LATE PALAEOZOIC MAGMATISM IN THE BASEMENT ROCKS SOUTHWEST OF MT. OLYMPOS, CENTRAL PELAGONIAN ZONE, GREECE: REMNANTS OF A PERMO-CARBONIFEROUS MAGMATIC ARC

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ABSTRACT

We dated basement rocks from several localities southwest of Mt. Olympos, as well as from a locality near the top of the mountain using the single zircon Pb/Pb evaporation technique. For the samples southwest of the mountain, the ages obtained range from ca. 280 to 290 Ma, with only a few zircon grains being around 300 Ma. By contrast, the sample from near the top of the mountain appears to be slightly younger, with ca. 270 Ma. These ages imply that the granitoids crystallized during Late Carboniferous - Early Permian times, and are therefore younger than the basement gneisses of other regions of the Pelagonian zone, which yielded zircon ages of around 300 Ma (e.g. Yarwood & Aftalion 1976, Mountrakis 1983, De Bono 1998, Engel & Reischmann 2001). However, the ages obtained in the present study are identical, within error, to the muscovite Ar-Ar cooling ages from Mt. Ossa (Lips 1998). Our geochronological data show that the magmatic evolution for this part of the basement of the Pelagonian Zone lasted at least 30 Ma.

KEY WORDS: Pelagonian Zone, Mt. Olympos, Greece, pre-Alpine basement, zircon geochronology.

1. INTRODUCTION – GEOLOGICAL BACKGROUND

The area occupied by what is known as the Pelagonian Zone is composed of several tectonic units (see Avgerinas 1999 for a recent summary and compilation of reference). The structurally lowermost unit is the neritic carbonate unit (Olympos unit), outcropping in the areas of Olympos, Ossa, Rizomata, and Krania (Fig. 1). The Olympos unit is overlain by the intermediate blueschist unit (Ambelakia unit), which, in turn, is overlain by the composite Pelagonian nappe.

In his pioneering work, Godfriaux (1968) maintained that the neritic carbonate unit represents pieces of the carbonate platform of the Adriatic-Apulian promontory of Gondwana (i.e. External Hellenides), now exposed in the form of tectonic windows amidst the Pelagonian Zone, an interpretation adopted by many subsequent workers (e.g. Schermer 1993). Schmitt (1983), however, was the first to oppose the widely accepted view of Godfriaux above, and proposed that the neritic carbonate unit palaeogeographically belongs to the Internal Hellenides (see also Vergιly & Mercier, 1990).

The Pelagonian nappe comprises (Kilias & Mountrakis 1989):

i) The pre-Alpine crystalline and magmatic masses of Voras, Vernon and Pieria-Kamvounia mountains as well as those outcropping further to the south (E. Mt. Othris, S. Mt. Pelion, Skiathos Isl., and N. Evia Isl.),

ii) The Permo-Triassic volcano-sedimentary series and the Triassic-Jurassic carbonates which are non- to only weakly metamorphosed at the western margin and more intensely metamorphosed at the eastern margin of the Pelagonian nappe,

iii) The ophiolites, characterized by Late Jurassic – Early Cretaceous deformation, and

iv) The transgressive Cretaceous limestones that pass upwards into Palaeocene flysch.

Strong tectonism during the Early Cretaceous and Tertiary brought about multiple zones of mylonitization and imbrication, and thrusting of the units from east to west. Granites, orthogneisses and metapelites are predominant amongst the pre-Alpine lithologies and constitute the crystalline basement of the Pelagonian Zone. The origin of this pre-Alpine basement, however, is poorly constrained due to the lack of reliable age determinations. A Carboniferous zircon U-Pb age of 302±5 Ma was reported from the Kastoria area, NW

Pelagonian Zone (Mountrakis 1983). A similar zircon U-Pb age of 302.4 +5/-15 Ma was published by Yarwood and Aftalion (1976) for granodiorites from the Kataphygion area, Pieria mountains, ´20 km NW of Mt. Olympos, central Pelagonian Zone (Fig. 1). De Bono (1998) measured zircon U-Pb ages in the range 308-320 Ma for granitic orthogneisses from NW and central Evia Island. Engel & Reischmann (1998, 2001) and Reischmann (1998) have also confirmed zircon Pb-Pb ages of ca. 300-315 Ma in the Cyclades (Attic-Cycladic Massif). It is therefore evident that Carboniferous magmatic activity was widespread over large parts of mainland Greece and the Aegean region. This Carboniferous magmatism may also have been responsible for the formation of crystalline massifs in the Sakarya continent, NW Turkey, where similar zircon Pb-Pb ages (313-293 Ma) have been reported (Фzmen & Reischmann 1999).

In this contribution we will focus on the geochronology of basement rocks in the Mt. Olympos region by single zircon Pb/Pb dating. The aim is to understand the origin of these pre-Alpine basement occurrences and to establish possible relations with other parts of the Pelagonian Zone.
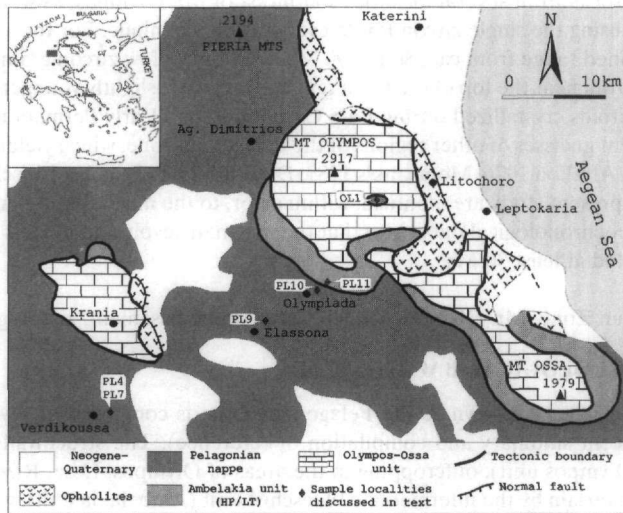

Figure 1. Simplified geological map of the central Pelagonian Zone, showing sample locations (modified after Kilias 1995).

2. ANALYTICAL METHODS

The samples, each weighing ca. 12 kg, were crushed using jaw crushers and a roller mill to produce powders of <0.50 mm particle size. Firstly, heavy minerals were concentrated using a Wilfley Table. Further concentration of the non-magnetic heavy minerals was achieved using a magnetic separator and heavy liquids. Final hand picking was done under a binocular microscope where zircons suitable for geochronological analysis were selected. Only zircon grains without visible core or inclusions were chosen.

In this study we used 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 fór Chemie in Mainz, Germany. The isotope ratios were measured on a secondary electron multiplier.

The $^{207}Pb/^{206}Pb$ ratios measured were corrected for common Pb after Stacey & Kramers (1975). No correction was made for mass fractionation, which is significantly less than the uncertainty of the isotope ratios measured (Kober 1987). More details of the method are given in Reischmann & Anthes (1996). The age calculations were performed using the decay constants of Steiger & Jðger (1977). Errors for the individual zircon measurements are reported as 2-sigma of the mean. The mean ages of the samples are given with standard. The analytical data are listed in Table 1.

3. GEOCHRONOLOGICAL RESULTS

Sample PL-4 was taken from a road cut between Elassona and Verdikoussa village, 6 km east of the latter locality (Fig. 1). The sample is a mainly medium-grained, undeformed, mesocratic granitic rock. It contains

sample	size (µm)	colour	habit		ratios	207Pb/206Pb	2sm	age (Ma)	error(Ma)
PI -4:									
A	350	pink	euhedral	clear	134	0.051981	0.000058	**284.6**	2.6
B	300	pink	euhedral	rel. turbid	119	0.052044	0.000072	**287.4**	3.2
C	300	pink	euhedral	clear	129	0.051983	0.000058	**284.7**	2.6
D	250	pink	euhedral	clear	68	0.052032	0.000123	**286.8**	5.4
E	300	pink	euhedral	clear	101	0.051942	0.000085	**282.9**	3.7
F	280	pink	euhedral	clear	67	0.051778	0.000099	**275.6**	4.4
G	300	pink	euhedral	rel. turbid	167	0.052085	0.000066	**289.2**	2.9
H	250	pink	fragment	clear	169	0.051872	0.000051	**279.8**	2.3
I	250	yellow	euhedral	rel. clear	51	0.051912	0.000100	**281.5**	4.5
J	230	yellow	fragment	rel. turbid	59	0.051948	0.000145	**283.1**	6.4
mean								**283.6**	**4.0**
PI -7:									
A	450	pink	euhedral	rel. turbid	197	0.052060	0.000043	**288.1**	1.9
B	250	pink	euhedral	rel. clear	92	0.052020	0.000137	**286.3**	6.0
C	350	yellow	euhedral	turbid	96	0.052439	0.000149	**304.6**	6.5
D	420	pink	euhedral	turbid	99	0.052360	0.000054	**301.2**	2.4
E	380	pink	euhedral	rel. clear	133	0.05188	0.000051	**280.1**	2.3
F	300	pink	fragment	turbid	177	0.053192	0.000057	337.0	2.4
H	290	yellow	fragment	turbid	147	0.051365	0.00012	257.3	5.4
I	330	yellow	euhedral	turbid	137	0.054078	0.000088	374.4	3.7
mean of A, B, E:								**284.8**	**4.2**
mean of C, D:								**302.9**	**2.4**
PI -9:									
A	400	pink	euhedral	rel. turbid	44	0.051793	0.000107	**276.3**	4.7
B	400	pink	fragment	rel. turbid	91	0.051988	0.000112	**284.9**	4.8
C	600	pink	euhedral	turbid	132	0.051984	0.000029	**284.7**	1.2
D	350	pink	euhedral	rel. turbid	82	0.051978	0.000097	**284.5**	4.3
E	350	pink	euhedral	rel. turbid	47	0.050963	0.000133	239.2	6.0
F	240	pink	fragment	clear	164	0.052043	0.000065	**287.3**	2.9
G	290	pink	fragment	turbid	109	0.052009	0.000044	**285.8**	1.9
H	250	pink	euhedral	clear	163	0.052391	0.000088	302.5	3.8
I	320	pink	euhedral	clear	158	0.052963	0.000091	327.2	3.9
mean of A, B, C, D, F, G:								**283.9**	**3.9**
PI -10:									
A	300	pink	euhedral	rel. turbid	26	0.05196	0.00023	**283.7**	9.9
B	300	pink	euhedral	rel. turbid	60	0.049543	0.000115	174.0	5.4
C	300	pink	euhedral	rel. turbid	74	0.051934	0.000111	**282.5**	4.9
D	400	pink	euhedral	turbid	139	0.052003	0.000035	**285.6**	1.5
E	250	pink	euhedral	trüb	105	0.051701	0.000049	**272.2**	2.2
F	280	pink	euhedral	rel. turbid	169	0.052143	0.000033	**291.7**	1.4
G	250	pink	euhedral	clear	152	0.052777	0.000061	319.2	2.6
H	410	pink	euhedral	rel. clear	54	0.052895	0.000278	324.3	12
mean of A, C, D, E, F:								**283.1**	**7.1**

Pl -11:

A	400	pink	euhedral	rel. turbid	133	0.051883	0.000102	**280.3**	4.5
B	280	pink	euhedral	turbid	99	0.051851	0.000131	**278.9**	5.8
C	400	pink	euhedral	rel. clear	177	0.051875	0.000058	**279.9**	2.6
D	310	pink	euhedral	rel. clear	174	0.052148	0.000048	**291.9**	2.1
E	260	pink	euhedral	rel. clear	35	0.051860	0.000132	**279.3**	5.8
F	400	pink	euhedral	turbid	136	0.055163	0.000103	418.9	4.2
G	350	pink	euhedral	turbid	136	0.051885	0.000058	**280.4**	2.6
H	350	pink	euhedral	turbid	133	0.051891	0.000051	**280.6**	2.2
mean of A, B, C, D, E, G, H:								**281.6**	**4.6**

Ol -1:

A	350	pink	euhedral	rel. turbid	253	0.072467	0.000085	999.1	2.4
B	300	pink	euhedral	turbid	115	0.051711	0.000099	**272.7**	4.4
C	280	pink	euhedral	clear	88	0.050676	0.000106	226.2	4.8
D	300	pink	euhedral	rel. turbid	113	0.051574	0.000079	**266.6**	3.5
E	350	pink	euhedral	rel. turbid	95	0.051764	0.000100	**275.0**	4.5
F	300	pink	euhedral	rel. turbid	126	0.05206	0.000031	**288.1**	1.4
G	400	pink	euhedral	rel. turbid	133	0.051909	0.000055	**281.4**	2.4
H	500	pink	euhedral	turbid	99	0.055997	0.000097	452.2	3.9
I	350	pink	euhedral	rel. turbid	85	0.051599	0.000099	**267.7**	4.4
J	300	pink	euhedral	turbid	111	0.053471	0.000048	348.8	2
K	180	pink	euhedral	clear	62	0.051663	0.000150	**270.5**	6.7
L	200	pink	euhedral	clear	103	0.052109	0.000057	**290.2**	2.5
M	300	pink	euhedral	rel. turbid	73	0.051289	0.000140	253.9	6.5
N	300	pink	euhedral	rel. turbid	88	0.051654	0.000087	**270.1**	3.9
O	300	pink	euhedral	rel. turbid	79	0.052905	0.000130	324.7	5.6
P	250	pink	euhedral	rel. turbid	54	0.051755	0.000090	**274.6**	4.0
Q	300	pink	euhedral	rel. turbid	71	0.051769	0.000100	**275.2**	4.6
mean of B, D, E, I, K, N, P, Q:								**271.6**	**3.3**
mean of F, G, L:								**286.6**	**4.6**

Table 1. Results of single evaporation analyses

quartz, feldspars and biotite with some K-feldspar phenocrysts reaching 2 cm in size. We consider this rock to belong to the Verdikoussa granite, which according to Pe-Piper et al. (1993a) intruded Pelagonian basement gneisses. However, we found a gradational contact between the gneisses and the granite, and no clear intrusive relationship between the two rock types. This indicates that the granite is an undeformed part of the gneisses.

The zircons of this granite are euhedral, pinkish in colour and mainly clear. Their length is up to 0.4 mm and they have a bi-pyramidal, long-prismatic morphology. Some measurements were performed on 0.3-0.4 mm fragments of originally even longer zircon grains. The ages obtained for this sample range from 275.6 Ma to 289.2 Ma. The zircon population appears to be rather homogeneous as far as colour, shape, and ages are concerned. Most of the grains yielded ages that cluster around 283.6±4.0 Ma (Fig. 4), which is suggested to be the intrusion age of the granite.

Sample PL-7 was taken from a locality 2.5 km east of sample PL-4 (Fig. 1). This sample is a medium-grained, porphyritic, weakly-deformed granite. The mineral assemblage is quartz, K-feldspar, plagioclase and biotite. This sample is very similar to PL-4 except for its slight deformation. It shows transitional contacts with its neighbouring granitic gneisses, which are strongly deformed. Once again no evidence for an intrusive relationship between granite and gneisses was observed. According to the geological map of Greece (IGME, 1983) this sampling site belongs to the basement gneisses.

The zircons of this sample are long-prismatic, euhedral, and up to 0.450 mm in size. The grains are predominantly clear, but turbid grains were also found. They are mainly pink, though yellow or brownish grains can also

be seen. The zircons of this sample yield ages between 257.3 Ma and 374.4 Ma. There seem to be two populations, one at ca. 302.9 Ma, and the other at 284.8 Ma. The younger age of 284.8±4.2 Ma is taken here as the intrusion age. The grains that yielded the ages of 374.4 Ma and 337.0 Ma are interpreted as inherited grains, or as composite grains reflecting a mixed age between the 284.8 Ma intrusive event and an unknown ancient source. The 302.9 Ma age is obviously also an intrusive age and might be interpreted as the crystallization of an early Pelagonian pluton that was intruded by the younger 284.8 Ma granite.

Sample PL-9 was taken ca. 12 km NE of Elassona, close to the village of Olympiada (Fig. 1). This deformed granite displays a pervasive foliation, but the original igneous texture is well preserved. Quartz, feldspars and biotite are the major mineral phases. The slightly greenish colour of the rock is caused by the formation of
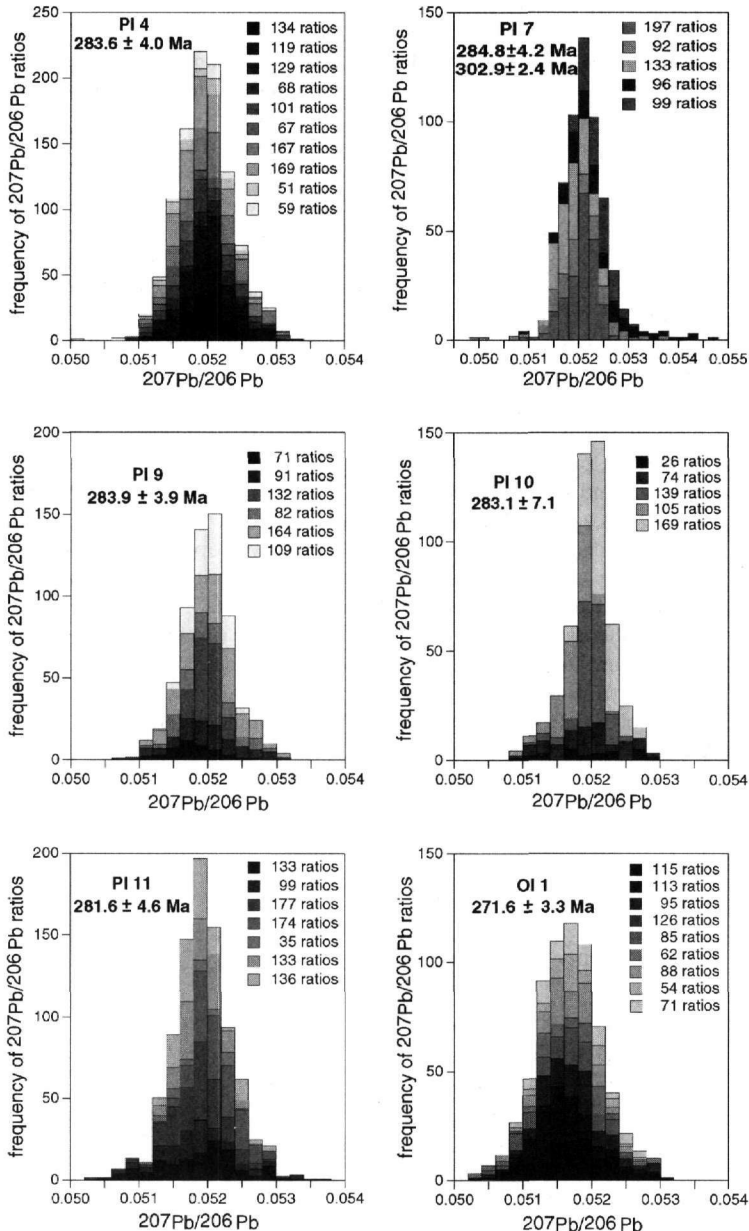
Figure 2. Histogram showing the individual $^{207}Pb/^{206}Pb$ single zircon analyses for the samples from the central Pelagonian zone.

chlorite. The sample location implies that this sample belongs to the basement gneisses.

The zircon population is homogeneous in appearance with euhedral grains up to 0.6 mm in size. These grains are long-prismatic, pink and mainly clear, with only a few grains being turbid. The ages of the zircons from this sample do not, however, form a homogeneous population. Most of the ages cluster in a narrow interval from 276.3-287.3 Ma with a mean age of 283.9±3.9 Ma. Two older grains were discerned with ages of 302.5 and 327.2 Ma respectively. By analogy to sample PL-7 we conclude that these ages either represent mixed ages between the 283.9 Ma event and a much older zircon source, or an early Pelagonian magmatic pulse. One grain yielded an age of 243.8±7.1 Ma, which might reflect Pb loss during a Triassic event or a diffusive Pb loss without age significance.

Sample PL-10 was collected 4 km east of Olympiada village (Fig. 1). This sample shows a schistose fabric due to pervasive foliation. Small, centimetre-sized kink folds suggesting the onset of crenulations fold the folia-tion itself. Despite the intense deformation, an igneous origin can still be assigned to the rock. The schist is of dioritic composition and consists of elongated feldspars and quartz, amphibole, biotite and chlorite. It is green-ish in colour due to the low grade alteration that accompanied deformation. This rock is part of the basement gneisses according to the geological map of Greece (IGME, 1983).

The zircons of this sample are euhedral, clear or slightly turbid, and up to 0.4 mm in size. Their colour is pink and their habit is long-prismatic and bi-pyramidal. The ages of the zircons from this sample vary between 174.0 Ma and 324.3 Ma. The majority of the zircons are close together with a mean age of 283.3±7.1 Ma. We interpret this age as the igneous formation age of the diorite. The grains yielding older ages, around ca. 320 Ma, are again interpreted as inherited grains of an older magmatic phase, and the 174 Ma age as due to secondary Pb depletion.

Sample PL-11 was taken from a locality 2 km east of PL-10 on the road to Kriovrisi, about 800 m above sea level (Fig. 1). The sample is similar to PL-10 but more strongly deformed and the original igneous texture is difficult to recognize. Apart from its pervasive schistosity, a second deformation is suggested by the development of crenulations. The minerals that can be identified are quartz, feldspars, chlorite and blue amphibole. The colour of the rock specimen is bluish-green or light-brownish on foliation planes due to the occurrence of iron hydroxides. According to the geological map of Greece (IGME, 1983), this rock belongs to the Ambelakia unit proper.

The zircons are euhedral, pink, long-prismatic, clear or turbid and up to 0.5 mm in size. The ages of the zircons range between 278.9 and 418.9 Ma. We consider the mean age of 281.6±4.6 Ma as the igneous formation age, whereas that of 418.9 Ma as an indication of zircon inheritance.

Sample OL-1 was collected at 1800 m above sea level on the SW slopes of Mt. Olympos (Fig. 1; see Avgerinas, 1999 for details). It is a weakly-deformed, medium-grained granodiorite with quartz, feldspars, amphibole, and biotite as major constituents. Chlorite is the main alteration product.

The zircons are pink, euhedral, up to 0.5 mm in size and mainly turbid; only a few grains are clear. The ages scatter between 226.2±4.8 and 999±2.0 Ma. The majority is grouped around a mean value of 271.6±3.3 Ma, which appears to date the intrusion age. A second small group of values is around 286.6±4.6 Ma. Secondary Pb loss is indicated by values of 226.2±4.8 Ma and 253.9±6.5 Ma. Some older, probably also inherited grains have ages of 324.7, 438.8, 452.2, and even 999.1 Ma. The scattering of ages obtained for this sample indicates that the intrusion is slightly younger compared to the other granites studied here, and that it incorporated material from other plutons.
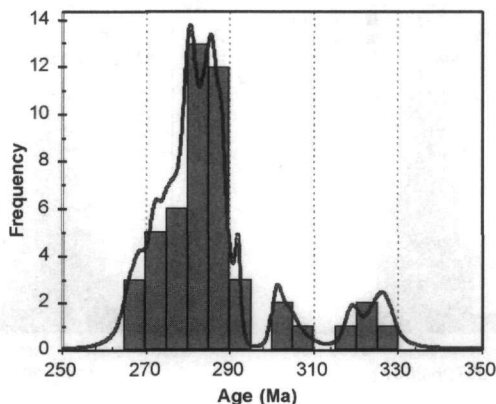

Figure 3. Histogram showing the age distribution of the analysed samples from the Late Carboniferous to Early Permian (330-260 Ma). Curve after Ludwig (1999).

4. DISCUSSION AND CONCLUSIONS

The rocks examined in the present study are geochemically classified as granodiorites and granites. They are peraluminous with an A/CNK value >1, and display similarities to I and S-type granites respectively. They are characterized by low HFSE concentrations with Nb < 15 ppm and Zr < 206 ppm. Such properties are typical of magmatic arc rocks formed in an active continental margin environment. Therefore, the geochemical composition of the granites and gneisses analysed in this study and in other regions of the Pelagonian Zone and the Attic-Cycladic Massif is similar to that of granites from modern active continental margins. Although certain Pelagonian granites had been interpreted as extension related (Kotopouli et al. 2000) the majority of these rocks have strong affinities to granites from convergent plate boundaries.

Investigation of the morphologies and the internal structures of the zircons underscore their igneous origin. Metamorphic zircon growth was not documented in our study. Consequently, the interpretation of the zircon ages as intrusion ages is justified. It should be noted that the zircons from the different localities preserved their age information despite Alpine deformation, metamorphism and secondary alteration.
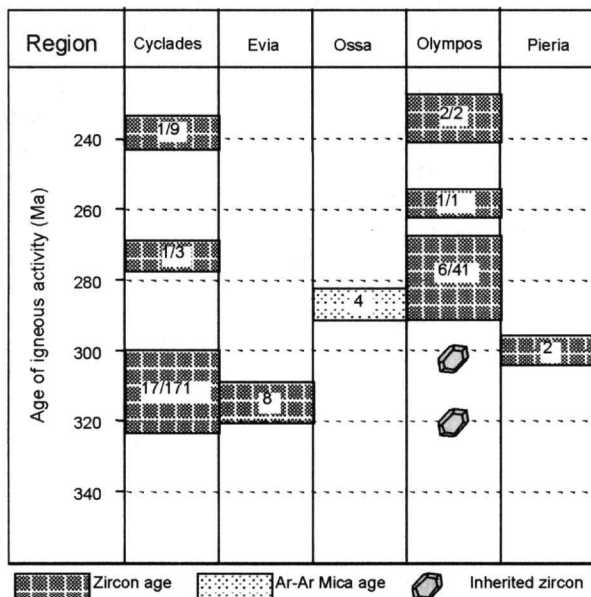

Figure 4. Distribution of igneous formation ages for the various parts of the Pelagonian Zone and the Attic-Cycladic Massif, with data sources (Yarwood & Aftalion 1976, Mountrakis 1983, De Bono 1998, Engel & Reischmann 1998, 2001, and Reischmann 1998). Numbers in boxes: number of samples / zircon grains analysed.

The crystalline basement ages obtained from zircons in this study bear some important implications for the evolution of the Pelagonian Zone. One of these implications concerns the age relations between the different rock units according to previous subdivisions (Schmitt 1983, Schermer 1993). Since all dated samples collected west of Mt. Olympos yield, within error, identical ages, there is no reason to assume that they belong to different units. The only difference between the rocks is the degree of deformation. Igneous formation for this part of the basement is therefore constrained to 280-290 Ma (Fig. 3). The asymmetry of the major peak on the age distribution curve is caused by the relatively younger age (271.6 Ma) of the Mt. Olympos sample OL-1. The inherited grains indicate two minor peaks at 300-310 Ma and around 320Ma (Fig. 3), similar to the age distribution seen in other regions of the Pelagonian Zone and the Attic-Cycladic Massif (Fig. 4). The ages of the inherited grains might be explained by early Pelagonian, (i.e. Late Carboniferous) granites that were subsequently intruded, or partly digested, or remelted by Early Permian granites. The even older zircons have been inherited from a hitherto unknown older source. A minor group of zircons indicates a Triassic age. This is not unique to the Olympos region but is also known from the Cyclades (Keay 1998, Reischmann 1998). We tentatively suggest that this age has a geological significance and might indicate a Triassic event, which can be related to an extensional regime as proposed by Pe-Piper (1997).

If we interpret all mean ages as igneous formation ages, this would imply that all rocks belong to the same

unit. This unit had undergone variable deformation that obscured the igneous appearance of the rocks and, to some extent, affected their chemical compositions. We propose that subdivision of the Pelagonian Zone into gneisses, granites and the Ambelakia unit is no longer appropriate, at least for our study area (see also Pe-Piper et al. 1993b).

The samples we analysed were collected along a SW-NE profile from Verdikoussa village to Mt. Olympos. We see a general increase in the degree of deformation towards the east with the strongest deformation seen in sample PL-11, which is close to the Olympos marbles and according to previous subdivisions would have been assigned an Ambelakia unit origin. All rocks analysed here are granitic-granodioritic in composition despite their variable deformation. Their chemistry is largely similar and their zircons are almost identical in terms of morphology, colour and age. We therefore interpret sample PL-11, and consequently the Ambelakia unit, as part of the basement unit. This basement consists of granites, which are variably deformed to gneisses and thrusted over the Olympos autochthon. The highest degree of deformation is at the base of the nappe (e.g. PL-11) where the granites had been severely overprinted and their igneous texture almost completely erased. Similar observations to the above were made by Lips (1998) for the western flank of Mt. Ossa. If we correlate the two tectonic windows of Olympos and Ossa, the interpretation is straightforward: the basement is a nappe, which appears complex because of the variable deformation. This complexity only reflects the heterogeneity of the deformation that affected various parts of the rather homogeneous granitic basement in different ways.

If we interpret the entire Pelagonian and the Attic-Cycladic Massif as a magmatic arc, then regional variations in the magmatic activity can be seen along strike. In the southern part of this arc, in the Cyclades area, the majority of ages lie between 300 and 320 Ma (Fig. 4). This also applies to Evia Island (De Bono 1998). In the central Pelagonian Zone around Mts. Ossa and Olympos, the 300 Ma age is documented only in inherited grains from this study, while the prevailing igneous phase occurred at ca. 270-290 Ma (Lips 1998 and this study). This implies a shift in magmatic activity along the arc from Late Carboniferous in the south to Early Permian in the north. In the very north of the Pelagonian Zone only a few zircon data are available which do not permit further speculation about timing of magmatic activity. It is, however, clear from the age data available that any attempt at a geodynamic reconstruction of the central Pelagonian must include an ocean on one side of the Pelagonian Zone for a period that lasted at least 30 Ma. Final closure of this ocean is unlikely to have taken place before the end of the arc activity, i.e. before ca. 270 Ma. Zircon ages similar to those of the Pelagonian-Attic-Cycladic magmatic arc (i.e. 320-270 Ma) have been obtained for orthogneiss samples from the Rhodope Massif in southern Bulgaria (319-305 Ma; Peytcheva & von Quadt 1995), as well as from NW Turkey (Okay et al. 1996, Фzmen & Reischmann 1999). Nevertheless, correlations across the Vardar zone should be handled with great care.

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