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PRE-ALPINE ORIGIN OF TECTONIC UNITS FROM THE METAMORPHIC COMPLEX OF NAXOS, GREECE, IDENTIFIED BY SINGLE ZIRCON Pb/Pb DATING

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ABSTRACT

Single zircon Pb/Pb ages of gneisses from different tectonic units are used to constrain the origin of the metamorphic complex of Naxos. Three distinct magmatic episodes are documented in the orthogneisses. According to their structural position, the lower unit is a migmatite with a magmatic age of 275±3 Ma, overlain by a tectonic unit containing a gneiss with an intrusion age of 233±2 Ma. The unit above includes an augengneiss with an igneous formation age of 316±4 Ma. This distribution of ages supports the nappe structure of the metamorphic complex. Zircon ages of the structurally interlayered metasediments range from 303 Ma to 1841 Ma. The ca. 300 Ma old zircons might be derived from gneisses such as those found this study. However, the source of the Proterozoic zircons remains enigmatic.

KEY WORDS: Attic-Cycladic massif, Naxos, Greece, pre-alpine basement, zircon geochronology

1. INTRODUCTION

The Cycladic islands in the Aegean sea are part of the Attic-Cycladic massif. The occurrences in this crystalline basement extend from the Pelagonian Zone in N Greece to the Menderes massif in W Turkey, and are considered to build up the median part of the Hellenides (Dürr 1986, Jacobshagen 1986). Alpine deformation, along with HP-LT metamorphism during the Eocene, as well as Barrow-type metamorphism and intrusion of granitoids during the late Oligocene and Miocene (Altherr et al. 1982), largely control the geological architecture. However, on some of the Cyclades such as Naxos, Paros, Ios and Sikinos, the pre-alpine basement could be identified despite the severe alpine overprint.

The origin of this pre-alpine basement is poorly constrained. An investigation of gneisses from Ios by Henjes-Kunst & Kreuzer (1982) gave Rb-Sr ages of ca. 500 Ma (Sr_i= 0.708), which they interpreted as an intrusion age, and U-Pb zircon ages of ca. 300 Ma, which they considered as the age of metamorphism. Andriessen et al. (1987) analyzed gneisses from Naxos which yielded a 372 +28/-24 Ma U/Pb zircon age. They also dated gneisses from Sikinos at 275±87 Ma using the Rb-Sr whole-rock method (Sr_i=0.714). These age data and the Sr initial ratios suggest a long-lasting Palaeozoic or Precambrian crustal history for the pre-alpine basement.

In this contribution I will focus on the geochronology of the island of Naxos by single zircon Pb/Pb dating. The aim is to unravel the age relations of the pre-alpine basement occurrences of Naxos, and to discuss implications for the tectonic evolution of the island and the Attic-Cycladic massif, with possible consequences for the interpretation of the geology of the Aegean region.

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2. GEOLOGICAL BACKGROUND

The metamorphic part of the central Aegean island of Naxos can be described as a metamorphic core complex exhumed during alpine processes. The core of the complex is built up by a locally migmatized granitic gneiss, surrounded by an envelope of mainly gneisses and amphibolites in the lower part and a unit of schists and marbles in the upper part (Jansen 1973 and 1976, Dürr 1986, Strumpf 1995). Due to intense folding and shearing, original field relations are now tectonically obliterated. Nevertheless, it is possible to characterize the following distinct rock assemblages.

The migmatite dome forms the lowermost unit. It contains big bodies of marbles and minor amphibolites, but the prevailing rock type is a leucocratic gneiss. Towards the centre, the layering of the gneisses is gradually replaced by the diffuse migmatitic structures that are probably related to the alpine (Oligocene/Miocene?) uplift of the dome. S-type and I-type granites and frequent pegmatites intruded the migmatite. If the correlation of these granites to the Naxos granite is correct, their age is ca. 11 Ma (Keay, 1998).

The next tectonic unit to the hangingwall, separated by small and rare ultramafic lenses (Strumpf 1995), is made up by predominantly leucocratic gneisses and minor amphibolites, but migmatitic structures are lacking.

This tectonic unit is followed by a series of gneisses, amphibolites, a quartzitic schist and an augengneiss. Above the augengneiss a sequence of calcite marble, schist, and amphibolite is exposed. Although this assemblage probably does not represent a formation of common origin, it is treated here as one entity.

The uppermost unit is mainly built up by schists and marbles. Some of the marbles are dolomitic in composition and Triassic in age (Dürr & Flügel 1979). It is within these marbles that the spectacular emery deposits of Naxos occur.

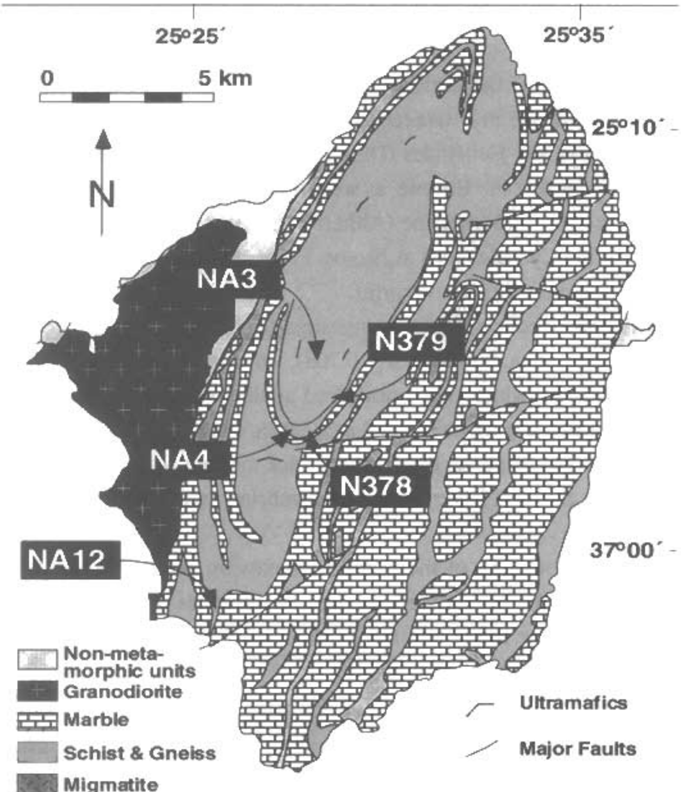

Fig. 1: Simplified geological map of Naxos, modified after Jansen (1973) and Strumpf (1995), showing sample locations.

3. ANALYTICAL METHODS

The samples were crushed using jaw crushers and a roller mill to produce powders of <0.50 mm particle size from which non-magnetic heavy minerals were concentrated using a Wilfley Table, magnetic separator, and heavy liquids. Final hand-picking was done under a binocular microscope where the zircons were chosen for geochronological analysis. Only zircon grains without visible core or inclusions were selected.

The method used in this study is the Pb/Pb single-grain evaporation method (Kober 1987) that involves the repeated evaporation and deposition of Pb from chemically untreated zircons in a double-filament arrangement. The mass-spectrometer used for this analysis was a Finnigan MAT 261 at the Max-Planck-Institut für Chemie in Mainz. The ratios were measured on a secondary electron multiplier.

During the analyses evaporation temperatures were increased to control whether changes occurred in the $^{207}Pb/^{206}Pb$ ratios, i.e. whether the zircon grains contained inherited parts or domains of partial Pb loss. The $^{207}Pb/^{206}Pb$ ratios were corrected for common Pb after Stacey and Kramers (1975). No correction was made for mass fractionation, which is significantly less than the uncertainty of the measured isotope ratios (Kober 1987). More details of the method are given in Reischmann and Anthes (1996). The age calculations were performed using the decay constants of Steiger and Jäger (1977). Errors for the individual zircon measurements and for the mean ages of the samples are given as 2-sigma of the mean. The analytical data are listed in Table 1.

4. GEOCHRONOLOGICAL RESULTS

Sample NA3 from the migmatite core was taken at the road cut between the villages of Potamia and Chalki in the southern part of the dome. The gneiss is leucocratic with quartz, feldspars, biotite, and muscovite as major minerals and tourmaline as a rare accessory phase. Zircons of this migmatite gneiss in general are yellowish, pink or colourless and mainly clear, but turbid or metamict grains were also found. Their length is up to 0.35 mm but the prevailing size is <0.200mm. The morphologies are characterized by pyramids with (101)>(211), whereas in the prisms both planes, the (100) plane and the (110), are well developed, as is visible in the scanning electron miroscope (SEM) photograph (Fig. 2). The most frequent types belong to S9 and S20, according to Pupin & Turco (1975). The cathodoluminescence (CL) study revealed magmatic zoning in all investigated crystals. Some show inherited cores (Fig. 3). It is noteworthy that such cores can clearly be detected by CL. However, in an optical microscope they might be hard to identify. The ages obtained from this sample range from 271 Ma to 314 Ma. Most of the grains cluster around 275±3Ma (Fig. 4), which is suggested to be the intrusion age of the magmatic protolith of the migmatite. Two grains, however, have a more complex isotopic composition. In a second evaporation step at higher temperatures, in which the internal part of the zircon is preferentially analyzed, their ages tend to be higher. This can be interpreted as an effect of an older core inside the zircon crystal. In grain B the age difference is only 13 Ma and it is difficult to decide whether this age difference is really significant. Grain D gave ages of 289±4 Ma and 314±4 Ma. This difference is significant and the most plausible explanation is that the 314 Ma is the age of an inherited core. The coincidence with the age of sample NA4 might be fortuitous, but, on the other hand, a relation to the other gneisses from the island is not unrealistic.

Sample NA379 is a medium grained, grey gneiss that occurs as layers within the various schists south of the migmatite dome. The mineral assemblage is typical for most gneisses of the island, with quartz, feldspars, biotite and muscovite. However, in contrast to sample NA4, the feldspar augen are missing. The sample was taken ca. 1.5 km SW of the village of Chalki.

The zircons of this sample belong to two populations, according to their morphologies. One group is long-prismatic and up to 0.200 mm in size. These grains are predominantly clear, and yellowish or colourless. The zircons of the other group are grey and turbid, and characterized by a short-prismatic morphology with dominating (100) in the prism and large (101) in the pyramid terminations. The (110) and the (211) planes are [illegible] can be missing completely which causes an octahedral shape (Fig. 2). These zircons are bigger than the others and can reach 0.5 mm in size. Interestingly, the internal structure appears to be diffuse or metamict in the CL photograph, where magmatic zoning is only detectable in the outermost rim (Fig. 3).

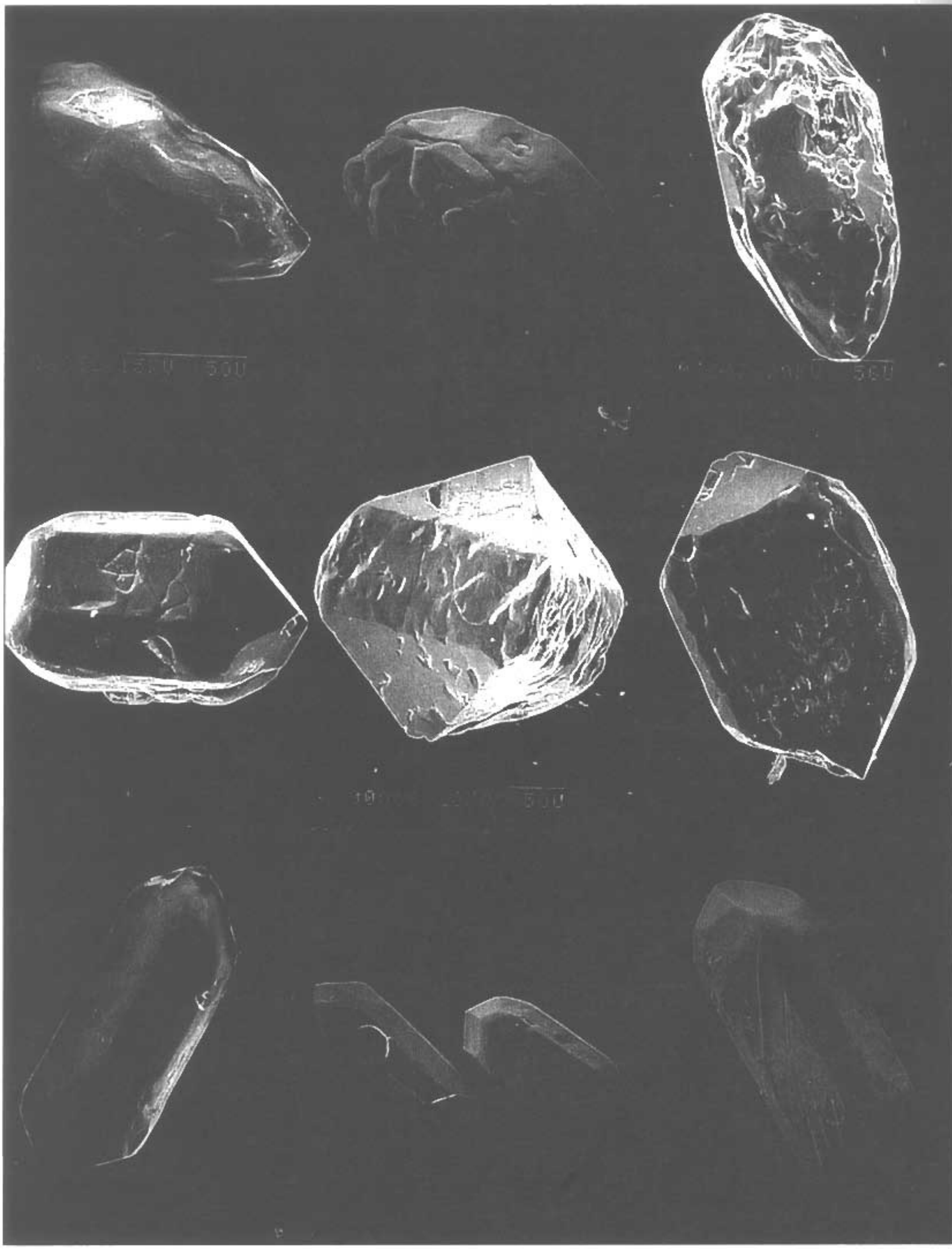

Fig. 2: SEM photographs of typical zircons from Naxos. From left to right. Top row: NA12, N378, N378. Centre N378, N379, N379. Bottom row: NA3, NA3, NA4.

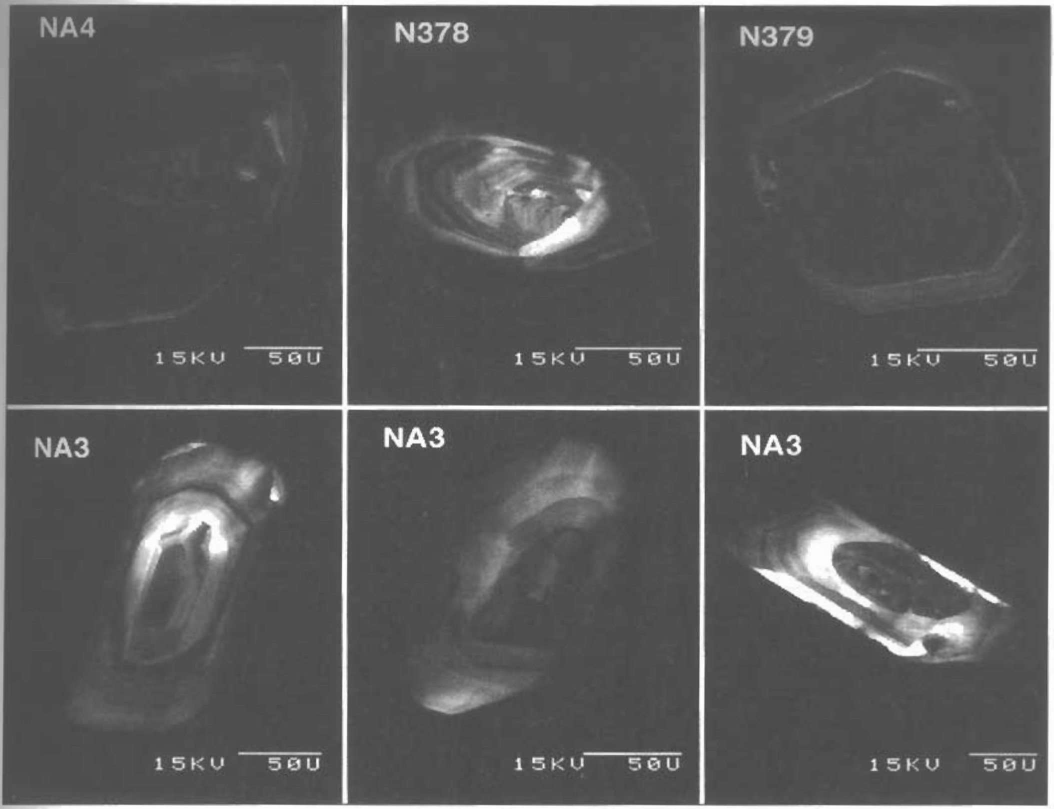

Fig. 3: Cathodoluminescence photographs of typical zircons from Naxos.

The zircons of this sample yield a mean age of 233±2 Ma (Fig. 4) which is taken as the intrusion age of the igneous precursor of the gneiss. One outlier is much younger with an age of 157±3 Ma. The bearing of this age is uncertain, probably it is caused by partial Pb loss or it is a mixed age of different domains of the analyzed grain. The two older grains of 258±3 Ma and 263±3 Ma are interpreted as mixed ages indicating the involvement of older cores of unknown age.

The quartzitic gneiss NA378 forms a marker horizon in the southern central part of the island where it can be followed for several kilometers. It is a few meters thick and light yellow-brownish in colour. Quartz, variable amounts of feldspars and white mica are the prevailing minerals. This metasediment was taken 2 km SW of the village of Chalki.

The zircon population is heterogeneous and comprises predominantly small grains < 0.150 mm. Only a few can reach up to 0.3 mm. Most of the zircon grains are typically detrital with rounded shape and pitted surface (Fig. 2 and 3). These zircons are colourless and translucent, or clear. Some rare grains, also clear and colourless, are multi-facetted, as is typical for a metamorphic origin.

The zircons measured show a wide age range. All three grains yielded different ages with different heating steps, always with older ages when the internal part of the zircon was analyzed at higher evaporation temperatures. These zircons are not single domain crystals with respect to their Pb isotopes, but rather must be regarded as composite grains. Measurements of the first evaporation step gave 327±3 Ma, 316±15 Ma, and 303±4 Ma (Fig. 4). Such ages of ca. 300 Ma are found in some rocks, such as sample NA4. This coincidence might imply that the granites of the NA4-type were one source of this metasediment. Consequently, the deposition of the sediment took place after ca. 300 Ma. Ages from the internal parts of the zircons range from 363±3 Ma to 1841±3 Ma and document a hitherto unknown Palaeozoic and even Proterozoic source region.

Table 1: Results of single zircon evaporation analyses

Sample		Temp. C	Ratios	207Pb/206Pb	2sm *10e-6	Age (Ma)	2sm	n
N378								
A.1	150, c, w, ps	1422	147	0.052946	58	327	3	
A.2		1453	97	0.056009	181	453	7	
B.1	100, c, w, mf	1415	39	0.052708	338	316	15	
B.2		1464	74	0.068455	393	882	12	
B.3		1493	135	0.112556	161	1841	3	
C.1	300, c, y, ps	1446	95	0.052412	90	303	4	
C.2		1485	139	0.053818	67	363	3	
N379								
A.1	200, c, y	1411	99	0.050964	149	239	7$	
A.2		1437	180	0.050834	43	233	2$	
A total			279	0.050880	61	236	3	
B	200, t, p	1488	178	0.049174	67	157	3$	
C	250, t, g	1530	96	0.050893	42	236	2	
D	200, c, y	1488	138	0.050815	63	233	3	
E	150, c, y	1431	80	0.050804	86	232	4	
F	200, c, y	1490	369	0.050790	41	231	2	
G	200, c, p	1524	95	0.058440	170	234	8	
H	300, t, g	1530	193	0.051499	57	263	3$	
I	200, t, g	1460	131	0.050713	51	228	2	
J.1	200, t , g	1490	75	0.050857	91	234	4	
J.2			280	0.051390	66	258	3$	
K	300, t, p	1464	75	0.050788	187	231	9	
	mean of A, C, D, E, F, G, I, J.1, K							
233	**2**	**9**						
NA3								
A	200, t, w	1520	145	0.051675	133	271	6	
B.1	200, t, w, m	1476	135	0.051824	120	278	5	
B.2		1512	181	0.052121	108	291	5$	
C	200, c, w	1500	93	0.051769	160	275	7	
D.1	300, c, p	1427	153	0.052069	86	289	4$	
D.2		1450	175	0.052658	100	314	4$	
E	250, c, y	1468	72	0.051786	163	276	7	
	mean of A, B.1, C, E						**275**	**3**
4								
NA4								
A.1	320, c, p	1470	97	0.052511	93	308	4$	
A.2		1500	116	0.052524	113	308	5$	
A total			213	0.052518	75	308	3	
B	300, c, p	1450	116	0.052740	64	318	3	
C	350, c, p	1534	65	0.053384	153	345	7$	
D	400, c, p	1500	176	0.052891	47	324	2	
E	300, c, w	1480	116	0.052634	85	313	4	
F	250, c, p	1470	211	0.052736	45	318	2	

Sample		Temp. C	Ratios	207Pb/206Pb	2sm *10e-6	Age (Ma)	2sm	n
G	400, c, p	1480	72	0.052707	122	316	5	
H	250, c, y	1440	151	0.052749	74	318	3	
	Mean of A, B, D, E, F, G, H							
316	**4**	**7**						
	Mean of B, E, F, G, H						**316**	**2**
5								
NA12								
A	200, c, y	1510	72	0.067986	133	868	4	
B	150, c, y	1530	36	0.084377	250	1301	6	
C	250, c, p, ps	1520	140	0.072935	53	1012	2	
D	200, c, p	1500	53	0.074206	99	1047	3	
E	200, c, p, ps	1500	40	0.074569	109	1057	3	

Abbreviations: c=clear, t=turbid, y=yellow, r=red, p=pink, w=white, mf= multi-facetted, m= metamict, ps = pitted surface, §=not used for average calculation

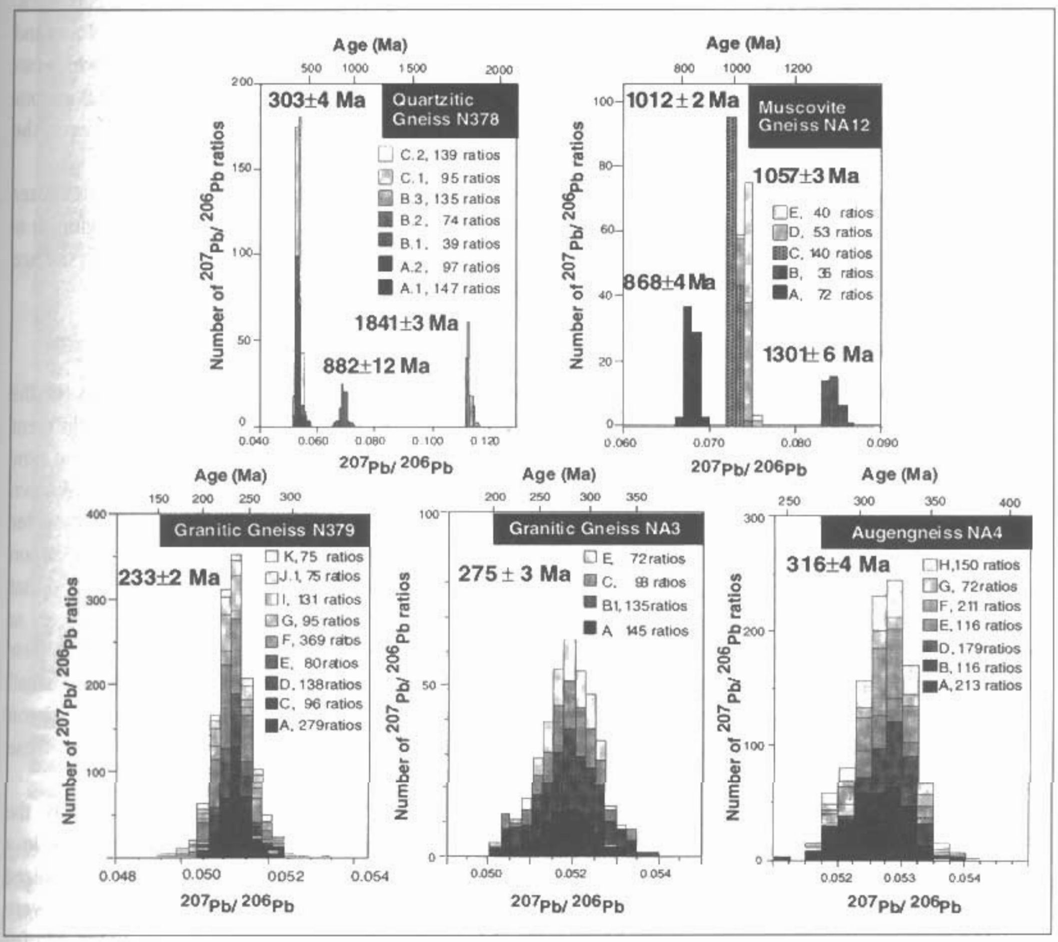

Fig. 4: Histogram showing the results of the $^{207}Pb/^{206}Pb$ single zircon analyses of the samples from Naxos.

The augengneiss sample NA4 was taken at the road cut between the villages of Sangri and Chalki. It is a coarse-grained, grey augengneiss with some brownish iron oxides as precipitates along the schistosity planes. This rock type is an orthogneiss that is geochemically characterized as a granite with S-type affinities. The gneiss now forms a tectonic slice between schists, marbles, and amphibolites and the quartzitic gneiss layer from which N378 was taken. Besides quartz, K-feldspar and plagioclase, it contains muscovite and biotite as major constituents. Frequent accessories are, among others, magnetite, apatite, zircon and in some cases tourmaline.

The zircons of this augengneiss are long-prismatic with typical igneous morphologies (Fig. 2). These grains have an internal igneous zonation that is clearly visible in the CL photographs and underlines their magmatic origin (Fig. 3). Some of the zircons have an inherited core inside.

The ages of the zircon grains analyzed scatter from 308-345 Ma. The most frequent ages of 7 grains are around 316±4 Ma (Fig. 4), which is interpreted as the mean age of zircon growth and thus as the intrusion age of the granite that was later deformed to become an augengneiss. It is noteworthy that some individual ages have smaller uncertainties than the scatter of the whole population. The range from 308-324 Ma might be an indication of a more complex Pb-isotope history, and infer that the population is not homogeneous. Pb-loss or inherited cores could be the reason for such an age distribution. The mean of the 5 zircon grains with a normal distribution is 316±2 Ma. The oldest age of grain C of 345±7 Ma is interpreted as the age of an inherited grain or as a mixture of the crystallisation age and the age of a core.

The gneiss sample NA12 is a grey muscovite-rich gneiss. It was taken in the SW corner of Naxos, ca. 1 km NE of the bay of Pyrgaki. The zircons of this sample display a variety of morphologies, colours and grain sizes. Some of the zircons have rounded terminations instead of angular, sharp pyramids, which can be taken as an argument for their sedimentary origin. Pitted surfaces, which characterize detrital zircons and are found frequently in the quartzitic gneiss N378 are not recognized in this sample. However, the zircon population agrees with a sedimentary origin of the gneiss sample.

The ages measured in this sample scatter from 868±4 Ma to 1301±6 Ma (Fig. 4). Three grains cluster between 1012±2 Ma and 1057±3 Ma, which might indicate the age range of a distinct source region. It is impossible to draw any conclusion on the deposition age of the sedimentary precursor. However, the age of the source region can clearly be identified as Precambrian.

5. DISCUSSION AND CONCLUSIONS

The ages of the crystalline basement found in this study have some important consequences for the understanding of the evolution of the Cyclades. The first point concerns the age relation of the different rock units. The orthogneisses dated in this study belong to a pre-alpine basement. The gneisses that now form tectonic slices between metasediments were derived from granitoids that intruded into an unknown country-rock during late Palaeozoic to early Mesozoic magmatic episodes. The data available so far indicate three distinct episodes at 316 Ma, 275 Ma, and 233 Ma. The detailed investigation of the zircon morphologies and their internal structures clearly prove that the zircons are of igneous origin and that metamorphic influence is of minor importance. Consequently, the interpretation of the zircon ages as intrusion ages is justified. It is worth mentioning, that the zircons from the different rock units keep their independent age information despite the Tertiary deformation and metamorphism. Although the small number of dated rocks does not allow a final conclusion, it has to be noted that the age of magmatic zircon growth and intrusion of the host rock was in all cases related to a pre-alpine event. Apparently, these magmatic activities seem were separated by some tens of millions of years.

The zircons of the augengneiss have an age of 316±4 Ma. This augengneiss is structurally the uppermost rock of the analyzed orthogneisses. This means that the oldest granitic rocks are now in a higher structural position than the younger orthogneisses. The ca. 316 Ma age has also been recognized recently in Paros (Engel & Reischmann, this volume). Further Carboniferous ages of 302 Ma were reported from the Pelagonian zone in W Macedonia (Mountrakis 1984). A similar age of 302±5 Ma for granodiorites, also from the Pelagonian zone in mainland Greece, was published by Yarwood & Aftalion

(1976). It is therefore evident that the Carboniferous magmatic activity was widespread over large parts of the Aegean region. This Carboniferous magmatism also indicates relations to the crystalline massifs in NE Greece, and possibly to the Sakarya continent in W Turkey. The traditional view that the Menderes massif in W Turkey forms the eastern continuation of the Cyclades (e.g. Dürr, 1986, Jacobshagen 1986) has to be modified for two reasons. First, because the Carboniferous magmatism is not known from the Menderes massif and second, because the main magmatic phase of the Menderes massif of ca. 550 Ma (e.g. Hetzel & Reischmann 1997) cannot be observed on the Cyclades. The late Palaeozoic basement of the Cyclades is therefore not related to the Menderes massif.

New results arising from this geochronological study on the gneisses from Naxos are the 275 Ma and the 233 Ma episodes that previously had not been reported for the Cyclades. The structurally lowermost unit, the migmatite core, yielded an age of 275±3 Ma which is interpreted as the intrusion age of the igneous precursor of the migmatite. This Permian rock, however, has a heterogeneous zircon population, similar to that of the Carboniferous gneiss, which might infer some relation between the two episodes. It is therefore difficult to evaluate, how much rocks of the younger magmatic episodes contribute to the pre-alpine basement. At least, such newly documented magmatic activities are promising targets for further investigations. A detailed resolution of these distinct magmatic events will be the subject of a subsequent study.

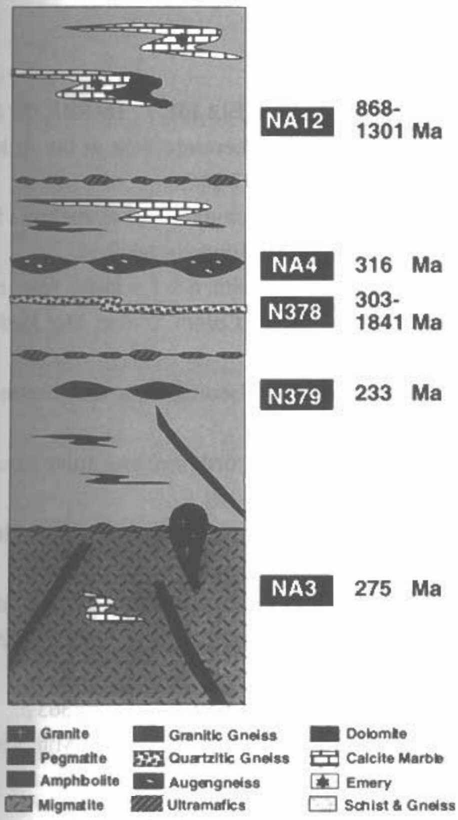

Fig. 5: Structural posistion of the tectonic units of the crystalline complex of Naxos. The tectonic units are separated by horizons decorated with lences of ultramafics. The ages refer to the samples measured in this study.

The Triassic event at 233 Ma is a distinct magmatic episode. Zircons from the granitic gneiss N379 that occurs above the migmatite are 233±2 Ma in age, thus considerably younger than the underlying core. This 233 Ma igneous event is not documented in the core, which implies that at that time the rock units were not in the same close spatial relationship as they are now.

The age distribution strongly supports the view that the metamorphic complex of Naxos is a nappe pile in which sedimentary and igneous rocks of Palaeozoic and Mesozoic age were tectonically juxtaposed to each other (Fig. 5). The view that the ultramafics mark pre-metamorphic thrusts between different nappes was already inferred by Jansen (1976) and Dürr (1986). Because the metamorphic rocks are almost devoid of fossils, this was difficult to prove without radiometric ages. The data of this study support such ideas. Some of the gneisses are of igneous origin since the morphologies and internal structures of the zircon grains clearly favour a magmatic crystallisation. Thus, the interstacking of meta-igneous rocks between meta-sedimentary rocks requires tectonic contacts. Furthermore, the sequence of orthogneisses Permian-Triassic-Carboniferous, again overlain by Triassic dolomites, can only be explained as a nappe pile. The original stratigraphic sequence is therefore difficult to reconstruct.

A further item that is partially constrained by the zircon data is the origin of the metasediments. The ages of the detrital zircons that are characterized by their pitted surface range from ca. 303 Ma to 1841 Ma, which underlines the heterogeneity of the source regions of the metasediments. Interestingly, none of the zircons of the two metasediments was younger than ca. 300 Ma. This might imply that the source regions were older. The ca. 233 Ma and 275 Ma old rocks found on Naxos would then not have contributed to the measured sediments. Instead, the Carboniferous augengneisses could be part of the source. If this is correct, the deposition age would be, roughly, Permian.

The source regions are even more difficult to identify. Due to the heterogeneity of the zircon populations, the ages of the metasediments cannot be taken as formation ages of the source regions. However, it is noteworthy that both samples contain zircons with Proterozoic ages. Such old zircons indicate a significant contribution to the metasediments from Proterozoic sources. The nature and geodynamic position of such source regions remains enigmatic.

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