotic (M2) overprint was induced about 25 ma ago.

The tectonic positions of the two areas in their respective orogenies are also comparable. Both areas are deep crustal zones and are positioned in the internal zones of the respective orogenies. In the Aegean area the Alpine orogeny is concave towards the north; in the western and Swiss Alps it is concave towards the ESE.

So the southern Cycladic area belongs to an extremely young tectono-metamorphic complex that is relevant for the understanding of the geodynamic evolution of the worldwide Alpine orogenic belt.

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APPENDIX (A 1 - A 11)

MICROPROBE ANALYSES OF SELECTED MINERALS FROM IOS AND NAXOS

The headings of the tables contain:

- sample number
- geographical co-ordinates
- rocktype
- internal analysis code
- (if present) indication of: core-rim pairs, type of amphibole (hbl.: brown hornblende; blue: greenblue- and bluish green-amphibole; lam.: lamellae), crystal shape

The analyses of the minerals of samples 6-6, 10.7 C, 11, 36 C, Io 39, 68 C, 85 C, 89 and 108-97 were performed at the electron microprobe laboratory of the Institute voor Aardwetenschappen, Vrije Universiteit Amsterdam, with financial and personnel support by Z.W.O. - W.A.C.O.M. (Research group for analytical chemistry of minerals and rocks subsidized by the Netherlands Organization of Pure Research).
Analyst: W.J. Lustenhouwer.
The analyses of minerals of samples I 29, I 32, Io 64, I 108 C and samples from Naxos were made with an electron microprobe, constructed by the Technische Physische Dienst, T.N.O. (TH - Delft) and financed by the Netherlands Organization of Pure Research.
Analyst: R.P.E. Poorter.
The analyses of sample I 76 were kindly placed at our disposal by A. Feenstra.

BLUE and GREEN AMPHIBOLES

Sample no.	I108C3							I 32	NAX 227			NAX 226					NAX 227	
Coord. Lat.	36°45'02"							36°44'58"	36°56'50''			36°56'50''						
Long.	25°16'02"							25°18'48"	25°29'25''			25°29'25''						
Rock type	eclogitic rock							idem	glaucophane schist			glaucophane schist					glaucophane schist	
	GL11	GL51	AK91	GL12	GL22	GL52	AK42	GL33	GL01	GL02	GL03	GL01	GL02	GL06	AK02	AK04	GLA	GLB
SiO_2	51.59	50.94	49.22	53.73	54.45	53.43	51.63	53.91	58.26	57.11	58.02	58.13	58.38	57.97	55.75	53.54	56.7	56.70
Al_2O_3	5.17	5.14	4.11	8.74	8.90	3.80	2.31	7.08	9.18	8.72	8.70	9.14	9.58	9.13	1.66	3.35	7.3	7.9
TiO_2	.08	.10	.06	.08	.06	.04	.04		-	.17	-	-	-	-	-	.09	-	4.81
Fe_2O_3	9.64	9.43	.28	5.05	7.16	15.71	3.10	5.08	6.83	6.97	6.77	3.41	5.73	4.06	9.20	14.38	6.44	10.47
FeO	17.37	18.61	21.67	16.10	15.44	12.56	16.75	16.29	8.72	9.84	10.10	11.27	9.03	11.49	7.10	4.80	10.81	-
MnO	.49	.20	.58	-	.03	.47	.70	.05	-	.06	.06	.05	.05	-	.12	.12	-	-
MgO	3.69	3.62	6.59	4.43	4.83	5.36	10.11	5.34	9.30	8.76	8.31	8.74	9.17	8.59	13.83	12.60	9.0	9.4
CaO	1.73	2.07	9.41	.96	.69	1.51	9.96	.96	.33	.47	.22	.31	.54	.33	6.31	4.96	.5	.6
Na_2O	5.65	5.93	1.67	5.91	6.48	5.04	1.55	6.65	6.98	7.07	7.25	7.40	6.72	7.45	3.36	3.93	7.5	7.5
K_2O	.07	.07	.24	.08	-	.09	.13	-							.06	.14		
	95.48	96.11	93.83	95.08	97.54	98.01	96.28	95.38	99.60	99.17	99.43	98.45	99.20	99.02	97.39	97.91	98.25	96.28
Si	7.85	7.77	7.73	7.94	7.87	7.84	7.77	7.99	7.94	7.89	8.02	8.04	7.97	8.00	7.94	7.63	7.96	7.98
Al^{IV}	.15	.23	.27	.06	.13	.16	.23	.01	.06	.11	-	-	.03	-	.06	.37	.04	.02
	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.04	8.00	8.00	8.00	8.00	8.00	8.00
Al^{IV}	.78	.69	.49	1.46	1.30	.50	.18	1.23	1.42	1.31	1.42	1.49	1.51	1.48	.22	.19	1.17	1.29
Ti	.01	.01	.01	.01	.01	.01	-	-	-	.02	-	-	-	-	-	.01	-	-
Fe^{3+}	1.10	1.08	.03	.56	.78	1.73	.35	.57	.70	.72	.70	.36	.59	.42	.99	1.54	.68	.51
Fe^{2+}	2.21	2.37	2.85	1.99	1.87	1.54	2.11	2.02	.99	1.14	1.17	1.30	1.03	1.33	.85	.57	1.28	1.23
Mn	.06	.03	.08	-	-	.06	.09	.01	-	.01	.01	.01	.01	-	.01	.01	-	-
Mg	.84	.82	1.54	.98	1.04	1.17	2.27	1.18	1.89	1.80	1.70	1.80	1.87	1.77	2.94	2.68	1.88	1.97
	5.00	5.00	5.00	5.00	5.00	5.01	5.00	5.01	5.00	5.00	5.00	4.96	5.01	5.00	5.01	5.00	5.01	5.00
Ca	.28	.34	1.58	.15	.11	.24	1.61	.15	.05	.07	.03	.05	.08	.05	.96	.76	.08	.09
Na	1.67	1.75	.51	1.69	1.82	1.43	.45	1.91	1.85	1.89	1.94	1.98	1.78	1.99	.93	1.09	2.04	2.05
K	.01	.01	.05	.02	-	.02	.02	-	-	-	-	-	-	-	.01	.03	-	-
	1.96	2.10	2.14	1.86	1.93	1.69	2.08	2.06	1.90	1.96	1.97	2.03	1.86	2.04	1.90	1.88	2.12	2.14

BLUE and GREEN AMPHIBOLES

sample no.	6-6		108-97										68 C			36 C		
coord. lat.	36°42'25"		36°45'25"										36°46'45"			36°42'00"		
long.	25°18'20"		25°16'17"										25°17'05"			25°18'58"		
rock type	garnet-mica schist		eclogitic rock										metamorphosed ultramafics			garnet-mica schist		
	GLAA	AKHA	GLB		GLC		GLD		GLA		AKA	AKB	AKAB	GLAD	GLAC	AKHF	AKHG	AKHGG
	core	rim	core	rim	core	rim	core	rim	core	rim								
SiO_2	56.95	48.80	55.00	53.30	54.15	54.35	52.40	52.80	54.90	52.75	55.50	55.60	54.70	58.05	57.90	50.20	52.30	50.25
Al_2O_3	11.90	11.45	3.25	5.00	3.75	4.70	4.75	5.00	3.80	4.70	1.35	1.25	2.65	10.70	10.35	7.20	4.00	6.20
TiO_2	.10	.25	-	-	-	-	-	-	-	-	-	-	-	-	-	.15	.05	.15
Fe_2O_3	2.62	6.83	12.05	10.80	11.13	11.19	11.19	11.93	11.51	11.87	9.29	7.41	3.99	1.08	1.82	3.13	2.93	6.42
FeO	12.12	10.33	10.13	10.38	9.89	9.24	9.74	9.04	10.11	9.45	2.76	1.74	9.10	11.15	10.25	12.34	12.11	10.48
MnO	-	.10	.45	.55	.50	.60	.65	.55	.35	.50	1.80	1.65	.10	.20	.05	.10	.15	.20
ZnO	-	-	1.10	1.00	1.05	1.05	1.10	1.20	.75	1.25	1.00	1.00	-	-	-	-	-	-
MgO	7.15	9.55	8.50	8.45	8.85	8.80	9.25	9.10	8.55	8.60	15.85	17.50	15.10	8.75	9.45	12.40	13.45	12.30
CaO	.45	6.35	1.15	2.40	2.20	1.85	3.70	2.80	1.20	2.30	7.80	9.25	10.10	.75	1.00	10.25	11.30	10.90
Na_2O	6.85	4.60	6.90	6.35	6.15	6.45	5.65	6.25	6.75	6.40	2.80	2.00	1.40	6.95	6.90	2.30	.95	1.00
K_2O	-	.20	.05	.10	.05	.05	.15	.10	-	.10	.10	.10	.10	-	-	.40	.25	-
	98.14	98.46	98.57	98.33	97.72	98.28	98.58	98.77	97.92	97.92	98.25	97.50	97.15	97.63	97.72	98.47	97.49	97.90
Si	7.89	7.00	7.93	7.71	7.86	7.81	7.60	7.61	7.93	7.68	7.82	7.83	7.82	8.03	7.99	7.25	7.59	7.28
Al^{IV}	.11	1.00	.07	.29	.14	.19	.40	.39	.07	.32	.18	.17	.18	-	.01	.75	.41	.72
	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.03	8.00	8.00	8.00	8.00
Al^{VI}	1.84	.94	.49	.56	.50	.60	.42	.46	.57	.48	.04	.03	.26	1.75	1.67	.48	.28	.34
Ti	.01	.03	-	-	-	-	-	-	-	-	-	-	-	-	-	.01	-	.01
Fe^{3+}	.27	.74	1.30	1.17	1.22	1.21	1.22	1.29	1.25	1.30	.99	.79	.42	.11	.19	.34	.32	.70
Fe^{2+}	1.40	1.24	1.21	1.26	1.20	1.11	1.18	1.09	1.22	1.15	.33	.20	1.09	1.29	1.18	1.49	1.47	1.27
Mn	-	.01	.05	.07	.06	.08	.07	.07	.04	.07	.21	.20	.01	.02	.01	.01	.02	.02
Zn	-	-	12	.11	.11	.11	.12	.13	.08	.13	.11	.11	-	-	-	-	-	-
Mg	1.48	2.04	1.83	1.83	1.91	1.89	1.99	1.96	1.84	1.87	3.32	3.67	3.22	1.81	1.95	2.67	2.91	2.66
	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Ca	.07	.98	.18	.38	.34	.29	.58	.44	.18	.36	1.18	1.39	1.55	.11	.15	1.58	1.75	1.69
Na	1.84	1.28	1.93	1.77	1.73	1.79	1.59	1.74	1.90	1.81	.77	.55	.39	1.86	1.85	.65	.26	.28
K	-	.04	.01	.02	.02	.01	.03	.02	-	.02	.02	.02	.02	-	-	.08	.04	-
	1.91	2.30	2.12	2.17	2.09	2.09	2.20	2.20	2.08	2.19	1.97	1.96	1.96	1.97	2.00	2.31	2.05	1.97

	BLUE and GREEN AMPHIBOLES										BROWN and BLUEGREEN AMPHIBOLES							
Sample no.	I 29										85 C							
Coord. Lat.	36°44'29"										36°43'57"							
Long.	25°20'34"										25°17'26"							
Rock type	glaucophane schist										metalamprophyre							
	GL11	GL21	GL31	GL91	GL18	GL28	GL17	GL19	GL39	GL129	AA	HA	HB	AB	BB	AC	ACC	HC
											blue	hbl.	hbl	blue	blue	blue	blue	blue
SiO_2	56.43	55.44	54.64	54.24	56.37	55.81	54.98	56.49	56.20	56.75	42.25	44.75	44.00	46.20	47.50	46.00	45.30	45.15
Al_2O_3	10.24	9.76	9.05	9.25	10.23	10.15	9.81	10.37	10.17	10.82	17.00	10.75	11.40	12.70	10.55	13.10	13.65	11.20
TiO_2	-	-	-	-	-	-	-	-	-	-	.45	1.10	1.10	.45	.45	.30	.55	1.05
Fe_2O_3	2.28	3.35	3.53	3.47	6.17	2.97	3.15	.66	2.51	.43	3.24	4.21	7.37	5.00	6.03	5.00	6.00	3.41
FeO	10.29	10.93	13.37	14.72	9.49	12.59	13.72	13.02	13.59	12.07	13.52	15.39	12.93	12.11	10.77	13.02	11.95	15.58
MnO	.09	.05	.08	.05	.19	.15	.03	.11	.32	.11	.05	.40	.45	.05	-	.05	.05	.25
MgO	8.23	7.37	6.66	5.61	7.53	7.11	6.30	7.48	6.36	8.02	7.75	8.70	8.60	9.00	10.45	8.50	8.65	8.80
CaO	.29	.17	.29	.33	.32	.32	.38	.21	.21	.21	10.00	11.00	10.80	8.90	9.20	9.15	9.00	10.85
Na_2O	6.66	6.51	7.18	6.88	6.17	7.18	7.06	7.10	6.96	7.40	2.95	1.80	1.35	2.90	2.50	2.80	3.00	1.75
K_2O	.02	.04	.02	.02	.01	-	.04	.02	0.06	.11	.60	.60	.60	.30	.35	.30	.30	.55
	94.53	93.62	94.82	94.67	96.48	96.28	94.97	95.46	96.38	95.92	97.81	98.70	98.60	97.61	97.80	98.22	98.45	98.59
Si	8.05	8.04	7.97	7.97	7.93	7.95	7.93	8.04	8.01	8.02	6.24	6.64	6.51	6.75	6.91	6.72	6.62	6.69
Al^{IV}	-	-	.03	.03	.07	.05	.07	-	-	-	1.76	1.36	1.49	1.25	1.09	1.28	1.38	1.31
	8.05	8.04	8.00	8.00	8.00	8.00	8.00	8.04	8.01	8.02	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al^{IV}	1.72	1.67	1.52	1.57	1.63	1.65	1.61	1.74	1.71	1.80	1.20	.52	.50	.94	.71	.97	.97	.65
Ti	-	-	-	-	-	-	-	-	-	-	.05	.12	.12	.05	.05	.03	.01	.12
Fe^{3+}	.24	.37	.39	.38	.65	.32	.35	.07	.27	.05	.36	.47	.82	.55	.66	.55	.66	.38
Fe^{2+}	1.23	1.32	1.63	1.81	1.12	1.50	1.67	1.55	1.62	1.43	1.67	1.91	1.60	1.48	1.31	1.59	1.46	1.93
Mn	.01	.01	.01	.01	.02	.02	-	.01	.04	.01	.01	.05	.06	.01	-	.01	.01	.03
Mg	1.75	1.59	1.45	1.23	1.58	1.51	1.37	1.59	1.35	1.69	1.71	1.93	1.90	1.96	2.27	1.85	1.89	1.89
	4.95	4.96	5.00	5.00	5.00	5.00	5.00	4.96	4.99	4.98	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Ca	.04	.03	.05	.05	.05	.05	.06	.03	.03	.03	1.58	1.75	1.71	1.39	1.43	1.43	1.41	1.72
Na	1.84	1.83	2.03	1.96	1.68	1.98	1.98	2.04	1.92	2.03	.83	.51	.38	.81	.69	.78	.84	.50
K	-	.01	-	-	-	-	-	-	-	.02	.11	.11	.12	.06	.07	.06	.06	.10
	1.88	1.87	2.08	2.01	1.73	2.03	2.05	2.07	1.95	2.08	2.52	2.37	2.21	2.26	2.19	2.27	2.31	2.32

BROWN and BLUEGREEN AMPHIBOLES

sample no.	lo 39												10.7 C	
coord. lat.	36°44'13"												36°43'31"	
long.	25°17'26"												25°16'55"	
rock type	metalamprophyre												meta diorite	
	AA	BAA	BAB	HA	LE	BE	AB	BB	HB	AC	BC	HC	AK	AR
	blue	blue	blue	lam.hbl.	lam.	blue	blue	blue	hbl.	blue	blue	hbl.	core	rim
SiO_2	49.55	48.35	48.30	48.30	54.65	48.85	54.80	48.95	53.75	51.00	48.85	47.30	42.85	44.65
Al_2O_3	9.50	8.40	8.65	8.85	1.05	8.35	2.50	8.05	3.95	8.90	8.85	9.45	13.25	11.95
TiO_2	.15	.75	.80	.90	.10	.80	-	.75	.05	.20	.75	1.35	.40	.35
Fe_2O_3	4.10	3.45	2.59	3.19	-	3.60	6.39	3.35	2.15	5.05	1.80	2.93	1.92	2.48
FeO	8.97	9.63	10.12	9.73	22.05	8.95	5.32	9.80	9.10	7.40	10.85	10.78	19.34	17.43
MnO	.10	.30	.20	.20	.85	.25	.10	.30	.15	.10	.30	.20	.05	.05
MgO	12.95	13.05	13.10	13.05	17.55	13.55	16.60	13.25	15.60	13.50	12.75	12.30	6.10	7.45
CaO	9.95	10.85	11.05	10.80	1.20	10.65	10.30	10.75	11.35	9.10	10.90	10.65	9.30	9.30
Na_2O	2.35	1.70	1.70	1.80	.40	1.85	.95	1.90	.90	2.25	1.80	2.00	3.35	3.15
K_2O	.20	.25	.25	.30	-	.25	.05	.25	.10	.20	.20	.40	1.35	1.10
	97.82	96.73	96.76	97.12	97.85	97.10	97.01	97.35	97.10	97.70	97.05	97.36	97.91	97.91
Si	7.09	7.05	7.04	7.01	7.94	7.06	7.76	7.09	7.68	7.22	7.09	6.90	6.52	6.71
Al^{IV}	.91	.95	.96	.99	.06	.94	.24	.91	.32	.78	.91	1.10	1.48	1.29
	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al^{VI}	.69	.49	.52	.52	.12	.49	.17	.46	.35	.71	.61	.52	.90	.82
Ti	.01	.08	.09	.10	.01	.09	-	.08	.01	.02	.09	.15	.04	.04
Fe^{3+}	.44	.38	.28	.35	-	.39	.68	.37	.23	.54	.20	.32	.22	.28
Fe^{2+}	1.07	1.17	1.24	1.18	2.68	1.08	.63	1.19	1.08	.87	1.31	1.32	2.46	2.19
Mn	.02	.04	.02	.03	.11	.03	.02	.04	.01	.01	.03	.02	-	-
Mg	2.77	2.84	2.85	2.82	3.80	2.92	3.50	2.86	3.32	2.85	2.76	2.67	1.38	1.67
	5.00	5.00	5.00	5.00	6.72	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Ca	1.53	1.70	1.73	1.67	.19	1.66	1.56	1.67	1.74	1.38	1.70	1.66	1.53	1.50
Na	.65	.49	.48	.51	.12	.52	.27	.53	.24	.70	.50	.57	1.00	.92
K	.03	.05	.04	.05	-	.04	.01	.05	.01	.03	.04	.07	.26	.21
	2.21	2.24	2.25	2.23	.31	2.22	1.84	2.25	1.99	2.11	2.24	2.30	2.79	2.63

PYROXENES

sample no.	68 C			108-97					I 32				Io 64				Nax 231	
coord. lat.	36°46'45"			36°45'25"					36°44'58"				36°45'46"				37°01'20''	
long.	25°17'05"			25°16'17"					25°15'48"				25°18'32"				25°26'20''	
rock type	metamorphosed ultramafics			eclogitic rock					eclogitic rock				metamorphosed iron lens				metagabbro	
	XA	XB	XB	PA	PB	PC	PD	PE	A 32	A 52	A 63	A 54	A 41	A 51	A 32	A 42		
				core	rim		grano-blastic	idiom.										
SiO_2	56.30	56.00	56.15	53.55	53.45	54.45	53.55	54.95	49.81	51.11	51.06	50.60	52.45	52.69	53.10	52.75	50.91	51.63
Al_2O_3	9.40	8.70	10.50	4.40	2.85	7.05	2.95	7.05	1.96	3.49	2.63	1.52	2.58	2.33	2.92	2.52	2.26	3.12
TiO_2	.05	-	-	-	-	-	-	.10	-	-	-	-	-	-	-	-	-	-
Fe_2O_3	2.23	1.37	1.28	17.19	19.24	15.72	18.15	13.73	18.98	14.36	12.61	15.70	17.03	19.92	13.74	18.48	8.60	8.55
FeO	4.69	5.18	5.74	1.17	.92	2.30	2.43	4.12	4.96	6.98	10.12	8.60	2.23	-	6.10	1.81	.66	.93
MnO	.30	.15	.10	.95	1.00	.20	.50	.25	.45	.40	.26	.65	.45	.51	.54	.56	.27	.27
MgO	7.20	7.30	5.60	5.00	5.20	3.40	5.00	3.40	2.77	2.72	2.74	2.77	4.45	4.89	4.42	4.73	11.44	11.19
CaO	13.25	14.00	12.55	10.15	9.75	8.25	10.30	8.15	10.15	10.94	11.15	11.76	9.91	11.02	10.31	10.84	19.11	19.75
Na_2O	7.00	6.60	7.60	8.60	8.65	9.85	8.30	9.65	7.74	7.53	6.82	6.77	8.51	8.70	7.74	8.31	3.23	3.30
	100.52	99.55	99.52	101.01	101.06	101.62	101.63	101.85	97.19	98.00	97.00	98.00	98.00	100.06	98.87	100.00	96.48	98.74
Si	2.01	2.02	2.03	1.97	1.98	1.98	1.98	2.00	1.97	1.99	2.01	1.99	2.01	1.98	2.02	1.99	1.95	1.93
Al^{IV}	-	-	-	0.03	0.02	0.02	0.02	-	0.03	0.01	-	.01	-	.02	-	.01	.05	.07
	2.01	2.02	2.03	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.01	2.00	2.01	2.00	2.02	2.00	2.00	2.00
Al^{VI}	.40	.37	.45	.16	.10	.28	.11	.31	.06	.15	.12	.06	.12	.10	.13	.10	.05	.07
Ti	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe^{3+}	.06	.04	.04	.48	.54	.43	.51	.37	.56	.42	.37	.46	.49	.56	.39	.52	.25	.24
Fe^{2+}	.14	.16	.17	.04	.03	.07	.08	.13	.16	.23	.33	.28	.07	-	.19	.06	.02	.03
Mn + Zn	.01	.01	-	.03	.03	.02	.03	.02	.02	.01	.01	.02	.01	.02	.02	.02	.01	.01
Mg	.38	.39	.30	.27	.29	.19	.28	.18	.16	.16	.16	.16	.25	.27	.25	.27	.65	.62
	.99	.98	.96	.98	.99	.99	.90	1.01	.96	.97	.99	.98	.94	.95	.98	.97	.98	.97
Ca	.51	.54	.49	.40	.39	.32	.41	.32	.45	.46	.47	.50	.41	.44	.42	.44	.78	.79
Na	.49	.46	.53	.61	.62	.70	.60	.68	.59	.57	.52	.52	.63	.64	.57	.61	.24	.24
	1.00	1.00	1.02	1.01	1.01	1.02	1.01	1.00	1.04	1.03	.99	1.02	1.04	1.08	1.02	1.05	1.02	1.03
jadeite	27	26	31	14	8	23	9	23	6	11	8	5	9	7	9	7	6	8
acmite	4	4	3	34	39	31	35	28	39	29	26	31	36	40	28	37	14	13
augite	69	70	66	52	53	46	56	49	55	60	66	64	55	53	63	56	80	79

PYROXENES

sample no.	Nax 231			
coord. lat.	37°01'20''			
long.	25°26'20''			
rock type	metagabbro			
SiO_2	52.18	52.45	52.28	52.86
Al_2O_3	3.26	2.68	2.93	11.83
TiO_2	-	-	-	1.98
Fe_2O_3	7.81	4.28	2.95	4.18
FeO	1.46	4.91	6.33	3.95
MnO	.27	.27	.27	.18
MgO	11.60	11.48	11.31	6.47
CaO	19.79	20.34	19.79	10.42
Na_2O	3.14	2.38	2.27	6.15
	99.15	98.79	98.13	98.02
Si	1.93	1.97	1.98	1.91
Al^{IV}	.07	.03	.02	.09
	2.00	2.00	2.00	2.00
Al^{VI}	.07	.09	.11	.41
Ti	-	-	-	.05
Fe^{3+}	.22	.12	.08	.17
Fe^{2+}	.05	.15	.20	.12
Mn	.01	.01	.01	.01
Mg	.64	.64	.64	.35
	.99	1.01	1.04	1.11
Ca	.79	.82	.80	.40
Na	.23	.17	.17	.43
	1.02	.99	.97	.83
jadeite	8	6	7	27
acmite	12	6	4	11
augite	80	88	89	61

GARNETS

	85 G		Io 39		10.7 C			6-6		36 C	
	36°43'57"		36°44'13"		36°43'31"			36°42'25"		36°42'00"	
	25°17'26"		25°17'26"		25°16'55"			25°18'20"		25°18'58"	
	metalamprophyre		metalamprophyre		metadiorite			garnet-mica schist		garnet-mica schist	
	GC	GC	GA	GA	GA	GB	GC	GA		GA	
								core	rim	core	rim
SiO_2	38.65	37.85	37.55	38.00	38.25	38.20	37.95	37.55	37.60	37.80	37.90
Al_2O_3	21.65	21.30	21.45	21.55	21.10	21.15	21.30	21.25	21.05	21.25	21.30
TiO_2	-	-	.15	.05	.30	.35	15	.10	.10	.15	.10
Fe_2O_3	.21	.24	-	-	1.19	-	-	-	-	-	-
FeO	24.60	34.35	26.80	28.55	23.03	22.80	25.15	29.55	30.65	28.20	28.55
MnO	.80	.95	1.50	.95	.15	.15	.20	1.20	.55	.60	.45
MgO	.70	2.35	2.00	1.60	.50	.55	.60	1.25	1.50	1.15	1.30
CaO	15.30	4.55	10.20	10.35	17.10	16.50	14.85	9.25	8.40	10.85	10.20
	101.91	101.59	99.65	101.05	101.62	99.70	100.20	100.15	99.85	100.00	99.80
Si	3.00	3.00	2.99	3.00	2.98	3.02	3.00	3.00	3.01	3.00	3.01
Al^{IV}	-	-	.01	-	.02	-	-	-	-	-	-
	3.00	3.00	3.00	3.00	3.00	3.02	3.00	3.00	3.01	3.00	3.01
Al^{VI}	1.98	1.99	2.00	2.00	1.92	1.97	1.99	2.00	1.99	1.99	2.00
Ti	-	-	.01	-	.02	.02	.01	.01	.01	.01	-
Fe^{3+}	.01	.01	-	-	.07	-	-	-	-	-	-
	1.99	2.00	2.01	2.00	2.01	1.99	2.00	2.01	2.00	2.00	2.00
Fe^{2+}	1.60	2.28	1.79	1.88	1.50	1.51	1.66	1.97	2.05	1.88	1.90
Mn	.05	.06	.10	.06	.01	.01	.02	.08	.04	.04	.03
Mg	.08	.28	.24	19	.06	.07	.07	.15	.18	14	16
Ca	1.27	.39	.87	.87	1.43	1.40	1.25	.79	.72	.93	.87
	3.00	3.01	3.00	3.00	3.00	2.99	3.00	2.99	2.99	2.99	2.96

GARNETS

sample no	89						
coord. lat.	36°43'09"						
long.	25°17'26"						
rock type	chloritoid bearing garnet-mica schist						
	GD			GE			
	core	inter	rim	core	core	rim	rim
SiO_2	37.05	37.50	38.05	36.85	37.75	37.15	37.60
Al_2O_3	20.95	21.00	21.15	21.05	21.10	20.90	21.10
TiO_2	-	.01	-	-	.15	-	.10
Cr_2O_3	.10	.05	-	.05	.05	.15	.10
Fe_2O_3	1.09	-	.21	.44	-	.82	-
FeO	33.21	31.35	30.00	33.61	29.35	33.21	31.30
MnO	2.45	.65	.95	3.60	1.15	2.50	.85
MgO	3.65	1.60	3.65	2.90	1.85	3.90	2.25
CaO	1.60	7.70	6.30	1.25	8.35	1.35	7.00
	100.10	99.95	100.31	99.75	99.75	99.98	100.30
Si	2.97	3.00	3.01	2.98	3.01	2.98	3.00
Al^{IV}	.03	-	-	.02	-	.02	-
	3.00	3.00	3.01	3.00	3.01	3.00	3.00
Al^{VI}	1.95	1.99	1.97	1.99	1.99	1.96	1.98
Ti	-	.01	-	-	.01	-	.01
Cr	.01	-	-	.01	.01	.01	.01
Fe^{3+}	.07	-	.01	.03	-	.05	-
	2.03	2.00	1.98	2.03	2.01	2.02	2.00
Fe^{2+}	2.23	2.10	1.98	2.27	1.96	2.23	2.09
Mn	.17	.05	.07	.25	.08	.17	.06
Mg	.44	.20	.43	.35	.22	.47	.27
Ca	.14	.66	.53	.11	.72	.12	.60
	2.98	3.01	3.01	2.98	2.98	2.99	3.02

	I 29			I 108C2				I 32		
	36°44'29"			36°45'02"				36°44'58'		
	25°20'34"			25°16'02"				25°18'48		
	glaucophane schist			eclogitic rock				eclogitic rock		
	GR118	GR128	GR138	GR021	GR011	GR012	GR22	GR14	GR24	GR34
SiO_2	35.27	36.78	36.98	36.86	36.92	37.01	37.27	36.16	35.98	36.00
Al_2O_3	19.61	19.39	19.29	19.77	19.50	18.07	18.31	17.71	17.44	18.27
TiO_2		-	-	.10	.06	10	.10	-	-	-
Fe_2O_3	2.33		.29	2.97	2.24	1.28	1.54	5.10	1.48	3.52
FeO	28.03	28.17	28.15	25.84	25.02	28.28	27.58	22.56	24.56	23.65
MnO	2.75	3.45	3.48	1.70	2.22	1.15	1.18	9.38	9.40	9.60
MgO	.55	.68	.82	.52	.38	.61	.63	-	-	-
CaO	8.07	8.72	8.63	12.24	12.66	10.79	11.58	8.69	6.93	7.56
	97.00	97.19	97.64	100.00	98.62	97.29	98.19	99.60	96.00	98.60
Si	2.96	3.05	3.05	2.97	3.00	3.07	3.06	2.98	3.07	2.99
Al^{IV}	.04	-	-	.03	-	-	-	.02	-	.01
	3.00	3.05	3.05	3.00	3.00	3.07	3.06	3.00	3.07	3.00
Al^{VI}	1.90	1.89	1.88	1.84	1.86	1.77	1.77	1.70	1.76	1.79
Ti	-	-	-	.01	-	.01	.01	-	-	-
Fe^{3+}	.15	-	.02	.18	.14	.08	.09	.32	.10	.22
	2.05	1.89	1.90	2.03	2.00	1.86	1.87	2.02	1.86	2.01
Fe^{2+}	1.97	1.96	1.94	1.74	1.70	1.96	1.89	1.56	1.75	1.64
Mn	.20	.24	.24	.12	.15	.08	.08	.66	.68	.68
Mg	.07	.08	.10	.06	.05	.08	.08	-	-	-
Ca	.73	.77	.76	1.06	1.10	.96	1.02	.77	.63	.67
	2.97	3.05	3.04	2.98	3.00	3.08	3.07	2.99	3.06	2.99

GARNETS

sample no.	108-97								68 C			
coord. lat.	36°45'25"								36°46'45"			
long.	25°16'17"								25°17'05"			
rock type	Eclogitic rock								Metamorphosed ultramafic bodies			
	GA		GB			GC			GB		GC	
	core	rim	core	inter	rim	core	inter	rim	core	rim	core	rim
SiO_2	37.85	37.50	37.10	37.45	37.45	36.85	37.45	37.30	37.60	37.90	37.55	37.85
Al_2O_3	20.10	20.45	20.60	20.30	19.70	20.10	20.35	19.90	20.65	21.10	20.95	21.00
TiO_2	.15	.05	.25	.15	.05	.45	.25	.10	.20	.05	.10	.05
Cr_2O_3	-	-	-	-	-	-	-	-	.10	.15	.05	.20
Fe_2O_3	.55	.33	-	.29	.52	-	-	.82	-	-	-	-
FeO	2.84	21.85	10.25	1.70	16.56	1.55	1.65	16.71	15.30	26.40	16.25	26.25
MnO	26.40	10.30	25.55	28.55	17.60	34.30	30.30	17.10	15.80	2.25	15.30	1.95
MgO	.35	.50	.75	.35	.45	.15	.55	.45	.45	1.40	.50	1.30
CaO	11.85	9.10	5.35	10.65	7.55	6.70	8.75	7.70	10.15	10.80	9.40	11.30
	100.09	100.08	99.85	99.45	99.88	100.10	99.30	100.08	100.25	100.05	100.10	99.90
Si	3.03	3.02	3.00	3.02	3.04	3.00	3.03	3.02	3.01	3.01	3.01	3.01
Al^{IV}	-	-	-	-	-	-	-	-	-	-	-	-
	3.03	3.02	3.00	3.02	3.04	3.00	3.03	3.02	3.01	3.01	3.01	3.01
Al^{VI}	1.89	1.94	1.97	1.93	1.89	1.93	1.94	1.90	1.95	1.98	1.98	1.97
Ti	.01	-	.02	.01	.01	.03	.02	.01	.01	.01	.01	.01
Cr	-	-	-	-	-	-	-	-	.01	.01	.01	.01
Fe^{3+}	.03	.02	-	.02	.03	-	-	.05	.01	.01	.01	.01
	1.93	1.96	1.99	1.96	1.93	1.95	1.96	1.96	1.97	2.00	2.00	1.99
Fe^{2+}	.19	1.47	.69	.11	1.12	.10	.11	1.13	1.02	1.76	1.09	1.75
MnO	1.79	.70	1.75	1.95	1.21	2.36	2.07	1.18	1.07	.15	1.04	.13
MgO	.04	.06	.09	.04	.05	.02	.07	.06	.05	.17	.06	.15
CaO	1.02	.78	.47	.92	.66	.58	.76	.67	.87	.92	.81	.97
	3.04	3.01	3.00	3.02	3.04	3.06	3.01	3.04	3.01	3.00	3.00	3.00

WHITE MICAS AND BIOTITES

sample no.	10.7 C			
coord. lat.	36°43'31"			
long.	25°16'55"			
rocktype	meta diorite			
	ME	MF	BE	BF
SiO_2	45.15	45.45	36.80	37.35
Al_2O_3	33.90	33.55	15.55	15.70
TiO_2	1.45	1.45	2.40	2.65
Fe_2O_3	-	-	-	-
FeO	1.30	1.45	22.40	22.50
MnO	-	.05	.35	.50
MgO	.70	.80	7.65	7.50
CaO	-	-	.10	.05
Na_2O	.40	.45	.10	.05
K_2O	11.15	11.10	9.15	9.20
	94.05	94.30	94.50	95.40
Si	6.13	6.16	5.74	5.76
Al^{IV}	1.87	1.84	2.26	2.24
	8.00	8.00	8.00	8.00
Al^{VI}	3.56	3.52	.60	.61
Ti	.15	.15	.28	.31
Fe^{3+}	-	-	-	-
Fe^{2+}	.15	.16	2.92	2.90
Mn	-	.01	.05	.05
Mg	.14	.16	1.78	1.73
	4.00	4.00	5.63	5.60
Ca	-	-	.02	.01
Na	.11	.13	.03	.02
K	1.94	1.92	1.82	1.81
	2.05	2.05	1.87	1.84

WHITE MICAS AND BIOTITES

sample no.	I 11								89				6-6					
coord. lat.	$36^{\circ}44'25''$								$36^{\circ}43'09''$				$36^{\circ}42'25''$					
long.	$25^{\circ}17'15''$								$25^{\circ}17'26''$				$25^{\circ}18'20''$					
rocktype	meta granite								garnet-mica schist				idem					
	MA	MB	BAA	BB	MC	MD	BC	BD	MA	MB	PA	PD	MB	MF	PB	BB	BAA	MA
SiO_2	45.95	45.90	34.70	34.65	45.85	45.55	34.65	34.30	51.20	52.00	48.85	47.75	50.10	49.70	47.45	38.65	39.25	50.05
Al_2O_3	35.50	34.60	16.95	17.00	34.75	35.20	18.20	17.95	26.20	26.00	30.10	31.50	28.00	28.05	38.50	16.60	15.95	27.95
TiO_2	1.05	1.10	1.30	1.60	.75	.90	2.35	2.55	.20	.20	.20	.20	.15	.35	-	1.25	1.15	.45
Fe_2O_3	.85	-	-	-	-	-	-	-	-	1.44	-	-	2.03	1.45	-	-	-	1.27
FeO	.58	1.35	26.90	26.45	1.25	1.20	25.70	26.90	1.60	.84	2.20	1.95	1.56	1.72	.50	16.75	16.80	1.79
MnO	-	-	.45	.35	-	-	.30	.35	-	-	-	.10	-	-	-	.20	.05	-
MgO	.60	.60	5.50	5.40	.55	.55	5.25	4.95	3.95	3.80	2.35	1.80	2.40	2.50	.15	11.95	12.50	2.50
CaO	-	-	.15	.20	-	-	-	-	-	-	-	-	-	-	.10	.15	.10	-
Na_2O	.55	.55	.15	.10	.55	.65	.10	.10	.30	.35	.80	.95	.60	.80	7.60	.15	.20	.65
K_2O	10.90	11.00	8.75	8.50	11.05	10.90	9.80	9.70	11.05	10.70	10.25	10.35	10.35	1.035	.75	8.60	9.00	10.40
	95.98	95.10	94.85	94.25	94.75	94.95	96.35	96.80	94.50	95.33	93.85	93.75	95.19	94.92	95.05	94.30	95.00	95.06
Si	6.09	6.15	5.52	5.53	6.16	6.10	5.41	5.36	6.89	6.92	6.56	6.43	6.71	6.68	6.09	5.82	5.87	6.71
Al^{IV}	1.91	1.85	2.48	2.47	1.84	1.99	2.59	2.64	1.11	1.08	1.44	1.57	1.29	1.32	1.91	2.18	2.13	1.29
	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al^{VI}	3.64	3.62	.70	.73	3.67	3.67	.76	.68	3.04	2.99	3.33	3.43	3.13	3.12	3.91	.76	.68	3.12
Ti	.10	.11	.16	.19	.07	.09	.28	.30	.02	.02	.02	.02	.01	.04	-	.14	.13	.05
Fe^{3+}	.08	-	-	-	-	-	-	-	-	.14	-	-	.20	.15	-	-	-	.13
Fe^{2+}	.06	.15	3.58	3.53	.14	.14	3.36	3.52	.18	.09	.24	.22	.18	.19	.06	2.11	2.10	.20
MnO	-	-	.05	.05	-	-	.04	.05	-	-	-	.01	-	-	-	.01	.01	-
MgO	.12	.12	1.31	1.28	.12	.10	1.22	1.16	.78	.75	.46	.36	.48	.50	.03	2.68	2.79	.50
	4.00	4.00	5.80	5.78	4.00	4.00	5.66	5.71	4.02	3.99	4.05	4.04	4.00	4.00	4.00	5.70	5.71	4.00
Ca	-	-	.02	.04	-	-	-	-	-	-	-	-	-	-	.02	.03	.02	-
Na	.14	.14	.05	.04	.15	.17	.03	.04	.08	.09	.21	.25	.16	.21	1.89	.05	.06	.17
K	1.84	1.88	1.78	1.73	1.90	1.87	1.96	1.93	1.90	1.82	1.75	1.77	1.77	1.77	.12	1.65	1.72	1.78
	1.98	2.02	1.85	1.81	2.05	2.04	1.99	1.97	1.98	1.91	1.96	2.02	1.93	1.98	2.03	1.73	1.80	1.95

WHITE MICAS AND BIOTITES

sample no	36 C	I 29										68 C	
coord. lat.	36°42'00"	36°44'29"										36°46'45"	
long.	25°18'58"	25°20'34"										25°17'05"	
rocktype	idem	glaucophane schist										metam. ultramafics	
	MF	M 98	M 108	M 137	M 147	M 49	M 59	M 89	M 99	M 71	M77	MFB	MFC
SiO_2	50.05	48.67	48.41	48.22	48.02	48.54	48.87	49.27	49.25	48.13	44.12	52.45	52.20
Al_2O_3	28.15	25.06	24.76	24.74	25.03	25.73	25.83	25.54	26.08	25.13	25.65	24.75	24.85
TiO_2	.35	-	-	-	-	-	-	-	-	-	-	.10	.15
Fe_2O_3	1.77	1.99	1.88	2.56	.39	1.84	1.99	.99	1.26	.53	6.21	2.73	2.42
FeO	.74	2.97	3.07	1.79	3.96	2.68	2.29	2.97	2.70	3.34	1.36	.72	1.05
MnO	-	.05	.03	-	-	-	-	-	-	-	-	-	-
MgO	2.85	2.15	2.05	2.24	2.09	2.39	2.36	2.53	2.37	2.39	1.66	4.00	3.75
CaO	-	.07	.07	.06	.09	-	-	-	-	.01	.09	-	-
Na_2O	.60	.59	.46	.61	.60	.90	.73	.66	.46	.89	.90	.25	.20
K_2O	10.35	9.98	9.90	8.98	10.34	10.07	9.92	10.38	10.52	10.08	9.92	10.80	10.70
	94.86	91.53	90.63	89.20	90.52	92.15	91.00	92.34	92.61	90.50	89.91	95.80	95.32
Si	6.70	6.83	6.86	6.87	6.84	6.77	6.80	6.85	6.82	6.83	6.41	6.97	6.97
Al^{IV}	1.30	1.17	1.14	1.13	1.16	1.23	1.20	1.15	1.18	1.17	1.59	1.03	1.03
	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al^{VI}	3.14	2.98	3.00	3.03	3.04	3.00	3.03	3.03	3.07	3.04	2.80	2.84	2.88
Ti	.04	-	-	-	-	-	-	-	-	-	-	.01	.01
Fe^{3+}	.18	.21	.20	.28	.05	.19	.21	.10	.13	.06	.68	.27	.24
Fe^{2+}	.08	.35	.36	.21	.47	.31	.27	.35	.31	.40	.17	.08	.12
Mn	-	.01	.01	-	-	-	-	-	-	-	-	-	-
Mg	.57	.45	.43	.48	.44	.50	.49	.52	.49	.50	.35	.80	.75
	4.01	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Ca	.16	.01	.01	.01	.01	-	-	-	-	-	.01	-	-
Na	.16	.16	.13	.17	.17	.24	.20	.18	.12	.24	.25	.06	.05
K	1.77	1.79	1.79	1.63	1.88	1.79	1.76	1.84	1.86	1.83	1.84	1.83	1.82
	1.93	1.96	1.93	1.81	2.06	2.03	1.96	2.02	1.98	2.07	2.00	1.89	1.87

EPIDOTES and ALLANITES

sample no.	36 C				108-97	
coord. lat.	36°42'00"				36°45'25"	
long.	25°18 58				25°16 17	
rocktype	garnet-mica schist				eclogitic rock	
	ALA	EA	ALB	EB	EBC	EBD
SiO_2	37.70	39.20	37.85	38.70	27.85	28.00
Al_2O_3	26.65	27.90	27.70	27.10	9.90	12.40
TiO_2	.10	-	.15	.10	-	-
Fe_2O_3	-	6.26	-	6.44	-	-
FeO	7.50	1.08	6.45	1.38	15.30	14.15
MnO	.05	-	.05	.10	.30	.40
MgO	.10	-	.10	.	-	.10
CaO	19.65	23.75	19.65	23.20	8.65	8.65
PbO	-	-	-	-	34.20	33.45
	91.75	98.19	91.95	97.02	96.20	97.15
Si		6.08		6.09	6.18	6.02
Al		5.09		5.03	2.59	3.14
Ti		.01		.01	-	-
Fe^{3+}		.73		.76	-	-
Fe^{2+}		.14		.18	2.84	2.54
Mn		-		.01	.06	.07
Mg		-		-	-	.03
Ca		3.95		3.91	2.05	1.99
Pb		-		-	1.91	1.81
		16.00		15.99	15.63	15.60

CHLORITOIDS

CHLORITES

sample no.	89				176		89		6-6
coord. lat.	36°43'09"				36°44'05"		36°43'09"		36°42'25"
long.	25°17'26"				25°15'39"		25°17'26"		25°18'20"
rocktype	garnet-mica schist				diasporite		garnet-mica schist		idem
	CAK	CAR	CDK	CDR			CHA	CHB	CB
SiO_2	25.00	24.15	24.40	24.95	24.95	24.60	24.75	25.10	26.45
Al_2O_3	41.35	41.10	40.80	41.85	41.33	40.51	21.75	21.65	20.15
TiO_2	-	-	-	-	-	-	-	-	.10
Fe_2O_3	-	-	-	-	-	-	-	-	-
FeO	20.20	21.50	22.05	19.50	23.03	23.83	25.60	26.20	22.80
MnO	10	.10	-	.10	.24	.27	.10	.10	-
ZnO	-	.05	.10	.05	-	-	.15	.10	-
MgO	5.40	4.60	4.25	5.90	3.33	3.14	14.70	14.45	17.60
	92.10	91.55	91.60	92.35	92.88	92.35	87.05	87.60	87.10
Si	2.02	1.99	2.01	2.01	2.03	2.03	5.27	5.32	5.53
Al^{IV}	-	.01	-	-	-	-	2.73	2.68	2.47
	2.02	2.00	2.01	2.01	2.03	2.03	8.00	8.00	8.00
Al^{VI}	3.95	3.97	3.96	3.97	2.97	3.93	2.72	2.74	2.50
Ti	-	-	-	-	-	-	-	-	.02
Fe^{3+}	-	-	-	-	-	-	-	-	-
Fe^{2+}	1.37	1.48	1.52	1.31	1.57	1.64	4.56	4.65	3.98
Mn	.01	.01	-	.01	.02	.02	.02	.02	-
Zn	-	-	.01	.01	-	-	.03	.02	-
Mg	.65	.56	.52	.71	.40	.39	4.67	4.56	5.48
	6.00	6.02	6.01	6.01	5.96	5.98	12.00	11.99	11.98

CHAPTER V

Geological map of Greece: The island of Ios.

by P.A. van der Maar and J.B.H. Jansen
(in press, Inst. of Geol. and Mineral Explor., Athens).

Legend of the Geological and Petrological map of the island of Ios

QUATERNARY

RECENT

al

Alluvium

Coastal plains and terraces, composed of sand, silt and gravel. The deposit occasionally is conglomeratic with a sandy matrix. Layers rich in pumice are found at several places in the deposit. The top of the terraces reaches about 5 m above sea level. Maximum thickness about 10 m.

Unconformity

PLEISTOCENE (probably)

cs

Cemented plain and slope deposits

Components, mainly marble, glaucophane schist, actinolite schist and chlorite schist in a reddish-brown carbonate matrix. In these deposits the fossil Helix is found. Maximum thickness about 40 m.

Unconformity

METAMORPHIC COMPLEX

GREENSCHIST FACIES METAMORPHISM of relatively high pressure (stilpnomelane).

HYDROTHERMAL ACTIVITY

q

Quartz lenses

Mostly occuring in the basement of the island. Milky quartz lenses occasionally contain some tourmaline. Along the margins of the lenses enrichments of chlorite and albite are observed, which are typical for the greenschist facies metamorphism. The major lens, situated in the centre of the augengneiss dome has been mined. Maximum dimensions are 20 x 100 metres.

OPHIOLITE SUITE, upper allochthonous unit.

MB

Metabasite

Consisting of chlorite, sericite and heavily altered amphibole and plagioclase. Epidote, calcite and albite replace the plagioclase; chlorite and hematite replace the amphibole. It is highly brecciated and veined throughout with quartz and calcite. The texture and mineral composition suggests a basite metamorphosed in greenschist facies. The only occurence is on the peninsula Kumbara in the extreme western part of the island.

Unconformity

GLAUCOPHANE SCHIST FACIES METAMORPHISM

MARBLE-SCHIST FORMATION, assumed to be the lower allochthonous unit, presumably of Mesozoïc sedimentary age. The formation yields an Alpine metamorphic age of about 43 Ma.

m

Marble

Generally the marble beds have no massive character and are in fact series of marble and thin schist layers. The maximum thickness (about 100 m) is reached on the Plakotó mountain. Strong lateral variations in thickness and in appearance are normal. The strikes and dips in the marbles follow the general dome structure and the lineations show a N-S pattern. In the north-west the marbles are in slightly overturned position (Akra Aspros Gremnos). The marble beds are calcitic as well as dolomitic. Locally they can be micaceous or bright red due to dispersed hematite. Coating by limonite and goethite also occurs. Hematite/ limonite pseudomorphs after pyrite in cubes as well as in pentagondodecaëdrons are found. Small quartz lenses up to a few tens of centimetres are found in the dolomitic marbles without any neoformation of tremolite or talc.

The two next rocktypes are restricted to the marbles in the northern part of the island.

D

Diasporites

The metabauxite lenses are up to 2 meter thick and occur in several marble beds. They are strongly folded. Their mineralogical association is diaspore-chloritoid-hematite-margarite-"columnar"calcite (supposedly pseudomorphic after aragonite)- and sometimes minor apatite and rutile. Some diasporites contain epidote and probably secondary kaolinite.

In one lens the association diaspore-kyanite-chloritoid-calcite-hematite-rutile has been found.

⚒ Fe

Fe-rich bodies

Three occurences have been found in the marble beds. The maximum size is 30 x 30 m. The lenses in the East and on the Plakotó mountain have been mined. The wéstern occurence is very small and consists of finegrained magnetite and hematite. Apart from Fe-oxides and secondary limonite the two major lenses contain the association omphacite-riebeckite-garnet-epidote-calcite and quartz. Muscovite, dark brown calcite, traces of malachite and azurite were also found as well as hematite pseudomorphs in pentagondodecaëdrons after pyrite.

ach

Albite-chlorite schist

Two zones are mapped. In the western part of the island a zone occurs in the lowest marble bed. It mainly consists of albite-chlorite-quartz-muscovite-epidote, sometimes with minor actinolite and apatite-sphene and ore minerals as accessory minerals. The zone locally contains albite-chlorite-epidote schist with red coloured quartz and hematite blades and chlorite schist with brown carbonate associated with fuchsite. In the northern zone the albite-chlorite-quartz schists contain several brown carbonate lenses with fuchsite. In one of the lenses the carbonate is associated with talc (Tc). In the western part of the northern zone a peculiar schist (bm) and a major quartz lens (q) are observed.

bm

Biotite-magnetite schist

Within the albite-chlorite schist a lens, consisting of biotite, phengite and magnetite is found, which measures about 100 m along strike.

a

Actinolite schist

It is a finegrained schist consisting of actinolite-quartz-albite-muscovite (phengite)-chlorite in the north-western part of the island. In the south-eastern part of the island a coarse-grained, garnet-bearing actinolite schist is found with minor tourmaline. The two actinolite schist units are lithologically more or less equivalent, although their stratigraphic correlation seems improbable.

ch

Chlorite-albite schist

In general the schist contains chlorite-albite-phengite-quartz-epidote. Locally carbonate, actinolite, garnet and glaucophane are observed. Two zones of the schist are mapped, both are laterally variable in mineralogical content. In the extreme western part the lower zone consists of practically pure actinolite (a_2). Eastward the actinolite disappears and the zone becomes moderately glaucophane-bearing for about 500 m along strike (gl_2). From the Plakotó mountain eastward the zone is again glaucophane-bearing (gl_2) and very locally weakly actinolite-bearing (a_2). Glaucophane as well as crossite crystals occur in the glaucophane-bearing parts, both showing a weak, often zonal pleochroism. They frequently become actinolitic towards the rims. Garnet occurs in the actinolite-bearing part and in those glaucophane-bearing parts, where the glaucophane crystals have an actinolitic rim. On Plakotó mountain a string of glaucophane rock is found (gl_1). The upper zone consists mainly of chlorite-albite schist with phengite, epidote and quartz. A few occurences of glaucophane-bearing schists (gl_2) and of actinolite-bearing schist (a_2) with garnet are found in the upper zone. A stretched body of about 1 km along strike is composed of chlorite schist with meta-ultramafic lenses (chu). The thickness of the upper zone is considerable and decreases towards the east.

a2

Actinolite-bearing parts

Are indicated on the map. They are observed in chlorite-albite schist and glaucophane schist.

gl2

Glaucophane-bearing parts

Are indicated on the map. They are only observed in the chlorite-albite schist.

chu

Chlorite schist

With metamorphosed ultramafic and mafic bodies. Separate, more or less monomineralic bodies of actinolite, talc and antigorite occur in this schist and have a radial pattern due to the oriented positions of the minerals. The maximum size of the bodies is about 0,5 m in diameter. The chlorite schist contains brown carbonate boulders with fuchsite and lenses of actinolite-chlorite-fuchsite-muscovite-zoisite-carbonate schist with minor quartz and occasionally garnet. In the last mentioned schist as well as in the surrounding chlorite schist pseudomorphs after lawsonite are found. The lawsonite is replaced by zoisite, muscovite, fuchsite, carbonate and actinolite.

gl1

Glaucophane rock

Composed of glaucophane, crossite, garnet, magnetite, calcite (columnar), epidote, with minor chlorite (secondary around garnet), apatite and sphene. These individual minerals tend to be concentrated in monomineralic "Schlieren". In the garnet-rich parts some albite has been found. The glaucophane and more abundant crossite have a zonal pleochroism and they sometimes become actinolitic towards the rims. In fact the rock is exposed as zone of separate rounded blocks with maximum diameter of 3 m in the enveloping glaucophane-bearing chlorite-albite schist (gl_2).

gl

Glaucophane schist

Contains glaucophane, crossite, albite, phengite, paragonite, quartz with accessory minerals apatite, sphene and ore. Garnet occurs, but not together with the assemblage albite plus glaucophane. Biotite is sometimes observed around the glaucophane and garnet. Relicts of chloritoid are found in the glaucophane and garnet crystals. Actinolite rims around the glaucophane are rare; in some places the schist is actinolite-bearing with garnet (a_2). The amphiboles and epidotes often show zonal pleochroism with a darker rim. The base of the glaucophane schist zone is formed by a white phengite-paragonite-carbonate-quartz schist with well developed glaucophane megacrysts. Three bodies of omphacite-riebeckite rock are found in this zone (OR).

OR

Omphacite-riebeckite rocks

Located in the western part of the island; consist of omphacite (finegrained), riebeckite, carbonate (columnar), magnetite, garnet, epidote with minor hematite, apatite and sphene. The bodies of this rock often show metasomatic outward zoning of the following mineral assemblages: omphacite-riebeckite centre; omphacite-riebeckite-garnet; garnet-epidote; and epidote-calcite along the margin with the country rock. In the garnet-epidote assemblage zone the secondary mineral stilpnomelane is observed. The bodies are more folded than the enveloping country rock and have a dinstinctively more massive character. The maximum size is about 3 by 4 m.

Tc

Talc lens

An isolated lens of talc is associated with chlorite, brown carbonate and fuchsite and located in the north-western part of the island.

Unconformity?

BASEMENT

Existing before the glaucophane schist facies metamorphism. Upon this basement the marble-schist formation is emplaced.

γ

Metamorphosed intrusive bodies

Are metagranites consisting of albite, muscovite, biotite, quartz with minor apatite and ore minerals. The eight bodies are grouped in five types: γ 1, γ 2 and γ 3 are situated in the northern garnet-mica schist zone.

A common feature of these bodies is the occurrence of biotite lenses up to a few tens of centimetres; γ 4 and γ5 are situated in the augengneiss-complex.

γ 1: The largest body occurs near the culmination of the northdipping anticline of the dome. It especially contains large microcline crystals.

γ 2: Two small bodies are exposed on one of which the main village of the island has been built. The metagranites also contain relicts of brown hornblende and newly formed garnet.

γ 3: Two small bodies are cross-cut by meta-lamprophyres. The primary magmatic mineral content of the meta-lamprophyres is assumed to be biotite, brown hornblende and plagioclase. The metamorphic association consists of muscovite, garnet, chlorite, albite and quartz.

γ 4: One small body near the contact with the garnet-mica schist. It contains biotite as accessory mineral. It resembles the augengneiss but is less lineated and of more massive character. The grainsize is larger than in the surrounding country-rock.

γ5: Two small bodies which have no sharp lithological boundaries with the augengneiss. Besides the already mentioned minerals the southern body also contains garnet surrounded by flakes of biotite.

qa

Albite-quartz gneiss

White-coloured finegrained rocks which occur in two different units. The major western unit consists of albite, quartz and muscovite. The direction of this unit fits the dome structure. The smaller unit consists purely of albite and quartz. Both units seem to be meta-aplites on account of the mineralogical composition, the finegrained texture and the structural occurrence.

og

Augengneiss

Consists of perthitic microcline "augen" (megacrysts) surrounded by albite, muscovite and quartz. The gneiss is sometimes mica-rich especially near the top of the Profitis Elias. The augengneiss locally is equigranular and has a granitic character. The augengneiss is interpreted to be a granite which is intruded in a country rock that later has been metamorphosed to so-called garnet-mica schist. Several different rock-types occur within the gneiss-complex: quartz-albite gneiss (qa); metamorphosed intrusive bodies (γ4, γ5); garnet-mica schist (gm); quartz lenses (q).

Throughout the gneiss-complex the schistosity is in accordance with the dome structure. The N-S lineation displayed by the elongated microcline "augen" and the microfolds in the micas is independent of the strike of the schistosity.

▨ gm

Garnet-mica schists

Are mainly mica-albite-garnet-actinolite-epidote-quartz schists with minor biotite, probably formed during a late metamorphic stage. Occasionally chlorite can be observed around the garnets. Throughout the garnet-mica schist small quartz lenses and tourmaline pods occur. Pegmatitic and aplitic veins are also locally found in the schists.

The N-S lineation displayed in the elongation axes of the quartz and feldspar crystals and in the direction of the preferred orientation of the folded micas is not affected by the strike of the schistosity which follows the pattern of the dome structure. The strong lateral variation in thickness of the northern zone is supposed to be mainly of tectonical origin. The thickness varies between 20 and 500 m. Two occurrences of the schist in the augengneiss are completely enclosed by gneiss and are interpreted to be roof-pendants of the country-rock in a granitic intrusion. They do not differ in mineralogy from the other zones except that they seem to contain more actinolite and tourmaline. The southern garnet-mica schist zone also contains a lot of tourmaline. In the northern zone of the garnet-mica schist several metamorphosed intrusive bodies are distributed (ϒ1, ϒ2, ϒ3). In the western part of the northern zone chloritoid occurs rather close to the contact with the augengneiss. In the uppermost part of the northern zone the schist becomes more chloritic locally with carbonate, limonite and hematite lenses, of which a few are indicated on the Map (He). A type of greenschist (a_1) is also mapped in this upperpart of the zone. The occurrence of peculiar rocktypes in the uppermost part of the garnet-mica schist zone and the assumed tectonic origin of the strong lateral variation in the thickness are arguments to suppose that the marble-schist formation was tectonically emplaced along a thrustplane during glaucophane schist facies metamorphism.

a1

Actinolite-garnet schist

Occurs in the garnet-mica schist zone close to the contact with the marble-schist formation. It contains the same minerals as the garnet-mica schist but it has a completely different texture. It consists of an equigranular finegrained groundmass with actinolite megacrysts (up to 1 cm). The maximum thickness is about 10 m.

✶ He

Hematite lenses

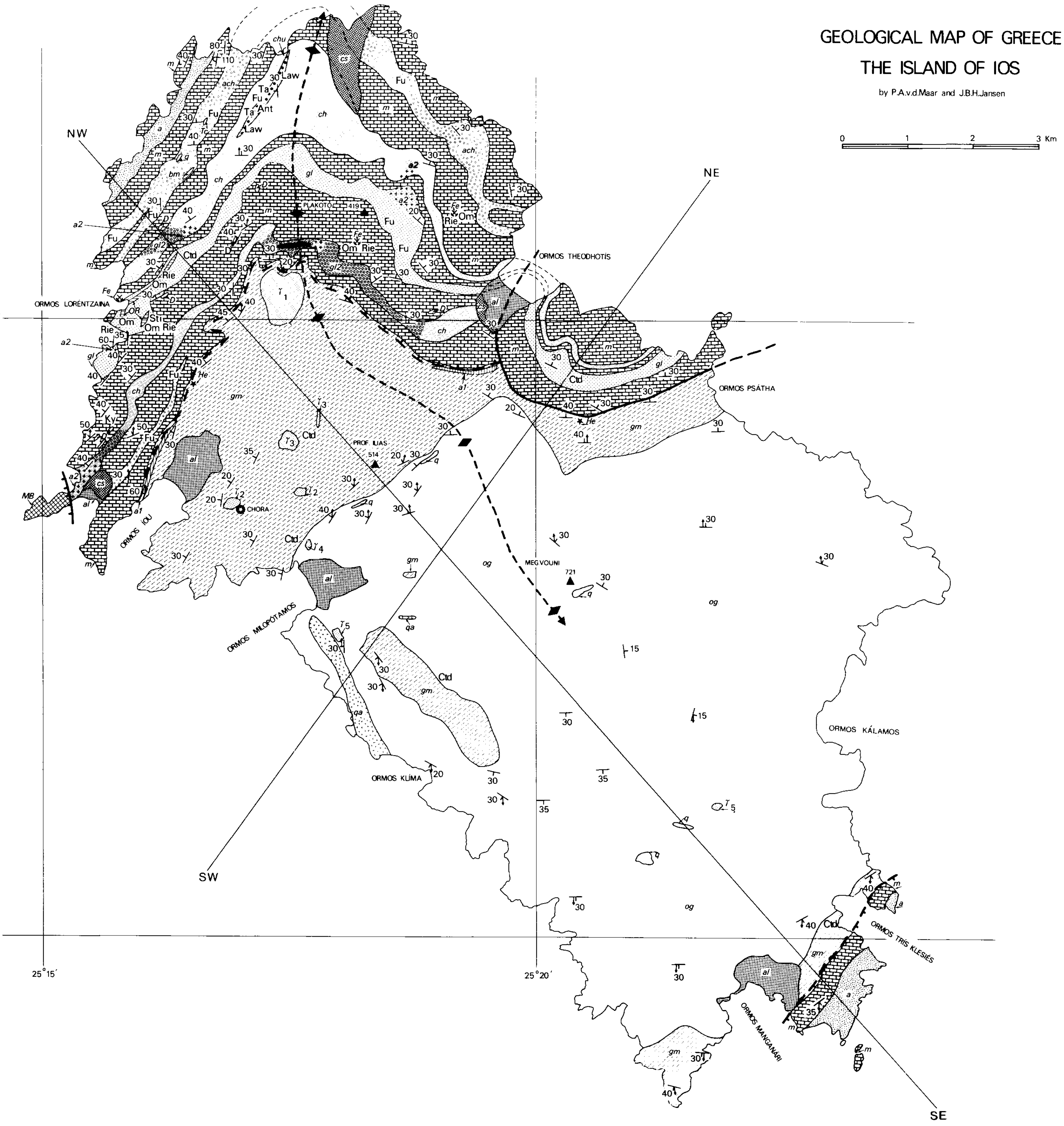
Contain a lot of limonite and goethite. The maximum thickness is about 5 m.

CURRICULUM VITAE

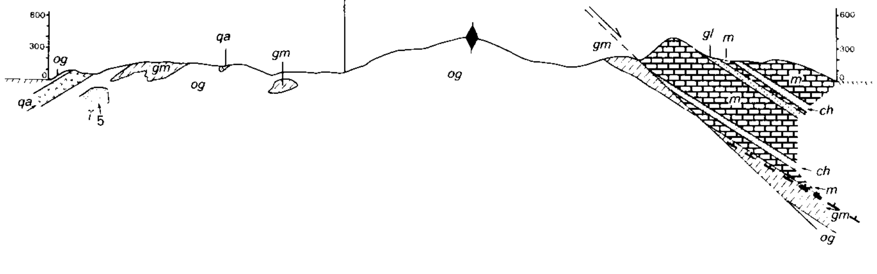
De schrijver van dit proefschrift behaalde in 1966 het diploma H.B.S.-B aan de Gemeentelijke H.B.S. (thans Scholengemeenschap de Bataafse Kamp) in Hengelo (O). In hetzelfde jaar werd een aanvang gemaakt met de studie in de Geologie aan de Rijksuniversiteit Utrecht. In 1971 behaalde hij het kandidaatsexamen G 2 (plus thermodynamica) en in 1978 legde hij het doktoraalexamen geologie af met het hoofdvak Geochemie en de bijvakken Petrologie, Strukturele Geologie en Toegepaste Geologie. Sinds 1976 werkt de schrijver aan een artikelenserie die mede de grondslag vormt van dit proefschrift. Van april 1979 tot januari 1981 was hij als wetenschappelijk medewerker verbonden aan de afdeling Geochemie van de Rijksuniversiteit Utrecht; vanaf april 1980 als programmeur voor de elektronen mikrosonde van de voornoemde afdeling.

GEOLOGICAL MAP OF GREECE
THE ISLAND OF IOS

by P.A.v.d.Maar and J.B.H.Jansen



IOS : cross section NE-SW



IOS : cross section NW-SE