Geological and geochronological data for Sikinos and Folegandros metamorphic units (Cyclades, Greece): Their tectono-stratigraphic significance

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ABSTRACT

Sikinos and Folegandros islands are comprised of various Mesozoic formations, which are detached on a pre-Alpidic basement. The inherited zircons from both the basement and blueschist series rocks of these islands have been dated by SHRIMP U-Pb geochronology. Zircons from the Sikinos metagranodiorite batholith yielded a range of ages (from ca. 860 to 290 Ma) with a concentration of Carboniferous ages consistent with a link to the Pelagonian basement of continental Greece. Ages of igneous zircons from the metabasic and quartz-chlorite schist samples from Sikinos and Folegandros blueschist units are dominantly Jurassic-Triassic (201±2 to 223±2 Ma) and Triassic (225±3 Ma) respectively. These ages can be related to the remnants of the Pindos or Vardar Neo-Tethyan oceanic crust and igneous activity in continental Greece.

1. INTRODUCTION

The islands of Sikinos and Folegandros belong to the Cycladic Archipelago of the Aegean Sea. The dominant morphological features of these islands are narrow ridges running parallel to the NE-SW and NW-SE directions of the islands respectively.

Sikinos and Folegandros form part of the median tectono-metamorphic Attic-Cycladic Complex, which is composed of an Alpine and pre-Alpidic tectonic pile (Papanikolaou, 1984; 1987). At least two main tectonic units can be recognised within the Alpine metamorphic complex of Cycladic islands (Altherr & Seidel, 1977; Dórr et al., 1978). An upper unit comprised of unmetamorphosed sedimentary and ophiolitic rocks (Rφesler, 1978), and a lower unit of Mesozoic platform sediments consisting of a sequence of metamorphosed neritic carbonates, psammitic to pelitic sediments and basic to acid volcanics (Dórr et al., 1978). Both units are structurally overlying a pre-Alpidic basement, consisting of schist, gneiss and amphibolite with metamorphosed intrusives (Henjes-Kunst & Kreuzer, 1982; van der Maar et al., 1981; Andriessen et al., 1987).

Both the basal and tectonically overlain marble-schist units were affected by intense Alpine metamorphism, in which two phases are recognised (Dórr et al., 1978; van der Maar, 1981; van der Maar et al., 1981). An older high-pressure/medium-temperature, M1 phase, under the blueschist facies conditions during the Eocene, and a younger Barrovian-type, M2 phase, under amphibolite to greenschist facies conditions during the Oligocene/Miocene (Altherr et al., 1979; Andriessen et al., 1979; Bonneau et al., 1980; Altherr et al., 1982).

The purpose of the present study was to re-examine the various tectono-metamorphic units of Sikinos and Folegandros, using the Sensitive High-mass-Resolution Ion MicroProbe (SHRIMP) U-Pb geochronology of zircons, to provide information about the early history of Cycladic crust.

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2.GEOLOGY AND LITHOSTRATIGRAPHIC SUCCESSION

2.1 Sikinos island

Sikinos consists of a sequence of tectono-metamorphic units. At least two major lithostratigraphic units can be distinguished: a basal unit consisting of pre-Alpine dominantly orthogneissic basement, and an upper tectonic unit containing Mesozoic formations that both have been affected by the Alpine orogeny.

a) The basal unit crops out along the SE coasts of the island, and consists of a medium to coarse-grained metagranodiorite intrusion into gneiss and schistose-gneiss.

The metagranodiorite is characterised by a heterogeneous mineralogical composition, with local enrichment of feldspar and Ti-biotite with or without hornblende. In general, the metagranodiorite consists of xenomorphic quartz, plagioclase, K-feldspar (orthoclase, microcline) with rare perthitic exsolutions in the presence of albite and zircon. The gneiss to schistose-gneiss consists of lepidoblastic muscovite layers, and rarely intercalations of biotite, as well as granoblastic quartz, K-feldspar and zircon. The schistose-gneiss differs from the gneiss in having a higher proportion of quartz. Overlying these formations is garnet-mica schist, which is cut by cm-sized aplitic dykes.

The granitoids of this unit, and their country rocks, are polymetamorphics, characterised by pre-Alpine (Variscan) amphibolite Barrovian facies metamorphism with peak temperatures of 570-650°C and pressures of around 5 kbar (Franz et al., 1993) and overprinted by two Alpine (Tertiary) metamorphic events. This pre-Alpidic amphibolite facies metamorphism is characterised by the presence of brown hornblende, passing during the retrograde phase of the Alpine metamorphism to actinolite and chlorite. However, the transformation of white mica into phengite, in these units suggests metamorphism up to blueschist facies took place during the Eocene (Franz et al., 1993).

Rb-Sr whole-rock measurements by Andriessen et al. (1987) from a granitoid intrusion within the Sikinos basement produced an imprecise age of 275±87 Ma. For this reason the crystallisation age of the above metagranodiorite may be re-examined, using the age of precipitation of zircon in the intrusive.

b) The upper unit crops out over the entire northeastern part of the island. As shown in Figure (1A), a tectonic contact separates the basal unit from the overlying upper unit. Metric size lenticular forms of coarse crystalline actinolitic schist mark the tectonic boundary between the two units. Overlying the basement is a tectonically detached glaucophane-bearing marble formation, up to 250 m thick. Overlying this formation is a tectonically emplaced sequence of glaucophane schist alternating with marble horizons, up to 1300 m thick, representing isoclinally folded meta-sediments and meta-volcanics.

The various lithological formations that tectonically overlie the detached glaucophane-bearing marble can be distinguished from base to top as is described below:

Glaucophane schist with cipolin marble (250 to 450 m thick) contains glaucophane, paragonite and chloritoid. In the lower parts of the schist metre-scale lenses of metabasic to greenschist rocks occur, grading to layers of thin-bedded, calcitic cipolin marble with dolomite.

Lower dolomitic marble (up to 200 m thick) medium-to thick-bedded. Locally ankeritized, thick-bedded marble, crosscut by a dense network of calcite veins and Fe-mineralisation, passing in the lower parts to thin-bedded cipolin marble.

Upwards, glaucophane schist with garnet (200 to 250 m thick) occupies a large part of the area extending between Chora and Episcopi. At its base, metabasic lenses (known as prasinites) of metric dimensions occur, while in its intermediate and upper parts it alternates with layers of metabasic schist to greenschist and cipolin marble. The glaucophane schist is characterised by Na-amphiboles, mainly glaucophane and garnet porphyroblasts. The metabasic rocks, with medium-crystalline-blastic texture are composed of albite, epidote, paragonite, chlorite, apatite and zircon.

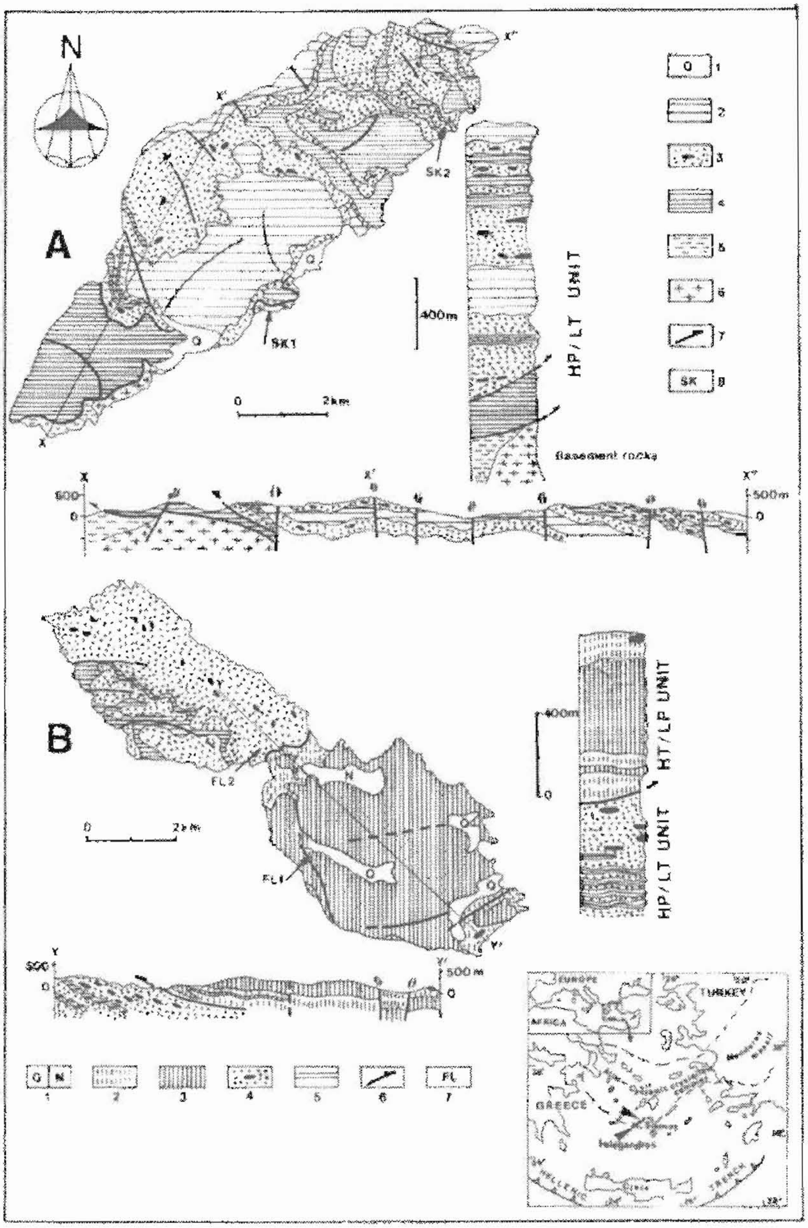

Figure 1. Simplified geological maps of **Sikinos** (**A**) and **Folegandros** (**B**) Islands with their tectono-stratigraphic columns and cross-sections (modified from Avdis & Photiades, 1999).
Sikinos (**A**) 1:alluvial deposits; 2:dolomitic marble; 3:glaucophane schist with metabasalt lenses, eclogite and serpentinite bodies; 4:glaucophane-bearing marble; 5:garnet-mica schist; 6: metagranodiorite and gneiss; 7:tectonic contact (detachment); 8:dated sample. **Folegandros** (**B**) 1:Quaternary and Neogene deposits; 2:schist with serpentinite bodies; 3: calcitic marble; 4:glaucophane schist with metabasalt lenses; 5:marble; 6:tectonic contact (detachment); 7:dated sample.

Table 1. Zircon igneous U-Pb representative analytical results for Sikinos and Folegandros islands
a. Data for Sikinos metagranodiorite sample (SK1).

Grain spot	U(ppm)	Th/U	% Pb	$^{206}Pb/^{238}U$ measured	±1σ	$^{207}Pb/^{206}Pb$ measured	±1σ	Age (Ma)	±1σ	*	Grain area	Des
SK1-1 1	106	0.30	0 17	0.13112	0.00144	0 05401	0 00127	311 2	3 6	1	rim	oz
SK1-2 1	381	0 10	0 10	0.12294	0 00341	0 05354	0 00057	313.8	8 5	1	termination	oz
SK1-2 2	739	0 11	0 04	0.11816	0.00599	0 05404	0.00029	357 2	17 6	1	termination	oz
SK1-3 1	*43*	*0 25*	*5 26*	*0 07528*	*0 00399*	*0 09785*	*0 00883*	*387 5*	*20 9*	*1*	*termination*	*oz*
SK1-5 1	346	0 13	0 40	0 11406	0 00382	0 05675	0 00053	342.4	11 2	1	termination	oz
SK1-5 2	78	0.22	0 14	0 11500	0.00173	0 05396	0 00148	315.0	4 6	1	core	oz
SK1-6 1	1147	0.08	0 52	0 13427	0 00308	0 05739	0 00083	330.7	7 4	1	rim	oz
SK1-7 1	194	0.32	2 74	0 15159	0 00131	0 07573	0 00188	332.6	3 2	1	termination	oz
SK1-8.1	172	0 18	0.07	0 13271	0 00116	0 05370	0 00089	329.1	2 9	1	termination	oz
SK1-9 1	246	0 13	0 14	0 12348	0 00067	0 05436	0 00052	332.6	1 8	1	termination	oz
SK1-10 1	314	0 16	0 04	0 12125	0 00202	0 05283	0 00039	332 9	5 4	1	termination	oz
SK1-11 1	197	0 18	0 08	0 12588	0 00248	0 05352	0.00063	320 3	6 2	1	rim	oz
SK1-12 1	*527*	*0 11*	*0 01*	*0 12045*	*0.00466*	*0.05406*	*0 00074*	*370.5*	*14 0*	*1*	*centre*	*oz*
SK1-13 1	*504*	*0 08*	*0.04*	*0 11336*	*0 00357*	*0 05437*	*0.00048*	*368.5*	*11 4*	*1*	*termination*	*oz*
SK1-14 1	105	0 35	0 68	0 14134	0 00196	0 05839	0.00215	314.5	4 5	1	rim	iz
SK1-15 1	159	0 86	0 19	0 13349	0 00117	0 05418	0.00084	309 6	2 9	1	in rim	oz
SK1-16 1	132	0 13	0 41	0 12413	0 00095	0.05597	0.00068	308.2	2.4	1	rim	oz
SK1-17 1	*193*	*0 03*	*0 51*	*0 37693*	*0 02725*	*0 07215*	*0.00293*	*858.6*	*58 2*	*1*	*core*	*oxc*
SK1-18 1	222	0 13	0.28	0 12087	0 00133	0.05470	0.00133	299.1	3 3	1	rim	oz
SK1-17 1	48	0 45	13 58	0.18486	0 00695	0.16407	0.03393	289.3	10 7	1	core	oz
SK1-18 1	249	0 17	5 25	0.21888	0 00595	0.09649	0.01856	338.2	9 3	1	rim	oz
SK1-19 1	42	0 40	5 91	0 18068	0 00570	0 10085	0.00697	287 3	9 1	1	in rim	oz
SK1-20 1	170	0 18	2 89	0 18511	0 00339	0.07658	0.01818	316.2	5 9	1	rim	oz
SK1-21 1	233	0 12	1 62	0 18149	0 00442	0.06595	0.00723	309.6	7 6	1	rim	oz
SK1-22.1	159	0 19	3 15	0 17623	0 00315	0.07870	0.00709	315 2	5 7	1	rim	oz
SK1-23 1	841	0.06	1 23	0.19668	0.00394	0.06301	0.00159	322 5	6 7	1	termination	oz
SK1-24 1	51	0 30	9 19	0.17167	0.00485	0.12787	0 02339	288 3	8 1	1	core	oz
SK1-25 1	403	0.20	1 71	0.18184	0.00338	0 06663	0.00650	306 1	5 9	1	termination	oz
SK1-26 1	43	0.30	9 08	0.18929	0.00752	0 12720	0 02288	299 8	11 8	1	rim	oz

b. Data for Sikinos metabasic schist sample (SK2).

Grain spot	Uppm	Th/U	% Pb	$^{206}Pb/^{238}U$ measured	±1σ	$^{207}Pb/^{206}Pb$ measured	±1σ	Age (Ma)	±1σ	*	Grain area	Des
SK2-1 1	194	0 52	1 07	0 10012	0 00118	0 05951	0.00198	224 3	2 6	1	core	oz
SK2-1 2	305	0 62	0 22	0 08284	0 00112	0 05252	0.00219	225.6	3 2	1	in rim	oz
SK2-1 3	270	0 54	3 91	0 07039	0 00170	0.08250	0.00856	200.9	5 0	1	edge	oz
SK2-2 1	379	0 63	0 39	0 10544	0 00155	0.05382	0.00150	220 4	3 2	1	rim	oz
SK2-2 2	516	0 47	0 73	0 07496	0 00181	0.05588	0 00186	186.1	4 5	1	rim	oz
SK2-3 1	1196	0 42	3 49	0 03128	0 00089	0.07628	0.00343	65.3	1 9	1	edge	oz
SK2-4 1	345	0 45	0 72	0 10312	0 00155	0 05650	0.00232	219 2	3 2	1	edge	oz
SK2-4 2	788	0 45	1 62	0 08444	0 00112	0.06309	0 00583	180 4	2 4	1	edge	oz
SK2-5.1	2033	0 48	22 11	0 03007	0 00052	0.23038	0 00905	46 5	0 8	1	edge	iz
SK2-6 1	576	0 39	0 88	0 07574	0.00194	0.05707	0.00208	185 1	4 7	1	centre	rz
SK2-7 1	365	0 35	0 99	0 10026	0.00133	0.05833	0 00130	201 1	2 7	1	rim	oz
SK2-8 1	657	0 44	0 82	0 08117	0.00133	0.05659	0 00131	183 8	3 0	1	rim	oz
SK2-9 1	1069	0.34	2 10	0 05778	0.00106	0.06616	0 00971	135 4	2 5	1	centre	iz
SK2-10 1	691	0 63	0 86	0 10245	0 00219	0.05725	0 00180	200 8	4 3	1	rim	oz
SK2-11 1	928	0 60	2 53	0 05665	0 00063	0 06959	0.00554	128.8	1 4	1	rim	iz
SK2-1 1b	1029	0 47	0 85	0 03708	0.00188	0.05448	0.00090	69 5	3.5	1	centre	oz
SK2-2 1b	717	0 37	1.41	0 07075	0.00074	0.06030	0.00174	128 4	1 3	1	edge	oz
SK2-3 1b	575	0 70	0 32	0 07027	0.00259	0.05207	0.00088	162 6	6 0	1	rim	oz
SK2-4 1b	344	0 41	1 25	0 12011	0 00222	0 06058	0.00196	201 5	3 7	1	centre	oz
SK2-5 1b	327	0 58	0 36	0 14586	0 00164	0 05385	0.00107	227 6	2.8	1	edge	oz
SK2-6 1b	429	0 51	1 02	0 10836	0.00232	0 05813	0 00089	177 1	3 8	1	rim	oz

c. Data for Folegandros quartz-chlorite schist sample (FL2).

Grain spot	Uppm	Th/U	% Pb	$^{206}Pb/^{238}U$ measured	±1σ	$^{207}Pb/^{206}Pb$ measured	±1σ	Age (Ma)	±1σ	*	Grain area	Des
FL2-1 1	*397*	*0 03*	*0 20*	*1 09998*	*0.01621*	*0 12575*	*0 00193*	*2022.6*	*32 2*	*3*	*core*	*oz*
FL2-1.2	*348*	*0 10*	*0 10*	*1.25809*	*0.02448*	*0 12718*	*0 00263*	*2044.1*	*38 0*	*3*	*rim*	*oz*
FL2-2 1	*179*	*0 06*	*0 66*	*0.25516*	*0.00634*	*0.06152*	*0 00302*	*451.9*	*11 1*	*1*	*termination*	*oz*
FL2-3 1	*160*	*0 11*	*0 20*	*1.72922*	*0 02682*	*0.20821*	*0 00322*	*2880.1*	*26 2*	*3*	*rim*	*oz*
FL2-4 1	425	0 42	0.25	0.05279	0.00213	0 05305	0.00248	237.1	9 7	1	core	oz
FL2-4 2	151	0 86	0 98	0.07838	0.00323	0 05943	0 00535	249 7	10 1	1	rim	oz
FL2-4 3	92	1 95	2 54	0.06482	0.00351	0 07192	0 00689	215 6	11 5	1	Rim	oz
FL2-5 1	294	0 30	0 30	0.07346	0 00396	0.05794	0 00208	429 7	23 5	1	core	oxc
FL2-5 2	213	0.57	0 75	0.09199	0.00220	0.05864	0 00176	299 2	7 0	1	Rim	oz
FL2-6 1	106	0 49	0.62	0.04189	0.00224	0 05442	0.00488	155 0	8 2	1	Rim	oz
FL2-6 2	97	0 78	1.36	0 05568	0 00248	0 06102	0.00382	172 1	7 6	1	core	oz
FL2-7 1	743	0 26	0 57	0.06248	0.00168	0 05530	0.00198	218 0	5 8	1	Rim	oz
FL2-7 2	151	0 61	1 05	0.08685	0 00125	0.06019	0.00190	255 1	3 6	1	core	oz
FL2-8 1	*106*	*0 44*	*0 50*	*0 41273*	*0.01076*	*0.09191*	*0 00222*	*1373 3*	*84 1*	*3*	*core*	*ixc*
FL2-8.2	*433*	*0 19*	*1 53*	*0.27761*	*0.01453*	*0 08185*	*0.00245*	*904 5*	*44 3*	*1*	*Rim*	*oz*
FL2-9.1	607	0 37	5 53	0.01955	0 00275	0.09469	0.01628	91 3	12 8	1	termination	oz
FL2-9.2	692	0 52	0.53	0 04438	0 00079	0.05330	0.00134	138 0	2 4	1	core	iz
FL2-10.1	*354*	*0 57*	*0 20*	*0 50487*	*0 01382*	*0.20801*	*0 00179*	*2879.9*	*15 2*	*3*	*core*	*oz*
FL2-11.1	736	0 61	0.75	0 06923	0 00111	0.05708	0.00177	229.9	3 7	1	Rim	uol
FL2-11 2	38	0 68	3.51	0 07802	0.00473	0 08038	0.00732	230.3	13.7	1	in rim	oz
FL2-12 1	*496*	*0 47*	*0 30*	*0 32396*	*0 04548*	*0.19082*	*0 00500*	*2732 6*	*47.6*	*3*	*termination*	*oz*
FL2-13 1	*644*	*0 19*	*0 58*	*0 14286*	*0 01110*	*0.05927*	*0 00115*	*744 8*	*55.6*	*1*	*Rim*	*oz*
FL2-14 1	*553*	*0 11*	*0 70*	*0.17194*	*0.00226*	*0.06311*	*0.00121*	*502.0*	*6 4*	*1*	*Rim*	*oz*
FL2-15 1	*226*	*0 29*	*8.89*	*0.22729*	*0.00535*	*0 13242*	*0.00114*	*529.6*	*12 1*	*1*	*Rim*	*oz*
FL2-16 1	*44*	*0 48*	*7 66*	*0 22729*	*0.00535*	*0 12231*	*0 00428*	*536 4*	*12 3*	*1*	*Rim*	*oz*
FL2-17 1	*123*	*0 16*	*1 41*	*0.22729*	*0 00535*	*0 07095*	*0.00255*	*571 2*	*13 0*	*1*	*Rim*	*oz*
FL2-18 1	*91*	*0 62*	*15 73*	*0.22729*	*0.00535*	*0 18875*	*0.00492*	*491 3*	*11 3*	*1*	*Rim*	*oz*
FL2-19 1	*550*	*0 10*	*1 43*	*0.22729*	*0 00535*	*0.07106*	*0 00104*	*571 1*	*13 0*	*1*	*term*	*oz*

* Common Pb correction applied: 1 - ^{207}Pb correction applied to $^{206}Pb/^{238}U$ age; 3 - ^{204}Pb correction applied to $^{207}Pb/^{206}Pb$ age

Des:- Description of internal zircon structure revealed by cathodoluminescence: oz (regular oscillatory zoning); oxc (oscillatory zoned xenocrystic core); uol (unzoned overgrowth low luminescence); ixc (irregularly zoned xenocrystic core); iz (irregularly zoned grain)

Note: Italicised data has previously been reported in Keay and Lister's 2002 study on the provenance of Aegean rocks.

The volcanic originated greenschist formation develops large garnet crystals, which are characterised by medium-crystalline to microaugen texture, while their structure is massive and parallel to the schistosity. The microaugens consist of either albite xenoblasts with poikilitic texture, or by garnet porphyroblasts. Glaucophane, muscovite, paragonite, actinolite, quartz, zircon and epidote also form part of the paragenesis.

Marble-schist formation (300 m thick), medium-thick-bedded, calcitic marble, passing upwards to thin-bedded, microcrystalline with quartzite lenses, and microbeddings, becoming dolomitic towards its base. Marble and dolomite locally contain dispersed pyrite crystals and in various parts of the upper members, diasporite pockets up to 1m in scale are observed. Moreover, at the upper parts, this marble passes gradually to calcschist and then it changes to glaucophane schist, rich in lenticular intercalations of schistose eclogitic bodies. In the intermediate members, it becomes mica-schist bearing microconglomerate horizons rich in glaucophane schist and metavolcanic elongated cobbles. In the upper members of the formation glaucophane schist prevails, rich in eclogite, matabasic to greenschist lenses, which coexist rarely with serpentinite.

Upper dolomitic marble (100 m thick) is medium-thick-bedded to massive and traversed by carbonate and rarely quartz veins. It occurs along the northeastern edge of the island.

This unit contains evidence of two separate metamorphic events consisting of a high-pressure metamorphism (M1) under eclogite to glaucophane schist facies conditions, which was overprinted by a greenschist facies Barrovian metamorphism (M2), (Altherr et al., 1979; Andriessen et al., 1979; van der Maar et al., 1981; Franz et al., 1993).

2.2 Folegandros island

In the southeastern part of the Island (Fig.1B), an upper unit with low-grade metamorphism appears in tectonic contact with a lower one, which is characterised by high-grade metamorphism (Sowa 1985; Avdis & Photiades 1999).

a) The lower unit, up to 500m in thick, is characterized by blueschist sequence where glaucophane schists prevail. It also consists of greenschists with glaucophane porphyroblastes, comprising metabasic schist lenses deriving from altered basic volcanic rocks with residual porphyritic texture and thin-bedded marble intercalation. The lower parts of the sequence pass to the thin-medium-bedded marble through a transitional zone, consisting of marble layers with calcschist, chlorite, actinolite and glaucophane schists. At the base, glaucophane schist with marble alternations is dominant. In general, these rocks are characterized by the blueschist metamorphic facies of Eocene, passing to greenschist facies during Oligocene-Miocene.

b) The upper unit is characterized by low-grade metamorphism formations that from the base to top is composed by micaceous and calcitic schists, thin-medium-bedded marble sequence, up to 400m in thick, where at its base in the non metamorphic biomicrite relics were identified *Miliolidae, Ophthalmidiidae* and *Lagenidae* of probable Jurassic (?) to Cretaceous (?) age (N. Carras determinations in Avdis & Photiades, 1999). Calcschist, sericite and mica schists (100-150m in thick) overlying marble sequence and in their upper members serpentinite bodies occur of metric dimensions.

2.3 Tectonic

The outcrop-scale structures for Sikinos and Folegandros blueschist units are characterised by an initial deformation phase of isoclinal folding, with folds having a NW-SE direction (N130°), and being recumbent towards the SW. The folded rocks are affected by synkinematic metamorphism, under blueschist (glaucophane) facies conditions. The isoclinal folding and blueschist metamorphism is followed by a strong Alpine strain-slip deformation phase locally associated with greenschist facies conditions and, with axes having the same direction as the earlier folding. These tectonic events deformed the glaucophane schist, and probably representing tectonic transport from NE to SW, similar to the present plate-kinematics of the Hellenic arc and trench system (Papanikolaou, 1987).

However, the Folegandros upper unit has not experienced Alpine high-pressure metamorphism and it is tectonically separated by the lower blueschist one, via a low angle fault plane with N40° direction and southeastward dip.

The nature of the contact between the basement and the overlying blueschist and/or unmetamorphosed units is originally interpreted as tectonic (Papanikolaou 1980) or interpreted as thrust fault (van der Maar & Jansen 1993; Grutter 1993; Franz et al., 1993), while others have interpreted the contact as a detachment, normal fault (Lister et al., 1984), due to their reactivation during the Miocene extensional event, which is also explained by collapse of the Aegean crust during granitoid intrusions (see Lee & Lister 1992).

3. ANALYTICAL METHODS

The U-Th-Pb composition of zircons from basement and blueschist units of Sikinos and Folegandros islands were measured using the

Australian National University's Sensitive High-mass-Resolution Ion MicroProbes (SHRIMP). Grains of zircon were separated from well-selected samples, using standard magnetic and density separation techniques. Approximately 100 zircon grains from each sample were randomly hand-picked to ensure adequate representation of all zircon populations. These zircons were then mounted in epoxy resin, and sectioned in half by polishing, to expose cores and rims. SHRIMP I and II ion microprobes were used according to current operating procedures to determine U, Th and Pb/U in the sample zircons relative to those in the 572 Ma SL13 reference zircon. The probe diameter varied from 15-30 microns. Overnight pumping of the sample chamber minimised the effect of hydride interferences. Variable discrimination in Pb+/U+ was corrected using the established power-law relationship between Pb+/U+ and UO+/U+ (Claoui-Long et al., 1995). Small adjustments to the assigned 206Pb/238Pb age of 572 Ma for SL13 were made per session, to allow for sampling fluctuations arising from its bimodal distribution (Compston, 1996). The errors in the ages were augmented by a 2.5% uncertainty in the U/Pb standard calibration line. For zircons younger than 800 Ma, common Pb was estimated by the 207Pb-method (Compston et al., 1984).

Zircons were imaged both before and after SHRIMP analysis using cathodoluminescence (CL) techniques. The zircon grains reveal well-developed crystal faces, and exhibit oscillatory growth zoning in CL.

4. RESULTS

The Sikinos metagranodiorite sample (SK1) consists of quartz-K-feldspar-plagioclase-biotite, with zircons mainly hosted by biotite and quartz. Ages from thirty analyses of twenty-six zircon grains ranged from ca. 860 to 290 Ma (Table 1). Zircon grains appeared typically magmatic and were consistently around 200 μm in length with regular oscillatory zoning and only rare core structures. Two main groups of zircons were identified; one at 311 ± 1 Ma (n = 12) and the other at 333 ± 1 Ma (n = 12). The large population at ca. 310 Ma is interpreted as the emplacement age of the orthogneiss protolith while the older peak represents an early-formed inherited component that may reflect remobilisation of the magma. The spread of older ages represent inherited components preserved in the igneous zircon grains.

Sample SK2, the Sikinos metabasic schist, contains zircons that are irregularly-shaped, pitted and contain numerous inclusions. The zircons commonly display oscillatory zoning with rare inherited cores. Twenty-one analyses of seventeen zircon grains yield ages ranging from ca. 230 to 45 Ma (Table 1). The youngest age is from a zircon with unusually high uranium content that grew in a fracture in a pre-existing zircon grain. It is possible that this grain could represent new metamorphic zircon growth. The next youngest zircon grain at ca. 60 Ma is from a zircon with a mottled appearance, possibly due to new growth or recrystallisation, whereas the other few ages younger than 180 Ma are form unzoned portions of otherwise oscillatory-zoned grains. The first clearly magmatic-appearing, oscillatory-zoned zircon is 180 Ma in age, placing a maximum constraint on the timing of sedimentation to form the schist protolith. This sample also contains a dominant population of Jurassic-Triassic inheritance at 201 ± 2 Ma (n = 4) and at 223 ± 2 Ma (n = 5).

Sample FL2 is strongly foliated quartz-chlorite schist with minor calcite from Folegandros, and shows textural evidence of garnets entirely pseudomorphed by quartz and chlorite. The sample contains a mixed, typically detrital, population of zircons consisting of rounded, honey-coloured, irregular and oscillatory zoned grains, as well as more angular, elongate to euhedral, colourless and oscillatory zoned grains. Analyses of nineteen zircons indicate a range of ages from ca. 2880 to 90 Ma (Table 1). The youngest age in this population has a large uncertainty due to its relatively high common Pb content (Table 1). The next youngest age is ca. 140 Ma, and this is taken to represent the protolith age for the Folegandros schist. A number of zircons contain Triassic inheritance at 225 ± 3 (n=5) Ma.

5. DISCUSSION

The U-Pb geochronology of igneous zircons from the Sikinos metagranodiorite sample (Table 1) indicates that the granitoid was emplaced during the Late Carboniferous (between 330 - 300 Ma) during the late stages of the Variscan orogeny. This supports the suggestion that pre-Mesozoic basement exists in the Cyclades (e.g., van der Maar and Jansen, 1983). The restricted range in ages from 330-300 Ma determined for the intrusion of the basement orthogneiss protolith, conflicts with previous interpretations of the Pan-African basement age for the Cyclades (Henjes-Kunst and Kreuzer, 1982; Andriessen et al., 1987). The interpretation that the ages represent the timing of cooling and emplacement of granitoid magma is supported by the metamorphic growth of recrystallisation, as has previously been suggested (Henjes-Kunst and Kreuzer, 1982). Although the granitoid precursors to the gneisses were most likely S-type, there is no evidence to suggest that the zircon ages are entirely inherited (i.e. that no new zircon growth occurred during granitoid production).

The zircon igneous ages from the Sikinos metabasic and Folegandros quartz-chlorite schist samples, both from blueschist units, (Table 1) are dominantly Jurassic-Triassic. These ages represent the time at which the zircons formed prior to metamorphism and place a maximum age constrain on the timing of sedimentation to form the protoliths to the schists. The protoliths must have been deposited in the Triassic-Jurassic or possibly later. This is consistent with fossil evidence of Triassic deposition (Dórr et al., 1978 and references therein) for the schists from blueschist units in the Cyclades. The presumed Eocene timing of M1 metamorphism (Andriessen et al., 1979) places a minimum age constraint on the time of sedimentation, while the recognition of Cretaceous-aged metamorphic zircon overgrowths suggests that the rocks have experienced a complicated pre-M1 history. For these reasons, it seems more likely that the sediments forming these rocks were deposited in the Triassic-Jurassic and underwent pre-M1 metamorphism that may be correlated to the Early Cretaceous event, under epidote-amphibolite facies conditions that recorded in Pelagonian domain in continental Greece (Yarwood & Dixon 1977; Perraki et al., 2002). These sediments were most likely deposited in an active tectonic environment similar to a modern-day back-arc basin, accompanied by Triassic volcanism, before they underwent Cretaceous and then Tertiary metamorphism associated with the Alpine orogeny.

6. CONCLUSIONS

The basal unit in the SE part of the island of Sikinos consists of gneiss and schistose gneiss associated with a granodiorite intrusive rock. The metagranodiorite sample yields zircon crystallisation ages varying from ca. 860 to 290 Ma suggesting a Devonian to Carboniferous age of igneous emplacement. These radiometric measurements are significant, because they support the existence of a basement, which acts as a window, through which the metamorphosed remnant of pre-Alpidic crystalline basement in the Cyclades is exposed. The lower unit of Sikinos consists of pre-Alpidic basement, which was recognised also on the islands of Ios, Naxos, Paros and Syros, in tectonic contact with the overlying Alpine formations of Mesozoic age (van der Maar, 1981; van der Maar et al., 1981; Henjes-Kunst & Kreuzer, 1982; Bonneau, 1984; Andriessen et al., 1987; Engel and Reischmann 1998; Keay 1998). The pre-Alpidic basement of Cyclades is thought to link to the Pelagonian basement of continental Greece (Mountrakis 1984; Pe-Piper et al., 1993; Vavassis et al., 2000).

The blueschist units in Sikinos and Folegandros islands represent isoclinally folded metasediments and metavolcanic ophiolitic relicts, geochemically originating from acid volcanic rocks similar to those in island arcs and basic volcanic rocks of MORB affinities (Davis & Dietrich, 1986; Dietrich & Davis, 1986).

Along with the basement, the blueschist units have also undergone the same history of Eocene high-P/low-T metamorphism and Oligo-Miocene greenschist to amphibolite facies metamorphism (Altherr et al., 1979; Andriessen et al., 1979), prior to Mio-Pliocene exhumation as in the case of the metamorphic events, which have affected most of the Cycladic islands. The Folegandros upper unit has not experienced Alpine high-pressure metamorphism and it can be correlated with similar units found in several Cycladic islands and which were emplaced during the Middle-Upper Miocene (Photiades, 2002 and references therein).

The Jurassic-Triassic ages found in zircons from the Sikinos metabasic schist and the Folegandros quartz-chlorite schist indicate that these samples may represent the oldest remnants of the Pindos or Vardar Ocean. It seems likely that the basalts or ophiolites of the Cycladic blueschist units must have been generated in the Triassic and then uplifted and eroded to form sedimentary sequences, such as the quartz-chlorite schist of Folegandros, during the Jurassic and prior to the Eocene metamorphism.

Furthermore, these ages reinforce the idea that the possible beginning of oceanic development within the Tethys Hellenic sector began during the Triassic (Bortolotti et al., 2001, 2002, 2003; Saccani et al., 2002; 2004). Simultaneously, the occurrences in the Hellenides of MOR ophiolites of Middle Triassic to Middle Jurassic ages and IAT to boninitic rocks of suprasubduction zone that occur during the Middle Jurassic are favored for the existence of only the Vardar Ocean (Bortolotti et al. 2003).

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