

Zircon geochronology of basement rocks from the Pelagonian Zone, Greece: constraints on the pre-Alpine evolution of the westernmost Internal Hellenides

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Abstract The Pelagonian Zone of Greece is the westernmost segment of the Internal Hellenides comprising widespread crystalline basement exposures of granites and orthogneisses. We dated these basement rocks in order to identify the major crust-forming episodes and to understand the evolutionary history of the area. In our study we investigated granites, gneisses, meta-rhyolites and mylonites from the major occurrences of the Pelagonian Zone. We applied single-zircon dating techniques such as Pb–Pb evaporation, conventional U–Pb and SHRIMP. The majority of the basement rocks gave Permo–Carboniferous intrusion ages, thus emphasizing the importance of this crust-forming event for the Internal Hellenides of Greece. Triassic intrusion ages were obtained, however, for a meta-rhyolite from the western Pelagonian Zone and two mylonites from the eastern Pelagonian Zone. These ages are interpreted to reflect magmatism accompanying early rifting that led to the subsequent opening of the Pindos Ocean to the west and the Meliata Ocean to the east of the Pelagonian Zone. The geochronological results demonstrate that the

magmatic episodes during which most of the Pelagonian Zone crystalline basement formed are predominantly pre-Alpine in age.

Keywords Pelagonian Zone · Zircon geochronology · Basement rocks · Greece

Introduction and regional geology

The Pelagonian Zone is part of the Hellenide orogen, which is, in turn, an eastern Mediterranean segment of the Alpine–Himalayan mountain chain. Together with the Vardar Zone, the Serbo-Macedonian Massif and the Rhodope Massif further east, the Pelagonian Zone belongs to the Internal Hellenides and for decades has been investigated with respect to structural geology, geochemistry, petrology and geochronology (e.g. Aubouin et al. 1963; Celet and Ferrière 1978; Mountrakis 1984; Kiliass and Mountrakis 1989; Schermer 1990; Pe-Piper et al. 1993a, b; Koroneos et al. 1993; Katerinopoulos et al. 1998; Lips et al. 1998; Vavassis et al. 2000; Reischmann et al. 2001). In terms of rock types, the Pelagonian Zone comprises granites, ortho- and paragneisses (forming the Palaeozoic metamorphic basement), late Palaeozoic to Mesozoic metasedimentary rocks (mostly metaclastic sequences and carbonate cover), ophiolites showing Late Jurassic to Early Cretaceous deformation and Tertiary to recent sediments (e.g. Celet and Ferrière 1978; Jacobshagen 1986 and references therein; Kiliass and Mountrakis 1989; Pe-Piper and Piper 2002 and references therein). Geochemical studies of Palaeozoic basement rocks indicate that they formed in a subduction-zone environment and mostly favour an active continental

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margin setting (e.g. Pe-Piper et al. 1993a, b; Katerinopoulos et al. 1998; Vavassis et al. 2000; Reischmann et al. 2001; Anders et al. 2002). The Late Precambrian to Mesozoic evolution of the eastern Mediterranean was marked by the opening and closure of ocean basins and continental crust formation in the accompanying subduction zones (e.g. Stampfli et al. 2001; Stampfli and Borel 2002). Orogenic processes due to initial collision of the Apulian plate with the Eurasian plate during Mesozoic and Cainozoic times and subsequent collapse and extension are responsible for the present-day appearance of the Hellenides. These Alpine orogenic processes obscured the pre-Alpine history of the Hellenide region. A geochronological study of what were presumed to be Palaeozoic crustal rocks can help to unravel the pre-Alpine history of the Pelagonian Zone. Previous geochronological investigations of the Pelagonian Zone were carried out, for example, by Yarwood and Aftalion (1976), who obtained a U–Pb zircon age of 302 ± 5 Ma from High Pieria Mts., NE Pelagonian Zone. Other studies report results based on the Rb–Sr, K–Ar or Ar–Ar methods of dating (Barton 1976; Schermer 1990; Koroneos et al. 1993; Katerinopoulos et al. 1998; Lips et al. 1998), though these methods are often not suitable for dating primary intrusion events. U–Pb zircon ages of basement rocks from the Pelagonian Zone are so far rather scarce. Apart from the Pieria Mt. age obtained by Yarwood and Aftalion (1976), other U–Pb zircon ages for the Pelagonian Zone include those of the Verdikoussa area (Reischmann et al. 2001) and Evia (De Bono 1998; Vavassis et al. 2000), where Permo-Carboniferous intrusion ages were found, and those of the NW Pelagonian Zone (Mountrakis 1984; Anders et al. 2003), where Neoproterozoic basement rocks with intrusion ages of ca. 700 Ma were additionally identified and interpreted in terms of an exotic terrane named Florina Terrane (Anders et al. 2003, 2006). The aim of this study was therefore to improve our knowledge of basement formation in the Pelagonian Zone. Zircon geochronology is especially suited for obtaining information about intrusion ages and the timing of magmatism, because zircons, apart from being common accessory minerals in felsic rocks, have a high closure temperature that allows dating of the intrusion event, and they are rather resistant against resetting of the U–Pb isotopic system during later metamorphic events or alteration (Lee et al. 1997; Cherniak and Watson 2000; Parrish 2001; Corfu et al. 2003). Age information on basement rocks from the Pelagonian Zone will give us a more detailed picture of the existence and regional distribution of distinct magmatic episodes, information necessary

for palinspastic reconstructions. A detailed geochronological study will provide important clues regarding the evolution of the Pelagonian Zone and will shed ample light on the pre-Alpine history of the Internal Hellenides.

Sample description and geochronology

Samples were collected from major basement exposures along the length of the Pelagonian Zone (see Fig. 1a). In the northern part of the Pelagonian Zone, sampling areas include the Voras Mountains in the northeast, close to the border with the Former Yugoslav Republic of Macedonia (F.Y.R.O.M.) (Fig. 1b), and the Varnous Mts. in the northwest (Fig. 1c). Progressing southwards sampling localities include outcrops south of Veria (Fig. 1a), a basement exposure NE of Mt. Olympos (Fig. 1d), the Verdikoussa area (Fig. 1d), Mt. Ossa and Mavrovouni (Fig. 1e), Mt. Pilion and Skiathos Island (the westernmost island of the N. Sporades; Fig. 1f). The southernmost samples were taken from the northern part of Evia Island and from Skyros Island (Fig. 1a). Three different methods of single-zircon dating were applied, namely the Pb–Pb evaporation method (Kober 1986, 1987), the conventional U–Pb method (isotope dilution; Krogh 1973; Wendt and Todt 1991) and the sensitive high-resolution ion microprobe (SHRIMP) method (e.g. Compston et al. 1984). SHRIMP dating was performed on samples for which both the Pb–Pb and the conventional U–Pb methods failed to produce satisfactory results. Cathodoluminescence (CL) images typical for zircons from Pelagonian Zone basement rocks are shown in Fig. 2. Analytical results are listed in Tables 1, 2 and 3 and shown in Figs. 3, 4, 5, 6, 7, 8 and 9. Pb–Pb evaporation data are shown as histograms, while conventional U–Pb and SHRIMP results are displayed as concordia diagrams. Details of analytical procedures are given in Appendix. The following description of the samples is arranged from north to south.

Voras Mts.

The Voras Mts. in northern Greece stretch from the Pelagonian Zone in the west eastwards into the Vardar Zone (Fig. 1a). They are recognised as a pile of westward-stacked thrust sheets (Brown and Robertson 2004). The westernmost part of the chain, forming the footwall onto which the lowermost thrust sheet was thrust, is the Kaimakchalan Massif, which belongs to the Pelagonian Zone (Mountrakis 1982, 1984; Jacobsen 1986). One granite (Ka-X5) was sampled

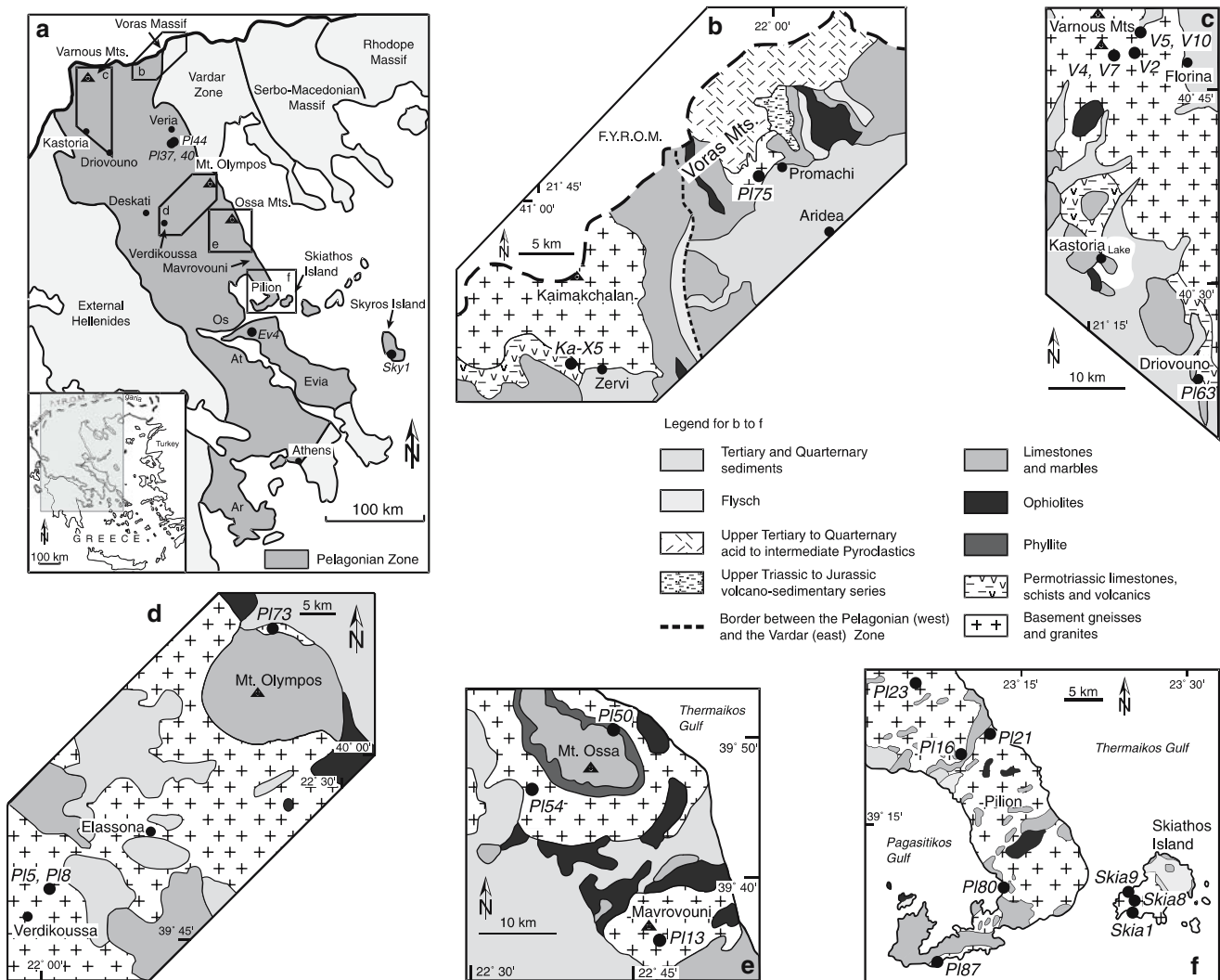


Fig. 1 Overview of the study area and the sample locations. **a** Map showing the structural zones of northern Greece, simplified after Kondopoulou (2000). The black polygons indicate the blow-ups **b–f**. Sample numbers are shown in *italics*.

from this westernmost part, while one orthogneiss (PI75) was taken further east in the Voras Mts., west of Promachi village (Likostomo-Promachi Unit of Brown and Robertson 2004) (Fig. 1b).

PI75 is a light-coloured granitic gneiss and consists mainly of quartz, K-feldspar, plagioclase, white mica and epidote. PI75 was dated with the single-zircon conventional U–Pb method (Fig. 3a). Two zircon grains define a concordant age of 285 ± 2 Ma (MSWD of concordance = 0.039). This age is interpreted to date the intrusion event. Two grains display Pb loss and one grain falls on the reverse side of the concordia line.

Granite Ka-X5 was sampled in the western part of the Voras Mts. The main minerals are quartz, severely sericitised plagioclase, K-feldspar, biotite and epidote. Dating with the single-zircon Pb–Pb evaporation

method did not yield clear-cut results (Fig. 3b). One grain contains an older Pb component and yielded an age of ca. 413 Ma (Table 2), while two other grains show signs of Pb loss. Nevertheless, the majority of the zircon grains cluster at 276 ± 9 Ma (MSWD = 9.5). Therefore, an Upper Carboniferous/Lower Permian intrusion age can be assumed. This assumption is also supported by the result of the single-zircon conventional U–Pb dating approach (Fig. 3c) that yielded an upper intercept age of about 293 ± 9 Ma (MSWD = 0.43).

Varnous Mts.

The Varnous Mts. in the NW Pelagionian Zone consist of intrusive rocks, ranging in composition from mafic to

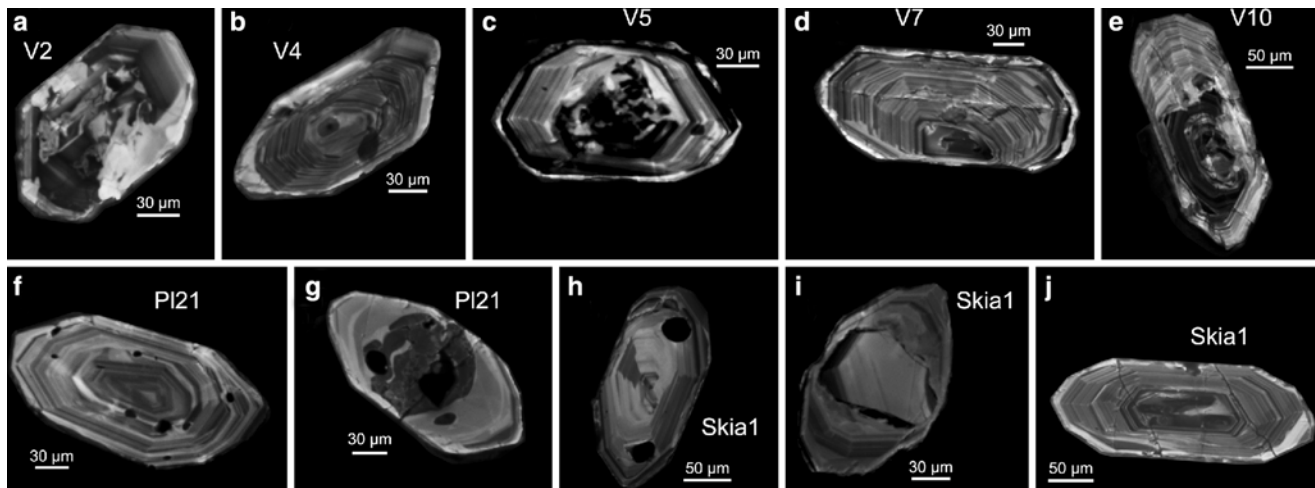


Fig. 2 Cathodoluminescence images of zircons from the Varnous Mts., Mt. Pilon and Skiathos Island

felsic. Deformation is absent or only weak. Some of the mafic rocks occur as enclaves in the felsic rocks. Five plutonic rocks were sampled from the Varnous Mts. (V10, V2, V4, V5, V7; Fig. 1c). Differences in grain size and relative proportions, as well as in the degree of alteration of the minerals quartz, K-feldspar, plagioclase (often showing saussuritisation), biotite, titanite, apatite and epidote/clinozoisite are obvious. V2 and V4 are fine-grained mafic rocks, while V5, V7 and V10 are coarse-grained and of intermediate (V7, V10) or felsic (V5) composition. Titanite occurs mostly as large euhedral grains up to 2.5 mm in length, but in the sample V5 only remnants of titanite are found. Zircons from all samples were dated by the single-zircon Pb–Pb evaporation method. Moreover, zircons from sample V7 were additionally dated by the single-zircon conventional U–Pb method. The resulting ages are: 282 ± 8 Ma (V2), 296 ± 6 Ma (V4), 289 ± 8 Ma (V5), 290 ± 6 Ma (V10) and $294 \pm 4/282 \pm 1$ Ma (V7, Pb–Pb evaporation method/conventional U–Pb method, respectively). The ages thus cover a narrow range from 282 ± 1 to 296 ± 6 Ma (Fig. 4a–f) and indicate a time span of about 14 Ma for igneous activity. Ages of individual zircon grains for each sample form a homogeneous group, the only exception being sample V2, where two age groups were found. An older age of 282 ± 8 Ma is calculated as the mean age of four grains (grains V2 B, C, F and D, Fig. 4a) and interpreted to reflect the intrusion event. The other four grains gave a mean age of 262 ± 8 Ma (grains V2 A, E, G and H, not shown in Fig. 4). This age most likely reflects Pb loss. Generally, Pb loss seems more likely to have occurred during a later thermal event than during a late magmatic pulse and zircon growth at 262 Ma because CL images show the patchy pattern often obtained during

recrystallisation (Fig. 2a). For sample V7, there is a discrepancy in the ages obtained using the Pb–Pb evaporation (294 ± 4 Ma) and the conventional U–Pb methods (concordant age of 282 ± 1 Ma). This might be explained by the different response of these two dating methods to the existence of small overgrowths on zircon grains, which are visible as bright rims in CL images (Fig. 2d). Such overgrowths could have led to the slightly younger age obtained by conventional U–Pb analyses when the whole grain was dissolved and analysed. Applying the Pb–Pb evaporation method, such a rim could have been evaporated during the first phase of the heating procedure, before the deposition of Pb on the ionisation filament. Bright overgrowths, visible in CL images, are a common feature of the zircon grains in most of the Varnous pluton samples, e.g. samples V4 and V5 (Fig. 2b, c). Complex internal structures are also typical (e.g. V5, Fig. 2c; V10, Fig. 2e). They are, however, unlikely to point to an older inherited component because this feature is relatively common and there is no indication for an older inherited Pb component from the geochronological analyses. The only indication for a minor inherited component would be an age of ca. 312 Ma obtained from a zircon grain of sample V4 (grain B, Table 2); no older ages were obtained from the Varnous pluton samples.

Driovouno

Along the northwestern margin of the Pelagonian Zone Permo-Triassic metaclastic sequences occur with rhyolite flows embedded in their upper parts, which are overlain by Triassic–Jurassic carbonates (Mountrakis et al. 1987). Sample Pl63 (the westernmost sample of

Table 1 Results of single-zircon U–Pb isotope dilution analyses

Sample	Grain no.	Measured ratios (fract. corrected)			Radiogenic ratios ^a			Apparent ages											
		²⁰⁶ Pb/ ²⁰⁴ Pb	2σ	²⁰⁷ Pb/ ²⁰⁶ Pb	2σ	²⁰⁷ Pb/ ²³⁵ U	2σ	²⁰⁶ Pb/ ²³⁸ U	2σ	U _{tot} / Pb*	²⁰⁶ Pb/ ²³⁸ U (Ma)	2σ	²⁰⁷ Pb/ ²³⁵ U (Ma)	2σ	²⁰⁷ Pb/ ²⁰⁶ Pb (Ma)	2σ			
P175	1	294	2	0.10171	0.00057	0.3005	0.0067	0.04146	0.00034	0.60	0.05258	0.00055	19.3	262	2	267	5	311	24
P175	2	1,069	6	0.06595	0.00010	0.3205	0.0027	0.04438	0.00021	0.78	0.05238	0.00019	20.3	280	1	282	2	302	8
P175	3	786	16	0.07023	0.00028	0.3224	0.0075	0.04506	0.00037	0.53	0.05189	0.00065	19.4	284	2	284	6	281	29
P175	4	753	36	0.07088	0.00042	0.3242	0.0132	0.04550	0.00052	0.34	0.05168	0.00145	18.8	287	3	285	10	271	66
P175	5	1,531	35	0.06143	0.00016	0.3562	0.0061	0.04961	0.00043	0.79	0.05207	0.00034	18.5	312	3	309	5	288	15
Ka-X5	6	427	1	0.08614	0.00021	0.2902	0.0043	0.04057	0.00033	0.55	0.05189	0.00061	21.7	256	2	259	3	280	27
Ka-X5	7	305	1	0.10018	0.00009	0.3143	0.0043	0.04370	0.00034	0.63	0.05216	0.00048	18.0	276	2	278	3	292	21
Ka-X5	8	1,127	7	0.06518	0.00002	0.3191	0.0028	0.04434	0.00031	0.92	0.05220	0.00015	19.7	280	2	281	2	294	7
Ka-X5	9	560	2	0.07972	0.00004	0.3231	0.0026	0.04370	0.00024	0.77	0.05362	0.00023	19.5	276	1	284	2	355	10
Ka-X5	10	359	1	0.09369	0.00018	0.3287	0.0083	0.04504	0.00075	0.46	0.05294	0.00158	19.3	284	5	289	6	326	69
Ka-X5	11	1,286	9	0.06484	0.00006	0.3375	0.0038	0.04575	0.00038	0.93	0.05351	0.00018	20.3	288	2	295	3	351	7
V7	12	1,171	20	0.06384	0.00018	0.3157	0.0051	0.04447	0.00035	0.67	0.05149	0.00042	17.6	281	2	279	4	263	19
V7	13	2,156	166	0.05841	0.00019	0.3184	0.0067	0.04457	0.00029	0.41	0.05181	0.00070	17.8	281	2	281	5	277	31
V7	14	365	6	0.09091	0.00021	0.3142	0.0069	0.04467	0.00020	0.20	0.05102	0.00092	17.0	282	1	277	5	242	42
V7	15	2,486	85	0.05750	0.00019	0.3211	0.0040	0.04493	0.00020	0.51	0.05183	0.00036	17.3	283	1	283	3	278	16
V7	16	4,270	160	0.05543	0.00010	0.3224	0.0034	0.04488	0.00027	0.81	0.05210	0.00022	16.8	283	2	284	3	290	10
V7	17	1,008	3	0.06607	0.00007	0.3214	0.0035	0.04510	0.00036	0.90	0.05169	0.00019	17.0	284	2	283	3	272	9
V7	18	280	3	0.10463	0.00020	0.3246	0.0090	0.04490	0.00038	0.26	0.05243	0.00147	17.3	283	2	285	7	304	65
P137	19	605	8	0.07606	0.00029	0.2908	0.0057	0.04037	0.00025	0.44	0.05225	0.00061	22.0	255	2	259	4	296	27
P137	20	600	19	0.07668	0.00016	0.3105	0.0078	0.04288	0.00027	0.25	0.05251	0.00107	20.5	271	2	275	6	308	47
P137	21	348	14	0.09353	0.00025	0.3147	0.0160	0.04407	0.00049	0.19	0.05178	0.00235	20.7	278	3	278	12	276	108
P137	22	751	6	0.07156	0.00007	0.3255	0.0042	0.04494	0.00033	0.94	0.05252	0.00013	20.0	283	2	286	3	308	6
P137	23	317	2	0.09904	0.00017	0.3371	0.0056	0.04593	0.00031	0.51	0.05323	0.00057	19.9	289	2	295	4	339	25
P137	24	206	1	0.12339	0.00006	0.3342	0.0035	0.04643	0.00022	0.35	0.05220	0.00060	18.7	293	1	293	3	294	26
P137	25	533	2	0.08395	0.00003	0.3675	0.0029	0.04697	0.00026	0.80	0.05675	0.00023	19.6	296	2	318	2	482	9
P137	26	554	34	0.07968	0.00027	0.3728	0.0171	0.05027	0.00043	0.21	0.05379	0.00187	18.0	316	3	322	13	362	80
P137	27	631	5	0.07936	0.00005	0.4709	0.0035	0.06068	0.00020	0.49	0.05629	0.00031	14.6	380	1	392	2	464	12
P137	28	1,268	12	0.07018	0.00004	0.5377	0.0037	0.06637	0.00029	0.80	0.05876	0.00019	14.0	414	2	437	2	558	7
P140	29	276	2	0.10475	0.00006	0.3113	0.0043	0.04362	0.00025	0.41	0.05176	0.00060	21.0	275	2	275	3	275	27
P140	30	716	12	0.07563	0.00034	0.4189	0.0086	0.05492	0.00042	0.44	0.05532	0.00079	16.0	345	3	355	6	425	32
P140	31	1,593	7	0.06460	0.00002	0.4363	0.0068	0.05702	0.00082	0.99	0.05550	0.00009	15.6	357	5	368	5	432	4
P140	32	931	36	0.07296	0.00025	0.4931	0.0101	0.06229	0.00032	0.26	0.05742	0.00093	14.2	390	2	407	7	508	36
P140	33	1,898	63	0.06453	0.00008	0.5233	0.0078	0.06666	0.00057	0.78	0.05694	0.00037	13.1	416	3	427	5	489	15
P140	34	645	6	0.08638	0.00022	0.5370	0.0084	0.06067	0.00050	0.71	0.06420	0.00051	14.3	380	3	436	6	748	17
P144	35	403	5	0.08517	0.00020	0.1441	0.0038	0.02133	0.00018	0.41	0.04898	0.00085	43.9	136	1	137	3	147	41
P144	36	154	1	0.14371	0.00060	0.1438	0.0050	0.02145	0.00014	0.17	0.04865	0.00150	43.7	137	1	136	4	131	74
P144	37	166	1	0.13730	0.00033	0.1462	0.0045	0.02160	0.00022	0.42	0.04910	0.00099	43.7	138	1	139	4	153	48
P144	38	414	5	0.08421	0.00025	0.1473	0.0035	0.02182	0.00015	0.37	0.04897	0.00080	42.1	139	1	140	3	146	39
P144	39	435	3	0.08213	0.00010	0.1512	0.0023	0.02248	0.00012	0.68	0.04878	0.00025	40.4	143	1	143	2	137	12
P144	40	311	1	0.09609	0.00026	0.1525	0.0025	0.02248	0.00010	0.36	0.04922	0.00052	40.7	143	1	144	2	158	25
P144	41	640	7	0.07252	0.00029	0.1566	0.0031	0.02278	0.00013	0.42	0.04985	0.00057	41.3	145	1	148	3	188	27
P163 ^b	42	104	1	0.19194	0.00028	0.2684	0.0081	0.03766	0.00018	0.10	0.05169	0.00165	21.1	238	1	241	7	272	75

Table 1 continued

Sample	Grain no.	Measured ratios (fract. corrected)			Radiogenic ratios ^a			Apparent ages		
		$^{206}\text{Pb}/^{204}\text{Pb}$	2σ	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	2σ	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	2σ	$^{207}\text{Pb}/^{206}\text{Pb}$
										(Ma)
P163 ^b	43	329	2	0.09509	0.00016	0.00023	0.03858	0.05067	0.00050	244
P163 ^b	44	123	1	0.17055	0.00023	0.00055	0.03899	0.05099	0.00158	247
P163 ^b	45	174	1	0.13529	0.00019	0.00039	0.04373	0.05114	0.00116	276
P173	46	383	4	0.08923	0.00016	0.00007	0.01560	0.05123	0.00066	100
P173	47	842	3	0.06832	0.00006	0.00015	0.02173	0.05125	0.00010	139
P173	48	664	9	0.07313	0.00017	0.00018	0.02329	0.05136	0.00064	148
P173	49	407	5	0.08675	0.00004	0.00012	0.02659	0.05088	0.00064	169
P173	50	247	3	0.11089	0.00047	0.00044	0.02786	0.05172	0.00286	177
P173	51	716	29	0.07068	0.00018	0.00025	0.03501	0.05065	0.00108	222
P173	52	1,417	23	0.06046	0.00018	0.00020	0.03677	0.05060	0.00031	233
P173	53	541	17	0.07643	0.00007	0.00030	0.04144	0.05004	0.00093	262
P173	54	1,004	25	0.06416	0.00013	0.00034	0.04307	0.05047	0.00032	272
P173	55	1,118	15	0.06361	0.00014	0.00029	0.04341	0.05096	0.00031	274
P173	56	1,043	13	0.06628	0.00012	0.00036	0.04393	0.05273	0.00035	277
P173	57	673	16	0.07483	0.00032	0.00039	0.04951	0.05354	0.00102	312
P15	58	254	2	0.10904	0.00018	0.00030	0.04428	0.05167	0.00073	279
P15	59	918	19	0.06674	0.00009	0.00027	0.04433	0.05127	0.00049	280
P15	60	231	2	0.11557	0.00012	0.00022	0.03964	0.05223	0.00093	21.5
P15	61	664	25	0.07846	0.00052	0.00296	0.04294	0.05685	0.00146	20.5
P15	62	130	1	0.17579	0.00043	0.00057	0.04616	0.06508	0.00191	18.6
P15	63	282	1	0.10411	0.00021	0.00036	0.04562	0.05244	0.00065	19.0
P15	64	159	1	0.14624	0.00013	0.00039	0.04901	0.05459	0.00145	17.9
P15	65	2,280	152	0.06772	0.00018	0.00029	0.05968	0.06152	0.00062	15.1
P15	66	925	12	0.07795	0.00015	0.00072	0.05960	0.06239	0.00042	13.1
P15	67	1,983	61	0.06810	0.00006	0.00029	0.06131	0.06090	0.00029	14.2
P15	68	1,102	27	0.07509	0.00031	0.00044	0.06220	0.06220	0.00059	14.1
P15	69	1,397	28	0.07078	0.00013	0.00079	0.08776	0.06073	0.00035	10.3
P15	70	2,082	47	0.07216	0.00014	0.00099	0.10281	0.06533	0.00031	8.6
P15	71	1,235	9	0.09018	0.00045	0.00057	0.09958	0.07878	0.00026	8.4
P15	72	714	11	0.09645	0.00116	0.00137	0.11487	0.07669	0.00157	7.2
P150	73	304	4	0.09900	0.00031	0.00026	0.03791	0.05085	0.00119	22.4
P150	74	594	17	0.07631	0.00008	0.00020	0.04014	0.05203	0.00082	22.5
P150	75	254	1	0.10806	0.00028	0.00033	0.04196	0.05099	0.00070	21.8
P150	76	471	25	0.08290	0.00068	0.00048	0.04250	0.05213	0.00253	19.9
P150	77	4,202	104	0.13141	0.00010	0.00094	0.11388	0.12835	0.00017	7.4
P113	78	969	9	0.06627	0.00002	0.00017	0.04002	0.05151	0.00009	21.5
P113	79	231	2	0.11403	0.00010	0.00017	0.04425	0.05108	0.00079	19.4
P113	80	348	2	0.09257	0.00013	0.00027	0.04430	0.05129	0.00030	18.8
P113	81	405	4	0.08750	0.00045	0.00039	0.04492	0.05180	0.00105	20.3
P123	82	1,040	26	0.07152	0.00016	0.00078	0.06716	0.05774	0.00075	12.0
P123	83	2,188	36	0.06496	0.00010	0.00046	0.07344	0.05844	0.00021	10.6
P123	84	750	6	0.07776	0.00008	0.00094	0.08166	0.05851	0.00031	10.4

Table 1 continued

Sample	Grain no.	Measured ratios (fract. corrected)			Radiogenic ratios ^a			Apparent ages											
		$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	2σ	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	2σ	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	2σ	R	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	2σ	$U_{\text{tot}}/\text{Pb}^*$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	2σ	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	2σ	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	2σ		
Pt23	85	633	20	0.08332	0.00025	0.7658	0.0246	0.09148	0.00136	0.64	0.06072	0.00104	9.5	564	8	577	14	629	37
Pt23	86	1,302	22	0.07702	0.00006	0.9716	0.0096	0.10636	0.00055	0.80	0.06626	0.00025	8.2	652	3	689	5	814	8
Pt23	87	336	5	0.16672	0.00016	5.2083	0.1134	0.29662	0.00431	0.84	0.12735	0.00118	2.8	1,675	21	1,854	19	2,062	16
Pt21	88	652	3	0.07381	0.00050	0.2935	0.0069	0.04119	0.00035	0.50	0.05167	0.00073	22.8	260	2	261	5	271	33
Pt21	89	964	16	0.06681	0.00011	0.3000	0.0043	0.04204	0.00029	0.66	0.05175	0.00038	21.4	265	2	266	3	275	17
Pt21	90	673	11	0.07297	0.00018	0.3083	0.0063	0.04336	0.00032	0.51	0.05156	0.00060	20.0	274	2	273	5	266	22
Pt21	91	1,244	16	0.06368	0.00011	0.3155	0.0038	0.04398	0.00027	0.72	0.05204	0.00030	20.6	277	2	278	3	287	13
Pt21	92	409	2	0.08850	0.00018	0.3653	0.0067	0.04973	0.00041	0.63	0.05327	0.00051	18.8	313	2	316	5	340	22
Pt80	93	506	2	0.08151	0.00006	0.2580	0.0028	0.03557	0.00025	0.68	0.05261	0.00037	26.0	225	2	233	2	312	16
Pt80	94	174	0	0.13653	0.00009	0.2792	0.0045	0.03847	0.00033	0.27	0.05264	0.00142	24.2	243	2	250	4	313	63
Pt80	95	540	3	0.07967	0.00013	0.2997	0.0033	0.04128	0.00021	0.51	0.05265	0.00043	22.7	261	1	266	3	314	19
Pt80	96	425	3	0.08652	0.00015	0.3338	0.0053	0.04637	0.00031	0.42	0.05221	0.00068	19.9	292	2	292	4	294	30
Pt80	97	151	1	0.14863	0.00014	0.3746	0.0087	0.05236	0.00047	0.35	0.05189	0.00110	17.7	329	3	323	6	280	49
Skia1	98	717	11	0.07226	0.00003	0.2851	0.0040	0.03969	0.00025	0.59	0.05209	0.00042	22.8	251	2	255	3	289	18
Skia1	99	1,285	21	0.06338	0.00008	0.2863	0.0030	0.03990	0.00021	0.63	0.05203	0.00032	18.3	252	1	256	2	287	14
Skia1	100	722	17	0.07213	0.00010	0.3259	0.0088	0.04535	0.00064	0.72	0.05212	0.00068	19.3	286	4	286	7	291	30
Skia1	101	499	6	0.08120	0.00008	0.3268	0.0050	0.04544	0.00028	0.52	0.05216	0.00049	19.3	286	2	287	4	293	22
Skia1	102	741	7	0.07227	0.00005	0.3365	0.0033	0.04635	0.00021	0.55	0.05266	0.00034	19.5	292	1	295	3	314	15
Skia1	103	847	11	0.07117	0.00008	0.3809	0.0043	0.05122	0.00027	0.58	0.05393	0.00038	17.9	322	2	328	3	368	16
Skia8	104	398	0	0.08870	0.00011	0.2889	0.0027	0.04028	0.00025	0.68	0.05203	0.00033	23.5	255	2	258	2	287	15
Skia8	105	575	6	0.07744	0.00009	0.2934	0.0032	0.04093	0.00016	0.35	0.05199	0.00047	22.8	259	1	261	3	285	21
Skia8	106	1,048	20	0.06607	0.00011	0.3167	0.0039	0.04406	0.00021	0.47	0.05213	0.00043	21.1	278	1	179	3	291	19
Skia8	107	581	9	0.07716	0.00038	0.3235	0.0100	0.04502	0.00066	0.59	0.05211	0.00098	19.8	284	4	285	8	290	43
Skia8	108	973	23	0.06740	0.00006	0.3316	0.0049	0.04589	0.00030	0.55	0.05242	0.00049	20.0	290	2	291	4	304	21
Skia8	109	1,547	15	0.06215	0.00010	0.3407	0.0035	0.04682	0.00028	0.76	0.05278	0.00025	19.4	295	2	298	3	319	11
Skia9	110	474	4	0.08206	0.00039	0.2249	0.0041	0.03185	0.00014	0.23	0.05121	0.00082	29.3	202	1	206	3	250	37
Skia9	111	158	1	0.14405	0.00014	0.2474	0.0049	0.03491	0.00023	0.25	0.05139	0.00113	25.8	221	1	224	4	259	51
Skia9	112	508	13	0.07760	0.00022	0.2478	0.0075	0.03633	0.00032	0.35	0.04948	0.00104	25.2	230	2	225	6	170	50
Skia9	113	991	13	0.06642	0.00011	0.2893	0.0035	0.04056	0.00024	0.63	0.05173	0.00036	23.0	256	1	258	3	274	16
Skia9	114	761	6	0.07059	0.00012	0.2901	0.0032	0.04095	0.00024	0.66	0.05138	0.00033	22.8	259	1	259	3	258	15
Skia9	115	163	4	0.13776	0.00095	0.2959	0.0258	0.04427	0.00046	0.09	0.04847	0.00395	20.3	279	3	263	20	122	182
Skia9	116	538	6	0.07708	0.00006	0.3095	0.0044	0.04444	0.00026	0.74	0.05051	0.00025	19.9	280	2	274	3	219	12
Skia9	117	676	45	0.06949	0.00029	0.3019	0.0162	0.04519	0.00065	0.31	0.04845	0.00188	20.5	285	4	268	13	121	94
Skia9	118	404	6	0.08688	0.00019	0.3212	0.0072	0.04551	0.00025	0.31	0.05119	0.00079	19.4	287	2	283	6	249	36
Skia9	119	2,243	57	0.05931	0.00005	0.3461	0.0033	0.04747	0.00025	0.79	0.05288	0.00021	18.8	299	2	302	9	324	9
Skia9	120	583	77	0.07615	0.00116	0.3420	0.0352	0.04829	0.00049	0.06	0.05137	0.00477	18.0	304	3	299	27	257	229
Skia9	121	957	13	0.10866	0.00021	0.8453	0.0069	0.06486	0.00025	0.63	0.09451	0.00042	13.5	405	1	622	4	1,518	8

^a Corrected for fractionation, spike and common Pb

^b For sample Pl63 fractions of 2–3 zircons were analysed

Table 2 Results of single-zircon Pb–Pb evaporation geochronology

Sample	Number of ratios	$^{206}\text{Pb}/^{204}\text{Pb}$ measured	$^{207}\text{Pb}^*/^{206}\text{Pb}^{*a}$	Error 2σ	Age (Ma)	$\pm$ (Ma)
V2-A	58	6,468	0.051361	186	257	8
V2-B	151	2,058	0.051928	91	282	4
V2-C	129	2,103	0.052060	162	288	7
V2-D	190	11,558	0.051773	84	275	4
V2-E	76	5,591	0.051322	133	255	6
V2-F	153	10,770	0.051983	62	285	3
V2-G	95	10,986	0.051573	126	267	6
V2-H	124	5,380	0.051521	84	264	4
V4-A	97	6,476	0.051720	159	273	7
V4-B	113	3,496	0.052607	130	312	6
V4-C	191	25,582	0.052243	25	296	1
V4-D	93	1,788	0.052005	172	286	8
V4-E	38	2,601	0.051952	248	283	11
V4-F	57	6,084	0.051199	174	250	8
V4-G	58	3,642	0.049935	297	192	14
V4-H	37	4,055	0.051882	207	280	9
V5-A	131	14,513	0.052172	73	293	3
V5-B	133	14,653	0.051722	136	273	6
V5-C	38	22,245	0.051905	302	281	13
V5-D	75	9,199	0.051009	173	241	8
V5-E	188	16,091	0.052246	58	296	3
V5-F	210	23,231	0.052029	83	287	4
V5-G	156	9,797	0.051727	128	273	6
V5-H	37	12,104	0.052028	214	287	9
V5-I	76	14,035	0.051632	178	269	8
V7-A	171	10,649	0.052006	70	286	3
V7-B	152	8,840	0.052144	35	292	2
V7-C	132	21,299	0.052141	36	292	2
V7-D	110	19,132	0.052259	28	297	1
V7-E	152	5,263	0.052176	73	293	3
V7-F	129	11,179	0.052249	25	296	1
V7-G	152	13,523	0.051780	83	276	4
V7-H	152	10,283	0.052187	66	294	3
V7-I	152	6,660	0.052375	71	302	3
V10-A	171	7,214	0.051898	49	281	2
V10-B	189	10,051	0.052260	45	297	2
V10-C	96	5,998	0.051919	78	282	3
V10-D	176	9,110	0.052303	81	299	4
V10-E	173	10,288	0.052168	65	293	3
V10-F	200	1,772	0.052009	129	286	6
V10-G	183	16,970	0.052231	48	296	2
V10-H	195	9,365	0.051920	72	282	3
PI5 A	117	1,295	0.092091	275	1469	6
PI5 B	175	15,196	0.057016	74	492	3
PI5 C	92	1,966	0.051664	80	271	4
PI5 D	131	8,489	0.052095	68	290	3
PI5 E	173	6,288	0.052246	153	296	7
PI5 F	212	16,895	0.059217	179	575	7
PI5 G	97	8,364	0.060235	116	612	4
PI5 H	97	920	0.051809	205	277	9
PI5 I	133	2,076	0.081120	225	1224	5
Sky1-A	156	7,170	0.046389	52	18	3
Sky1-B	132	3,180	0.046452	110	21	6
Sky1-C	95	6,025	0.046189	99	8	5
Sky1-D	76	4,448	0.046239	166	10	9
PI8-A	134	6,747	0.051506	110	264	5
PI8-B	156	7,020	0.056916	64	488	2
PI8-C	139	6,128	0.078976	567	1,172	14
PI8-D	173	11,285	0.052710	61	316	3

Table 2 continued

Sample	Number of ratios	$^{206}\text{Pb}/^{204}\text{Pb}$ measured	$^{207}\text{Pb}^*/^{206}\text{Pb}^{*a}$	Error 2σ	Age (Ma)	$\pm$ (Ma)
PI8-E	152	35,044	0.055095	69	416	3
PI8-F	152	10,986	0.052033	100	287	4
PI8-G	94	1,558	0.051877	116	280	5
PI8-H	57	7,417	0.051831	197	278	9
PI8-I	114	15,674	0.114665	126	1,875	2
PI87-A	117	9,570	0.051829	126	278	6
PI87-B	151	7,453	0.051989	141	285	6
PI87-C	135	19,932	0.051910	133	281	6
PI87-D	80	7,184	0.051904	242	281	11
Ka-X5-A	133	1,138	0.051881	170	280	8
Ka-X5-B	76	4,001	0.055007	313	413	13
Ka-X5-C	109	2,740	0.051708	72	273	3
Ka-X5-D	150	1,945	0.051452	96	261	4
Ka-X5-E	160	5,237	0.051818	91	277	4
Ka-X5-F	57	2,567	0.051164	175	248	8
Ka-X5-G	96	873	0.052158	145	292	6
Ka-X5-H	208	1,408	0.051676	98	271	4

^a Radiogenic Pb, ratios were corrected for common Pb using the values of Stacey and Kramers (1975)

this study; Fig. 1c) was taken close to Driovouno village. The red meta-rhyolite consists of feldspar crystals in a matrix of spherulitic intergrowth of quartz and feldspar (devitrified glass?). Meta-rhyolite PI63 was dated by the conventional U–Pb method (Fig. 5a). As the size of the zircon grains was small (mostly about 50 μm), fractions of 2–3 grains were analysed. Two fractions yielded a concordant age of 244 ± 1 Ma (MSWD of concordance = 1.14). One fraction displays Pb loss while another fraction plots slightly reversely discordant in the concordia diagram.

Veria region

About 15 km south of the town of Veria (Fig. 1a) there are large exposures of granitic basement rocks. Deformation is variable and ranges from foliated gneisses to almost undeformed granites.

PI44 is a grey, mylonitic gneiss with small feldspar “augen”. Its main minerals are quartz, K-feldspar, plagioclase and white mica. Very minor biotite and minor epidote also occur. Mylonite PI44 was dated by the single-zircon conventional U–Pb method (Fig. 5b). Four zircon grains define a concordant age of 137 ± 1 Ma (95% conf. level, MSWD of concordance = 0.2). Two grains plot concordant at 143 ± 1 Ma (MSWD of concordance = 0.02). It is not possible to decide whether the younger age represents the intrusion age and the older age the existence of a subordinate inherited component or whether the older age dates the intrusion event and the younger age is

Table 3 Results of zircon SHRIMP dating

Sample ^a	Grain. spot	U (ppm)	Th (ppm)	Th/U	²⁰⁶ Pb _{rad} (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	<i>f</i> ₂₀₆ (%)	Radiogenic ratios, SQUID corrected ^{c,d}				
								²⁰⁷ Pb/ ²³⁵ U	Err ^e (%)	²⁰⁶ Pb/ ²³⁸ U	Err ^e (%)	<i>R</i>
PI40	7.1	149	138	0.93	6.1	0.00032	0.58	0.338	9.476	0.0469	1.3098	0.14
PI40	3.2	230	69	0.30	9.4	0.00018	0.33	0.336	6.228	0.0472	1.0426	0.17
PI40	6.1	306	152	0.50	12.6	0.00004	0.07	0.340	2.854	0.0478	0.8708	0.31
PI40	6.2	705	64	0.09	28.9	0.00011	0.20	0.346	2.008	0.0476	0.6497	0.32
PI40	2.1	493	236	0.48	20.3	— ^f	— ^f	0.352	1.983	0.0479	0.7317	0.37
PI40	3.1	573	198	0.35	23.6	0.00002	0.04	0.355	2.553	0.0480	0.7026	0.28
PI40	5.2	849	40	0.05	42.3	0.00000	0.00	0.448	1.376	0.0580	0.5863	0.43
PI40	1.1	111	31	0.28	8.2	— ^f	— ^f	0.726	3.027	0.0858	1.1554	0.38
PI40	4.1	247	144	0.58	24.4	0.00011	0.20	0.990	2.358	0.1149	0.7900	0.34
PI40	8.1	324	10	0.03	34.9	— ^f	— ^f	1.124	1.498	0.1255	0.7746	0.52
PI40	5.1	366	176	0.48	63.9	0.00001	0.02	2.294	1.107	0.2030	0.6301	0.57
PI37	6.2	95	111	1.16	3.9	0.00086	1.56	0.330	12.101	0.0464	1.4684	0.12
PI37	6.1	144	197	1.37	5.9	0.00047	0.86	0.327	9.226	0.0472	1.1874	0.13
PI37	10.2	506	126	0.25	21.1	0.00017	0.32	0.341	2.876	0.0484	0.6511	0.23
PI37	8.1	995	96	0.10	42.0	0.00014	0.26	0.347	2.096	0.0490	0.5274	0.25
PI37	9.1	1,533	119	0.08	65.1	0.00003	0.06	0.358	1.143	0.0494	0.4669	0.41
PI37	1.1	974	341	0.35	41.7	0.00013	0.24	0.354	1.994	0.0497	0.5291	0.27
PI37	1.2	753	309	0.41	32.7	0.00019	0.34	0.356	2.143	0.0504	0.5659	0.26
PI37	11.1	1,752	27	0.02	76.7	0.00009	0.16	0.359	1.307	0.0509	0.4536	0.35
PI37	3.1	1,641	485	0.30	72.2	0.00033	0.59	0.363	2.148	0.0509	0.4665	0.22
PI37	10.1	1,248	416	0.33	54.7	0.00005	0.09	0.366	1.496	0.0510	0.4844	0.32
PI37	4.1	2,696	265	0.10	122.2	0.00004	0.08	0.380	0.895	0.0527	0.4140	0.46
PI37	8.2	1,700	122	0.07	79.1	0.00014	0.25	0.395	1.460	0.0540	0.4536	0.31
PI37	5.1	327	137	0.42	26.9	— ^f	— ^f	0.835	1.436	0.0958	0.6412	0.45
PI37	7.1	583	543	0.93	50.2	0.00007	0.12	0.822	1.229	0.1000	0.5320	0.43
PI37	2.1	324	146	0.45	32.9	0.00002	0.04	1.030	1.427	0.1180	0.6294	0.44
PI54	14.1	449	115	0.26	19.0	0.00010	0.19	0.359	2.144	0.0491	0.7125	0.33
PI54	12.1	269	91	0.34	11.5	0.00018	0.32	0.356	2.672	0.0494	0.7932	0.30
PI54	17.1	328	143	0.44	14.0	0.00018	0.33	0.348	2.813	0.0496	0.9176	0.33
PI54	13.1	470	162	0.34	20.3	0.00012	0.23	0.362	2.301	0.0502	0.7013	0.30
PI54	15.1	194	66	0.34	12.3	0.00007	0.12	0.572	2.141	0.0741	0.8131	0.38
PI54	10.1	368	265	0.72	32.5	0.00007	0.13	0.866	1.225	0.1028	0.6799	0.55
PI16	21.2	94	44	0.47	3.1	0.00074	1.36	0.223	10.710	0.0373	1.6855	0.16
PI16	26.2	110	69	0.63	3.6	0.00091	1.67	0.221	12.926	0.0375	1.6792	0.13
PI16	37.1	115	56	0.49	3.8	0.00098	1.80	0.215	12.308	0.0380	1.6260	0.13
PI16	3.1	105	47	0.45	3.5	0.00076	1.39	0.241	9.290	0.0386	1.6245	0.17
PI16	13.2	110	83	0.75	3.8	0.00097	1.78	0.233	12.106	0.0391	1.6571	0.14
PI16	10.2	206	103	0.50	9.8	0.00021	0.38	0.394	3.727	0.0551	1.4017	0.38
PI16	10.1	268	151	0.56	13.0	0.00019	0.35	0.410	2.773	0.0561	1.3435	0.48
PI16	29.1	287	131	0.46	23.4	0.00006	0.11	0.790	2.093	0.0946	1.2824	0.61
Ev4	28.1	576	160	0.28	23.6	0.00015	0.28	0.341	1.755	0.0475	0.6755	0.38
Ev4	29.2	222	73	0.33	9.2	0.00025	0.46	0.331	4.504	0.0483	0.8425	0.19
Ev4	32.2	807	385	0.48	33.4	0.00009	0.16	0.344	1.355	0.0481	0.6454	0.48
Ev4	16.1	794	250	0.31	33.1	0.00008	0.15	0.351	1.336	0.0484	0.6401	0.48
Ev4	10.1	593	264	0.45	25.7	— ^f	— ^f	0.371	1.168	0.0505	0.6640	0.57
Ev4	32.1	741	281	0.38	32.6	0.00008	0.15	0.371	1.471	0.0512	0.8381	0.57
Ev4	29.1	239	364	1.53	64.4	0.00002	0.03	5.343	0.828	0.3142	0.6963	0.84

^a Samples PI40 and PI37 were dated at the Centre of Isotopic Research, St. Petersburg, Russia; samples PI54, PI16 and Ev4 were dated at ANU, Australia

^b *f*₂₀₆ (%) denotes the percentage of ²⁰⁶Pb that is common Pb

^c Errors in reference zircon calibration are not included in the given errors. Error in reference zircon calibration Temora was 0.33% for PI40 and 0.25% for PI37. Error in reference zircon calibration FC1 was 0.22% for PI54 and Ev4 and 0.31% for PI16

^d Common Pb correction by SQUID was performed using the measured ²⁰⁴Pb

^e Uncertainties are given at 1σ level

^f For some spots counts on ²⁰⁴Pb were below background level, a ²⁰⁴Pb/²⁰⁶Pb of 0.000001 was then assumed to perform the common Pb correction

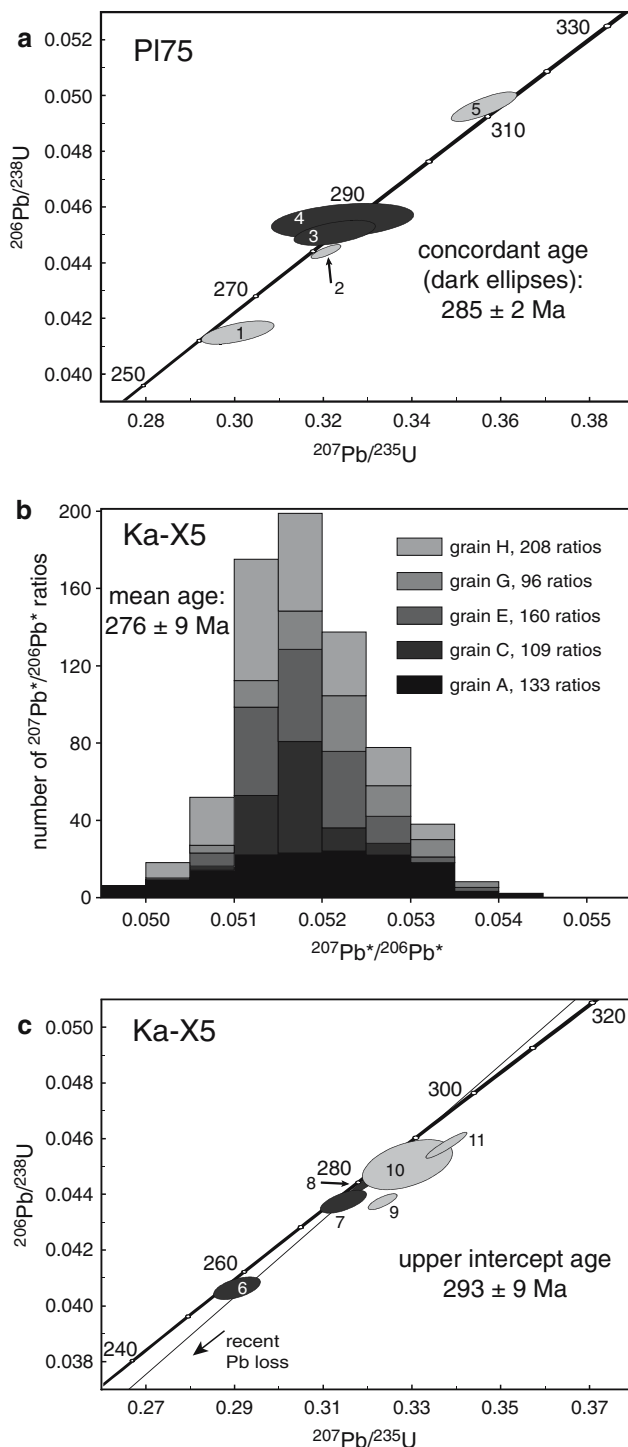


Fig. 3 Geochronological results for the basement rocks from the Voras Mts. The histogram shows the results of single-zircon Pb–Pb evaporation analyses while the concordia diagrams illustrate the results of the conventional U–Pb method. The discordia line in **c** was calculated with an assumed lower intercept age of 0 Ma

caused by Pb loss. The discordance of a zircon grain that plots close to the older age group in the concordia diagram could be taken to indicate the existence of an

inherited component. We interpret these data, nevertheless, to be a strong indication for a magmatic event at about 140 Ma.

PI37 and PI40 (Fig. 1a) are light-coloured granites that vary in their degree of deformation. They were sampled along road cuts approximately 500 m apart. PI37 is less deformed than PI40. Both granites consist mainly of quartz, K-feldspar, plagioclase, white mica and garnet < 0.5 mm across. Minor epidote and remnants of biotite also occur. The plagioclase shows severe alteration to epidote and white mica. Zircons from both samples show several events of growth and inheritance in CL images. These characteristics complicate the dating of the zircons and the interpretation of the resulting age. For instance, SHRIMP dating of sample PI37 resulted in a continuous spread of concordant ages from 339 ± 3 to 292 ± 8 Ma (Fig. 5c). A precise intrusion age cannot be inferred from this range in ages, which seems too long to reflect continuous magmatism. However, as the two youngest ages could reflect minor Pb loss (being measured on a narrow grain) and the two oldest ages are probably mixing ages between the young zircon rim and an older core, the age range can be narrowed down to about 300–320 Ma. This age range is assumed to reflect the intrusion age. A similar result was obtained applying the conventional U–Pb method (Fig. 5d), where six grains define a discordia with an upper intercept age of 307 ± 11 Ma (MSWD = 1.14) while the lower intercept (assumed at 0 Ma) reflects recent Pb loss. Dating by SHRIMP revealed two concordant ages for inherited grains; the obtained ages were 614 ± 6 and 719 ± 9 Ma.

For PI40, SHRIMP dating yielded a concordant age of 300 ± 2 Ma (MSWD of concordance = 0.8) that is interpreted as the intrusion age (Fig. 5e). This age is distinctly older than the one obtained from the single-zircon conventional U–Pb analyses, which is a lower intercept age of 272 ± 16 Ma (MSWD = 1.3; Fig. 5f). One grain, however, plots concordantly at 275 ± 2 Ma. This younger age could be caused by Pb loss that led to a shift towards younger ages but was not severe enough to result in discordance. Information about the ages of inherited components by the conventional U–Pb method is mostly imprecise. The upper intercept age of about 630 ± 44 Ma gives only the range of the inherited age, if no more than two components, inherited core and newly grown zircon at ca. 275 Ma, are present. This, however, is rather unlikely because partial Pb loss is assumed to have affected at least the youngest of the grains. SHRIMP analyses resulted in two concordant ages of 701 ± 10 and 764 ± 11 Ma, and in three slightly discordant ages that plot close to 365, 535 and 1,200 Ma respectively.

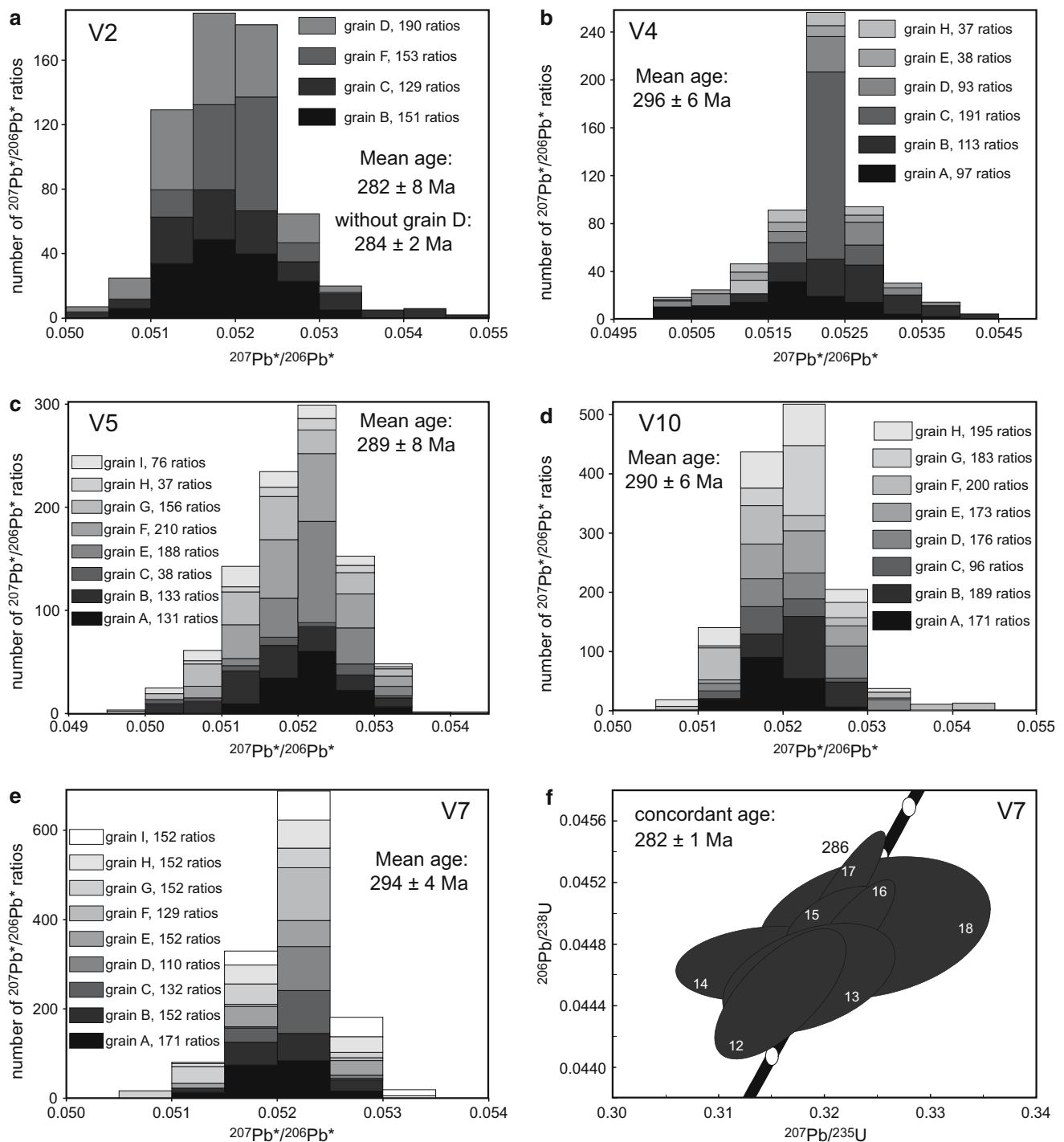


Fig. 4 Geochronological results from the Pb–Pb evaporation dating of basement rocks from the Varnous Mts. are displayed as histograms (a–e). Sample V7 was additionally dated by the conventional U–Pb method (f)

Mt. Olympus region

Strongly deformed, greenish “augen” gneisses crop out northeast of Mt. Olympus (Fig. 1d). The area of orthogneiss exposures is limited to the SW by the Mt. Olympus carbonates and to the north and east by

Tertiary to recent sediments. A coarse- and a fine-grained variety of this orthogneiss (samples PI74 and PI73, respectively) were sampled close to the monastery of Agios Nicolaos (not shown on the map). The mylonitic orthogneisses consist mainly of quartz, K-feldspar, chlorite, plagioclase and remnants of biotite

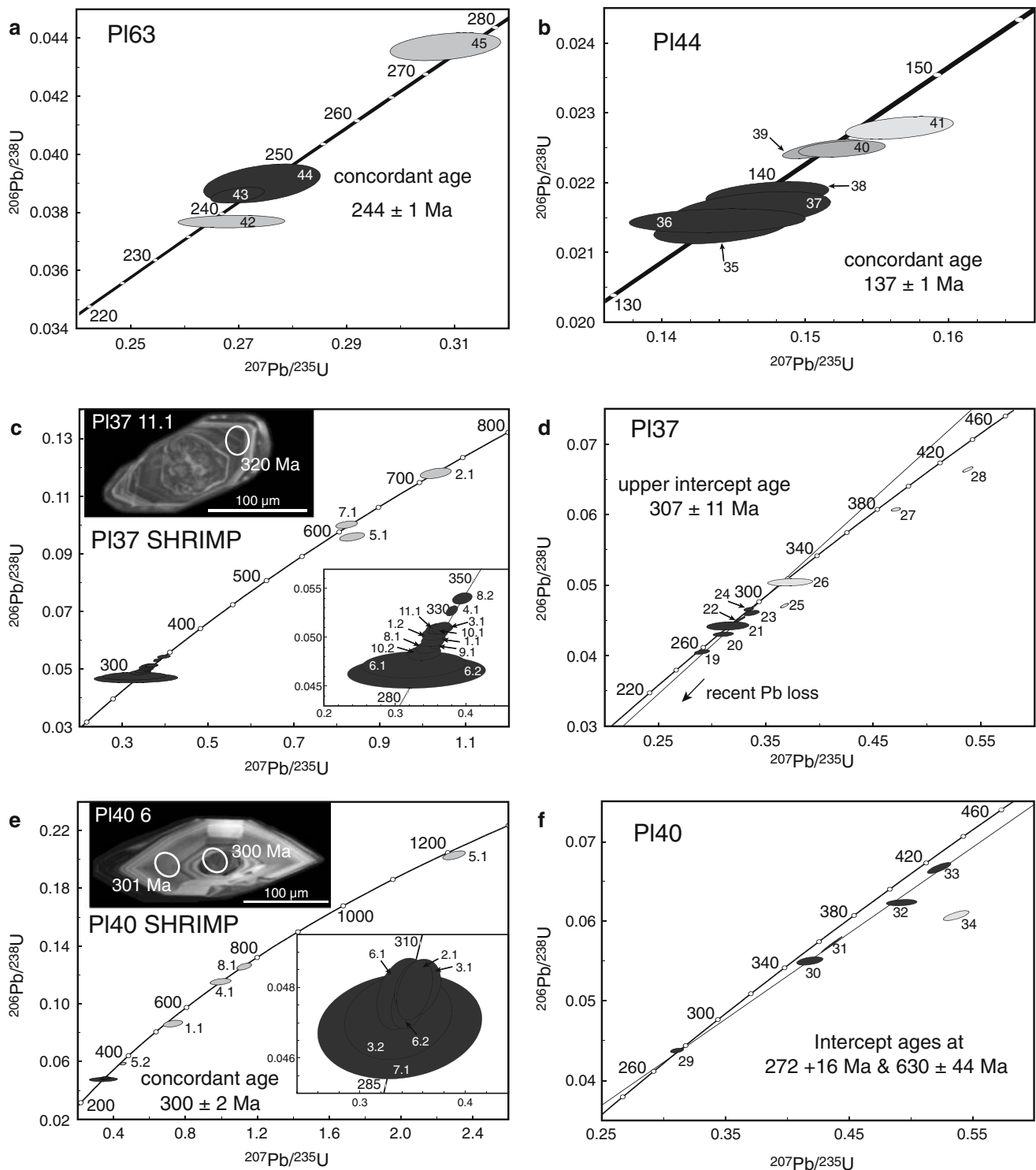


Fig. 5 Geochronological results of basement rocks from Driovouno (**a**) and the area south of Veria (**b–f**). The lower intercept age of sample PI38 was assumed to be 0 Ma (**d**)

and epidote. In the fine-grained variety, the feldspar “augen” have more or less disappeared. Zircons from the fine-grained orthogneiss PI73 were dated by the conventional single-zircon U–Pb method. Seven

discordant and three slightly reversely discordant zircon grains define a discordia line (Fig. 6a). The upper intercept age is 245 ± 8 Ma (MSWD = 1.5). The (forced) lower intercept age of about 0 Ma is inter-

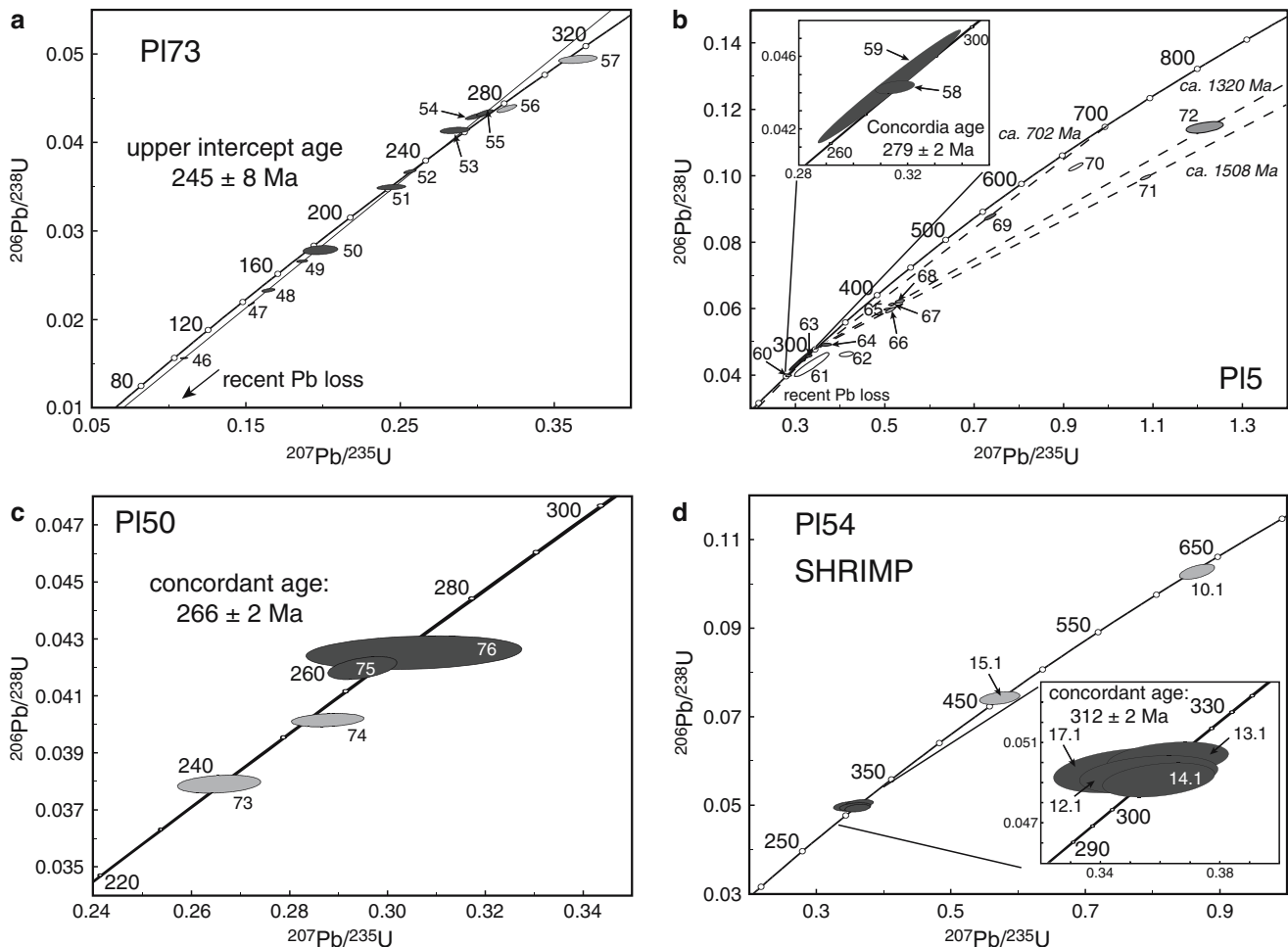


Fig. 6 Geochronological results of basement rocks from the Mt. Olympus and the Mt. Ossa areas. Concordia diagrams display the results of the conventional U–Pb method, unless stated otherwise. The lower intercept age of sample PI73 was assumed to be 0 Ma (a)

interpreted as recent Pb loss. Two older grains seem to reflect an inherited component.

Thessaly/Verdikoussa

The area around Verdikoussa (Fig. 1d) is characterised by large exposures of granites and gneisses. Deformation ranges from undeformed granites to variably deformed augengneisses and to highly sheared rocks in the east (“Ambelakia unit”). PI5 and PI8 are orthogneisses sampled east of Verdikoussa. They consist mainly of quartz, saussuritised plagioclase, K-feldspar, white mica and epidote/clinozoisite, ± titanite. PI8 additionally contains biotite and apatite; the feldspar is severely altered to sericite or epidote.

Zircon grains from orthogneiss PI5 were initially analysed using the Pb–Pb evaporation method. Four ages are in the range of 271–296 Ma, while five older grains scatter from 492 to 1,469 Ma (Table 2). This age distribution makes it impossible to identify the

intrusion age of the rock. Therefore, orthogneiss PI5 was dated by the single-zircon conventional U–Pb method (Fig. 6b). Two concordant grains define an age of 279 ± 2 Ma (MSWD of concordance = 3.7) that is interpreted as the protolith intrusion age. A wide scatter of discordant grains that are older than 279 Ma demonstrates the existence of inherited components in the zircon grains. Several discordia lines can be fitted through groups of these zircon grains. This method does not yield unequivocal results because it assumes that only two events are reflected in the analysis, namely the protolith component and the magmatic intrusion that led to new zircon growth. The method of fitting discordia lines through groups of grains with inherited components might nevertheless give some good indications about the age groups of source rocks contributing to magma genesis. The youngest age for a source component is obtained by three grains that define a discordia with an upper intercept age of 702 ± 36 Ma (MSWD = 1.5). The

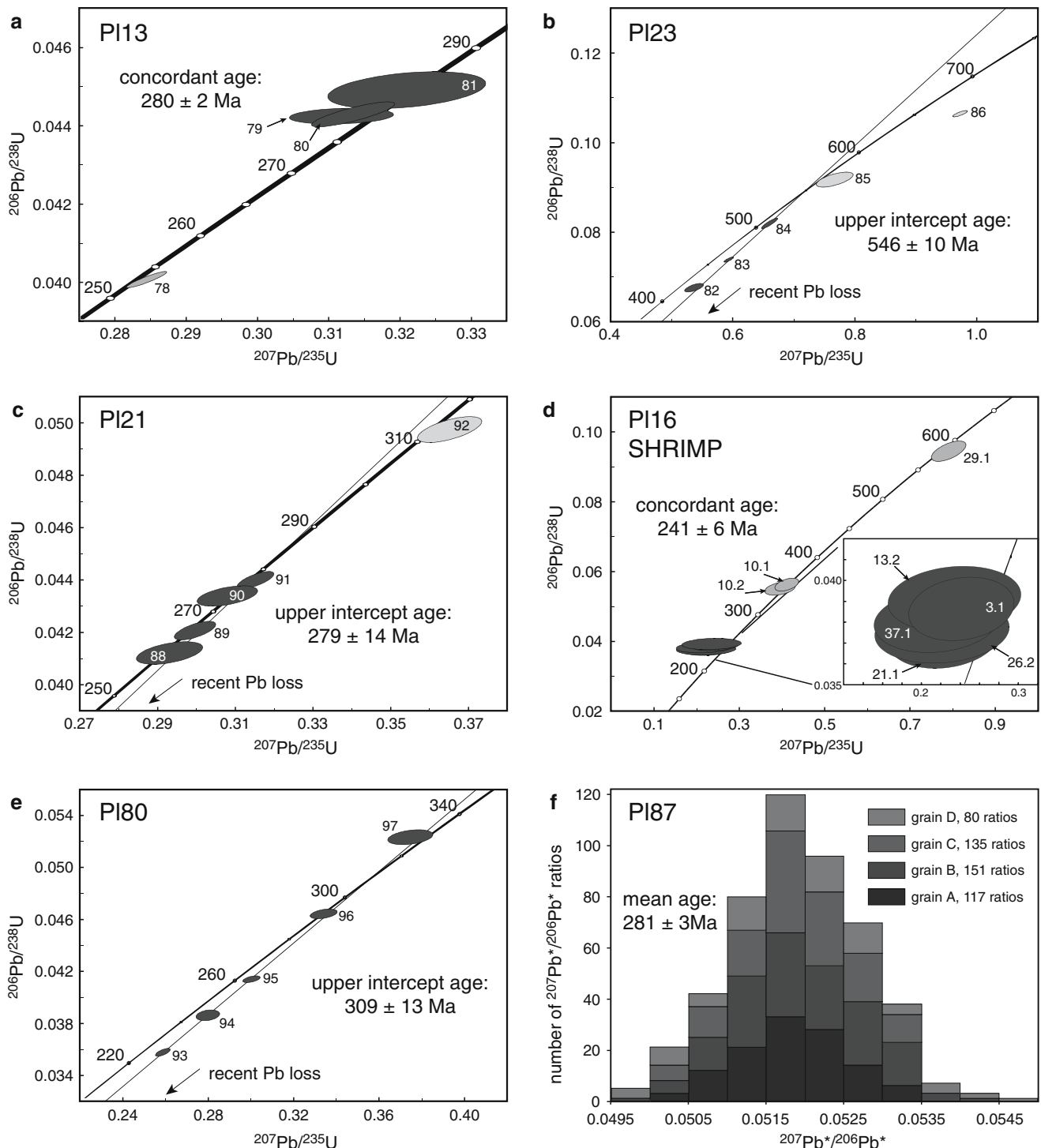


Fig. 7 Geochronological results of basement rocks from the Mavrovouni and Mt. Pilon areas. Concordia diagrams (a–e) display the results of the conventional U–Pb method, unless

lower intercept age of 273 ± 18 Ma is identical, within analytical error, to the magmatic intrusion age. Four zircon grains roughly define a discordia with an upper intercept age of $1,320 \pm 78$ Ma (MSWD = 5.7). The lower intercept age of 299 ± 27 Ma is again close,

stated otherwise. Histogram **f** shows the results of the single-zircon Pb–Pb evaporation method. If no lower intercept age is given (b, c and e), the discordia was forced through 0 Ma

within analytical error, to the magmatic intrusion age. Two zircon grains indicate an even older source component, for which an upper intercept age of $1,508 \pm 21$ Ma and a lower intercept age of 301 ± 7 Ma were obtained. One zircon grain did not

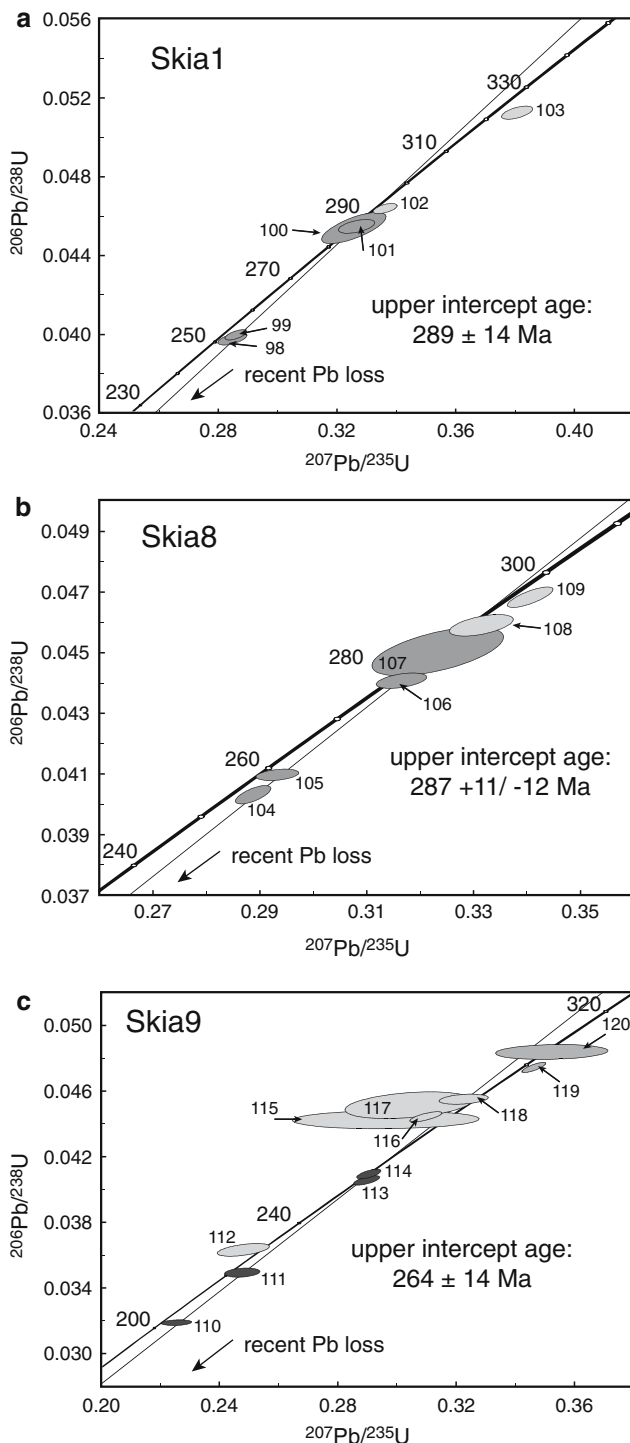


Fig. 8 Results of single-zircon conventional U–Pb analyses of basement rocks from Skiathos Island. For all samples a lower intercept age of 0 Ma was assumed

fit on either of the described discordia lines. If calculated through an age of 279 Ma (intrusion event), an upper intercept age of ca. 880 Ma is obtained. This age, however, could reflect the mixture of more than two components. One young zircon grain fits on a

discordia line between the magmatic event at 279 Ma and present day, demonstrating recent Pb loss.

Zircon grains from orthogneiss P18 were analysed using the Pb–Pb evaporation method. The ages obtained show a heterogeneous distribution that does not allow us to calculate an intrusion age. Some grains scatter around 280 Ma (Table 2), indicating a relation to the Permo-Carboniferous magmatic phase identified in several samples from the Pelagonian Zone. Four grains are older, ranging from 416 to 1,875 Ma, thus indicating the contribution from an older source.

Mt. Ossa

The region of Mt. Ossa (Fig. 1e), south of Mt. Olympos, comprises mostly basement gneisses and phyllites as well as a thick marble succession. Two samples were taken from this region. Sample P150 is a strongly deformed mylonite taken from the eastern flank of Mt. Ossa. The main minerals are quartz, K-feldspar, plagioclase, white mica and chlorite after mica, epidote and minor opaques. Five zircon grains of this mylonite were analysed using the conventional single-zircon U–Pb method (Fig. 6c). Two grains yielded a concordant age of 266 ± 2 Ma (MSWD of concordance = 1.15) while a third concordant grain yielded an age of 240 ± 2 Ma (MSWD of concordance = 0.039). One zircon grain plots slightly discordant between 260 and 240 Ma, a feature that is interpreted as Pb loss. Another grain with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of about 2,076 Ma (not shown in Fig. 6e) clearly displays an inherited component.

P154 is a greenish, strongly foliated mylonite sampled west of Mt. Ossa (Fig. 1e). Plagioclase, K-feldspar and quartz “augen” occur in a matrix of mainly quartz. White mica is concentrated in the foliation planes. Some minor epidote and opaques also occur. Mylonite P154 was dated with SHRIMP (Fig. 6d) and a concordant age of 312 ± 2 Ma (MSWD of concordance = 0.29) was obtained. This age is interpreted as the intrusion age. Two older concordant ages of 461 ± 10 and 632 ± 13 Ma indicate the involvement of an older crustal source in magma genesis.

Mavrovouni

Mavrovouni is another region of the Pelagonian Zone characterised by gneissic basement (Fig. 1e). P113 is a light-coloured, medium-grained orthogneiss that shows strong foliation. It consists of K-feldspar and large, deformed flakes of white mica in a fine-grained matrix of quartz, minor opaques and apatite. The Mavrovouni orthogneiss P113 was dated with the single-zircon

conventional U–Pb method (Fig. 7a). For three grains a concordant age of 280 ± 2 Ma (MSWD of concordance = 7) was obtained. This age is interpreted as the intrusion age. An almost concordant age of ca. 252 ± 12 Ma is attributed to a Pb-loss event, possibly during Lower Triassic times.

Pilion peninsula

The geology of the Pilion peninsula (Fig. 1f) is characterised by large occurrences of felsic to intermediate basement gneisses and schists in northern and south-eastern Mt. Pilion. In central and southwest Pilion marbles and limestones prevail. On the very south-western tip of the Pilion peninsula gneisses are once more exposed. Basement rocks are often severely deformed mylonites. Marbles and remnants of ophiolites are tectonically intercalated with the basement rocks (Wallbrecher 1976; Jacobshagen 1986).

The northernmost sample (PI23) was taken from a gneiss occurrence along the road east of Andraki hill (not shown in Fig. 1f). The gneiss consists mainly of quartz, feldspar, white mica, chlorite, titanite and epidote. Single-zircon dating with the conventional U–Pb method resulted in an upper intercept age of 546 ± 10 Ma (MSWD = 0.96) (Fig. 7b). It is, however, not clear if this age really reflects the intrusion age of the granitic protolith of the gneiss. The abundance of inherited cores visible in CL images could indicate that this age might reflect the inherited age of a contributing source rock. Three older grains demonstrate the existence of a older inherited components. For the two younger grains showing inheritance, a discordia can be calculated that intersects with the concordia at 529 ± 39 and $1,292 \pm 170$ Ma (though two-point discordias are of doubtful reliability). Because the lower intercept is identical, within analytical error, to the obtained age of 546 ± 10 Ma, the upper intercept age of ca. 1,300 Ma could indicate the age of one of the contributing source rocks. The third of the grains showing inheritance has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of ca. 2,062 Ma and therefore reflects another, even older source component.

Orthogneiss PI21 was sampled on a road-cut approximately 4 km NE of the village of Milies (not shown in Fig. 1f). It consists mainly of sparse porphyroblasts of feldspar and white mica set in a fine-grained matrix containing quartz, K-feldspar, plagioclase, epidote and small garnets. PI21 was dated by the single-zircon conventional U–Pb method (Fig. 7c). Four grains are slightly discordant and yielded an upper intercept age of 279 ± 14 Ma (MSWD = 0.43) that is interpreted as intrusion age. It is also possible to

calculate concordant ages for each of these grains separately, but this results in a spread of the concordant ages from 260 ± 2 Ma for the youngest grain to 277 ± 2 Ma for the oldest grain. We interpret the younger ages as the probable result of very slight Pb loss and favour the oldest age as most likely resembling the intrusion age. This age is identical, within error, to the more imprecise upper intercept age, which supports our interpretation. One older grain is interpreted to reflect an older inherited component. Inheritance can be seen in CL images of zircons, where zircons with rounded cores and discordances in the zoning pattern occur besides those showing fine-scale, single-phase oscillatory zoning (Fig. 2g, f).

A rather dark green mylonite (sample PI16) with small feldspar “augen” was also collected in northern Pilion (Fig. 1f). This mylonite consists mainly of quartz, K-feldspar, white mica, chlorite and epidote and was sampled approximately 1.5 km east of Milies. Zircons from mylonite PI16 were dated using SHRIMP. Although most spots plot slightly reversely discordant in a concordia diagram, a relatively concordant age of 241 ± 6 Ma (MSWD of concordance = 13) was obtained (Fig. 7d). Two spots on an older zircon grain yielded a concordant age of 352 ± 7 Ma (MSWD = 0.72).

Orthogneisses from southern Pilion are represented by two samples (Fig. 1f). Sample PI80 was collected from a road cut in southwestern Pilion. It is a fine-grained greenish mylonitic orthogneiss and contains small feldspar “augen” and white mica flakes in a very fine-grained matrix of quartz, some feldspar, white mica and minor epidote. Mylonitic gneiss PI80 was dated using the single-zircon conventional U–Pb method (Fig. 7e). Five zircon grains define a discordia. The upper intercept of the discordia with the concordia line at 309 ± 13 Ma (MSWD = 0.63) is interpreted as the emplacement age.

A coarse-grained mylonite (PI87) was collected from the southern coast of the Pilion peninsula (Fig. 1f). Large, centimetre-sized, feldspar “augen” occur in bands of quartz, K-feldspar, plagioclase, biotite, epidote, white mica and apatite. Orthogneiss PI87 was dated using the single-zircon Pb–Pb evaporation method (Fig. 7f). Four grains yielded an age of 281 ± 3 Ma, which is perceived to closely resemble the intrusion age of the protolith of the orthogneiss.

Skiathos Island

The crystalline basement of western Skiathos Island comprises schists, para- and orthogneisses. Eastern Skiathos Island is dominated by Mesozoic limestones

and marbles as well as Upper Cretaceous to Tertiary flysch. Three orthogneisses from western Skiathos Island (Fig. 1f) were dated using the single-zircon conventional U–Pb method. The southernmost orthogneiss Skia1 was sampled ca. 300 m SE of Maratha village and consists mainly of quartz, sericitised and saussurised feldspar (K-feldspar and plagioclase), biotite, white mica, minor epidote/clinozoisite and minor apatite. Four zircon grains define a discordia with an upper intercept age of 289 ± 14 Ma (MSWD = 0.038, Fig. 8a), which is interpreted as the emplacement age. Two of the four grains display recent Pb loss while the other two grains fall on the concordia curve. From these latter two grains a concordant age of 286 ± 2 Ma (MSWD of concordance = 0.23) can be calculated. Two zircon grains that were not included in the age calculation plot discordantly towards older ages and are interpreted to have incorporated an older inherited component. This interpretation is reinforced by CL images of zircons that show relics of old detrital zircon in the core of the zircon (Fig. 2i). However, most zircons show single-phase magmatic oscillatory zoning in CL images (Fig. 2h, j).

Orthogneiss Skia8 was sampled from the central part of the basement complex of Skiathos Island. The main minerals are quartz, K-feldspar, saussurised plagioclase and white mica. Remnants of biotite occur in addition to minor epidote/clinozoisite. Zircons of orthogneiss Skia8 yielded an upper intercept age of 287^{+11}_{-12} Ma (MSWD = 0.047, Fig. 8b) that is taken as the intrusion age and that is identical, within error, to the intrusion age obtained for orthogneiss Skia1. For one concordant grain a concordant age of 284 ± 4 Ma can be calculated.

Skia9 is a medium-grained, garnet-bearing orthogneiss from the NW coast of Skiathos Island. It was sampled at the northeastern end of Mikro Aselinos Bay. Zircons were dated by the conventional single-zircon U–Pb method (Fig. 8c). A discordia line defined by four grains was calculated through the origin, representing recent Pb loss, and gives an upper intercept age of 264 ± 14 Ma (MSWD = 0.6). Three older grains (grains 119–121, grain 121 not shown in Fig. 8c) are interpreted to reflect the incorporation of an older, inherited component in the zircons. Grain 121 has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of ca. 1,518 Ma (Table 1). Five grains, however, fall on the left-hand side of the concordia line and plot reversely discordant in the concordia diagram. Four of those grains plot in the same range, close to the age of ca. 280 Ma on the concordia line. These results can be interpreted in two possible ways. The first approach is to reject all grains that fall on the left-hand side of the concordia, because this is caused by the

analytical process in the laboratory and hampers the extraction of age information. Then the upper intercept age of ca. 264 Ma would most likely be interpreted as the intrusion age. A second way to interpret the results is to attribute the old group of reversely plotting zircon grains to analytical difficulties, yet accept that they belong to an age group of about 270–290 Ma because they plot close to the concordia line. If the age of ca. 280 Ma were interpreted as the intrusion age, the protolith of orthogneiss Skia9 would have formed during the same time span as that of orthogneisses Skia1 and Skia8. A possible interpretation for the age of 264 Ma could then be a metamorphic overprint in the Upper Permian that only affected the U–Pb isotopic system of zircons in rocks from northern Skiathos Island.

Evia

One of the southernmost samples from the Pelagionian Zone was collected from northern Evia Island (Fig. 1a). Apart from the prevailing Mesozoic sedimentary successions, the northern part of Evia exhibits a small number of outcrops of crystalline basement rocks. Sample Ev4 is a dark-green gneiss that was taken from an outcrop at a road cut between Rovies and Marouli. It consists mainly of quartz, sericitised feldspar and chlorite after mica, calcite, apatite and epidote. Orthogneiss Ev4 was dated using SHRIMP (Fig. 9a). A concordant age of 303 ± 2 Ma (MSWD of concordance = 0.53) was obtained from the analyses of four spots. This age is interpreted to be the intrusion age of the protolith of this orthogneiss.

Skyros Island

The geology of Skyros Island is dominated by metaclastic rocks of Permo-Triassic age as well as metaclastics of probably Mesozoic age and Mesozoic marbles (Melentis 1973; Harder et al. cf. Pe-Piper 1991). In southwestern Skyros Island some severely altered granitoids of presumed Mesozoic age (Pe-Piper 1991) are exposed along small road cuts and one of them was sampled for geochronology (Fig. 1a). Zircons were dated with the single-zircon Pb–Pb evaporation method (Fig. 9b). The zircons turned out to be very young, and a Miocene intrusion age of 16 ± 8 Ma is assumed. A precise age cannot be given because the limit of this dating method is reached by such a young age (low radiogenic Pb concentration and large measurement errors).

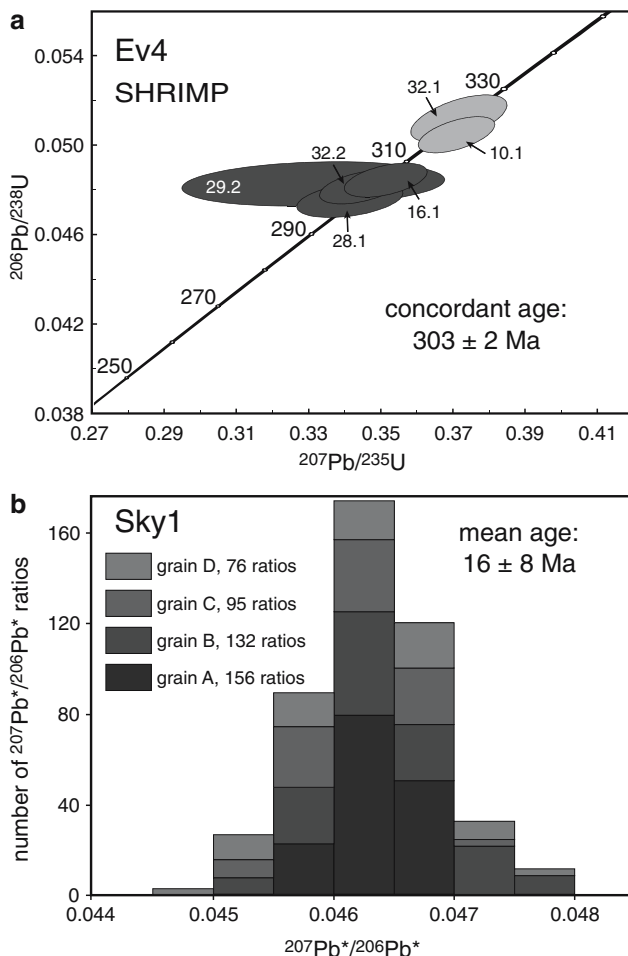


Fig. 9 Results for SHRIMP dating of Ev4 (a) and Pb–Pb evaporation dating of Skyl1 (b)

Summary and discussion

The geochronological results described above show the presence of at least five age groups for magmatic rocks in the western part of the Internal Hellenides. These igneous events are discussed in the following.

Tertiary

Tertiary magmatism is clearly indicated by the Skyros Island granitoid rock, although no precise intrusion age could be obtained because of the limits of dating young zircons by the Pb–Pb evaporation method. The Tertiary age supports the assumption of Fytikas et al. (1980) that these intrusive rocks are Cainozoic in age and do not have, as Pe-Piper (1991) suggested, a Mesozoic age.

Jurassic/Cretaceous

The second age group is represented by the Upper Jurassic/Lower Cretaceous meta-granite Pl44 sampled

south of Veria, which could be a rock of the westernmost Vardar Zone. Jurassic magmatism in the Vardar Zone as a result of ocean spreading and subduction-zone volcanism (Paikon Massif) is well known (e.g. Mercier et al. 1975; Anders et al. 2005). The Upper Jurassic age of this orthogneiss might either reflect an independent igneous pulse that has so far gone undetected in the Pelagonian Zone, or it might be related to Jurassic igneous activity in the Vardar Zone, in which case the granite was tectonically emplaced in its present position at the eastern margin of the Pelagonian Zone. There is abundant evidence for such tectonic movements in the area east of the Pelagonian Zone as shown by eastward thrusting of ophiolites and strike-slip faulting (e.g. Mercier et al. 1975; Mountrakis 1984; Bébien et al. 1986; Brown and Robertson 2004).

Triassic

Two different types of Triassic rocks from the Pelagonian Zone were dated in this study: a meta-rhyolite in the NW Pelagonian Zone (Pl63) and mylonitic orthogneisses in the Eastern Pelagonian Zone. Mountrakis et al. (1987) described meta-rhyolites that crop out near Driovouno village in the northwestern Pelagonian Zone and proposed an Early Triassic intrusion age for these rocks, because they lay stratigraphically below Middle Triassic limestones and intrusion contacts between the rhyolites and the limestones are absent. The Early Triassic age of the rhyolites inferred by Mountrakis et al. (1987) is now confirmed by our U–Pb dating of zircons from a meta-rhyolite close to Driovouno village, which resulted in an intrusion age of ca. 244 Ma. A Cretaceous age obtained by K–Ar geochronology of K-feldspar phenocrysts of the Driovouno rhyolites was ascribed by Mountrakis et al. (1987) to metasomatic overprint. The Triassic volcanic rocks in the western Pelagonian Zone are interpreted to be related to rifting in the realm of the later Pindos ocean (e.g. Robertson et al. 1991), although some authors argue in favour of all ophiolites being derived from one single ocean east of the Pelagonian Zone (e.g. Bortolotti et al. 2003).

Triassic zircon ages are also known from the eastern part of the Pelagonian Zone. Northeast of Mt. Olympus and in northern Mt. Pilion two rocks were dated at 245 ± 8 Ma (mylonitic orthogneiss Pl73) and 241 ± 6 Ma (mylonite Pl16), respectively. We interpret these ages as the intrusion ages of the protolith, whereas the age of the mylonitisation remains unknown. Other samples from the East Pelagonian Zone also seem to have been affected by a Late Permian to Triassic thermal event. For example, orthogneiss Skia9

from northern Skiathos Island either intruded during the latest Permian or a metamorphic event at that time led to resetting of the U–Pb system of zircons from this sample. Another example is mylonite Pl50 from the eastern flank of Mt. Ossa that is interpreted to have intruded at ca. 266 Ma and to have been overprinted at ca. 240 Ma. Interpretation of these Triassic rocks in a geodynamic context is difficult, because Triassic magmatism is considered to be related to post-Variscan extension, rifting and spreading of Neotethyan ocean basins (e.g. Mountrakis et al. 1987; Pe-Piper 1982, 1998; Stampfli et al. 2001; Pe-Piper and Piper 2002). For example, Sub-Pelagonian and Pelagonian Zone Triassic volcanic rocks are exposed in Argolis (e.g. Bortolotti et al. 2001, 2003), Chios Island (Pe-Piper 1982 and references therein), Evia (De Bono 1998; Pe-Piper 1998 and references therein; De Bono et al. 2001), Atalanti (Kauffmann 1976) and Mt. Othris (e.g. Kauffmann 1976). Most of the Triassic volcanic rocks in the Pelagonian Zone are basaltic in composition with rhyolites occurring rather rarely. Triassic rift-related magmatism is also known from the easternmost part of the Vardar Zone, where Triassic basalts and rhyolites have been reported (Kockel and Mollat 1977; Dimitriadis and Asvesta 1993), and from the Serbo-Macedonian Massif where the Triassic within-plate Arnaea granite has intruded Silurian basement orthogneisses (Himmerkus et al. 2004). The Vardar Zone constitutes proof of a Mesozoic ocean basin east of the Pelagonian Zone; in its western part Early Triassic spreading was suggested by Staïš and Ferrière (1991) and Brown and Robertson (2003). In analogy to such models we interpret our Triassic zircon ages to date the magmatic activity related to this extensional setting.

Permo-Carboniferous

The majority of the samples in this study belong to basement rocks that have Permo-Carboniferous intrusion ages. Since the pioneering work of Yarwood and Aftalion (1976) the Permo-Carboniferous period is regarded as an era of major magmatism in the region. The importance of this magmatic phase for the evolution of the Pelagonian Zone basement is further underscored by the results of this study. We have demonstrated that Permo-Carboniferous magmatism was widespread throughout the Pelagonian Zone and that for some areas, where basement rocks had hitherto been interpreted as belonging to the Pelagonian Zone on a structural or stratigraphic basis only these interpretations are correct on the basis of intrusion ages. For example, the Permo-Carboniferous protolith

ages of gneisses from Skiathos Island determined here are in accordance with the suggestion of Ferentinos (1973) who claimed that the metamorphic basement of western Skiathos Island is part of the Pelagonian Zone. Similarly, the gneisses of the Likostomo-Promachi Unit in the central part of the Voras Mts. were interpreted by Migiros and Galeos (1990) and Brown and Robertson (2004) as showing affinity to the Pelagonian Zone and not to the Serbo-Macedonian Massif. This interpretation is now confirmed by the age of 285 Ma obtained for orthogneiss Pl75, because Permo-Carboniferous intrusion ages are absent from the neighbouring parts of the Serbo-Macedonian Massif (Himmerkus et al. 2003).

Magmatic ages of Permo-Carboniferous basement rocks in the Pelagonian Zone range from ca. 320 Ma (Vavassis et al. 2000; De Bono 1998) to ca. 280 Ma (Reischmann et al. 2001; this study), indicating long-lived subduction-zone magmatism. A systematic northward younging of intrusion ages, as suggested by Reischmann et al. (2001), would indicate that the commencement of subduction-zone magmatism varied laterally. However, although most of the older ages are found in the southern parts of the Pelagonian Zone this hypothesis could not be confirmed by the ages obtained in our study. According to the palaeogeographic reconstructions, e.g. of Stampfli et al. (2001) and Stampfli and Borel (2002), the active continental margin was situated at the southern European margin.

The Varnous pluton in the northwestern Pelagonian Zone occupies an area where magmatism started at about 290 Ma and continued probably up until ca. 280 Ma. This is indicated by the spread of ages obtained for the various rocks from the Varnous pluton. The majority of the zircon ages are interpreted to represent the time of magmatic growth of the zircons, although some young ages clearly reflect Pb loss. The internal structure of zircons from the Varnous pluton, which are visible in CL images (Fig. 2), show diffuse areas of resorption, complex structures of cores or lighter-coloured rims. Geochronology provided no evidence for inherited components, therefore these structures are interpreted mostly as syn- to late magmatic, suggesting multiple intrusion events in a long-lived magma chamber system, or as post-magmatic, in which case recrystallisation can cause Pb loss and result in younger ages.

Precambrian

Rocks older than Upper Carboniferous were not encountered in this study except for gneiss Pl23 from northern Pilion, although in the western part of the

Pelagonian Zone Neoproterozoic basement rocks have been identified (Anders et al. 2003, 2006). It is, however, not clear whether the age of ca. 546 Ma of gneiss Pl23 dates the intrusion of the precursor granitoid or whether it reflects an older source.

Inherited cores in zircon grains in some samples with ages around 700 Ma could be an indication that detritus of the Neoproterozoic rocks from the northwestern Pelagonian Zone was incorporated in magma genesis during the Permo-Carboniferous magmatic event. All in all, inherited zircon components were found in several samples, mostly hinting at a Mesoproterozoic to Palaeoproterozoic source contribution.

Palaeogeographic considerations

Magmatic crystallisation ages of about 300 Ma are not only widespread in the Pelagonian Zone but also in the Attico-Cycladic Massif in the southeastern continuation of the Pelagonian Zone (Engel and Reischmann 1998, 1999; Reischmann 1998). This led Reischmann et al. (2001) to propose the presence of a huge Permo-Carboniferous magmatic arc in this region of the eastern Mediterranean. Other regions in the eastern Mediterranean in which Permo-Carboniferous basement rocks occur are the Sakarya Complex in NW Anatolia, Turkey (Özmen and Reischmann 1999), the Rhodope Massif of both NE Greece and S Bulgaria (Peytcheva and von Quadt 1995; Turpaud and Reischmann 2003; Peytcheva et al. 2004) and the Strandja Massif in E Thrace, Turkey (Okay et al. 2001). By contrast, Permo-Carboniferous basement rocks are not known from the Menderes Massif, which is the eastern prolongation of the Attico-Cycladic Massif in Turkey. Here, granitic rocks with magmatic ages of ca. 540 Ma prevail (e.g. Hetzel and Reischmann 1996; Loos and Reischmann 1999). It is therefore highly unlikely that the Menderes Massif forms the eastern continuation of the Pelagonian Zone and the Attico-Cycladic Massif, as was suggested by Dürr (1975). The geodynamic correlation of the different regions dominated by Permo-Carboniferous magmatism in the Eastern Mediterranean is a matter of ongoing discussion. With regard to the origin of gneiss Pl23 from northern Pilion, for which a zircon age of ca. 546 Ma was obtained, one could suggest a relation to the Menderes Massif. A second explanation is that this rock formed part of the basement on which the Pelagonian Permo-Carboniferous magmatic arc developed, as is the case for the Florina-Terrane in the NW Pelagonian Zone (Anders et al. 2006). Apart from the Menderes Massif, latest Precambrian magmatism has also been recorded in the Istanbul Zone of NW Turkey (Chen et al. 2002),

the Serbo-Macedonian Massif of northern Greece (Himmerkus et al. 2003) and the Kraište region of western Bulgaria, where Graf (2001) obtained magmatic ages of about 550 Ma for basement rocks. So far it is not possible to draw a clear correlation between orthogneiss Pl23 from northern Pilion and rocks from any of the above regions of Latest Precambrian basement exposures.

In the context of the palaeogeographical reconstructions of Stampfli et al. (2001), it becomes clear that the Permo-Carboniferous northward subduction of Palaeotethys beneath the southern margin of Europe with its attendant magmatism was the dominant contribution to the formation of what is nowadays the Pelagonian Zone. The Early Triassic felsic magmatism, for which we here report the first zircon ages, is then the expression of Late Permian/Early Triassic extension that led to the development of ocean basins both east and west of the Pelagonian Zone. The so far sole Upper Jurassic/Cretaceous zircon age from the northeast Pelagonian Zone could have formed during subduction in the Meliata oceanic domain. During later shortening and obduction remnants of such oceanic crust could have been incorporated into the eastern Pelagonian Zone.

Conclusions

Permo-Carboniferous basement rocks occur throughout the entire Pelagonian Zone and form the predominant age group. Among the different crust-forming events in the western Internal Hellenides this episode of magmatism is by far the most important and is related to a continental magmatic arc setting. Permo-Carboniferous magmatism occurred over a relatively large time span from ca. 320 to ca. 280 Ma. Commencement of magmatism does not vary systematically throughout the Pelagonian Zone.

Inherited zircon components identified in orthogneisses from the eastern Pelagonian Zone (e.g. south of Veria and in Verdikoussa area) indicate the previous existence of Neoproterozoic basement in the region into which the Permo-Carboniferous magmas had intruded. Inheritance is a widespread feature of zircon populations in orthogneisses from the Pelagonian Zone and signifies the contribution of Precambrian basement to the source of the Palaeozoic and Mesozoic magmatic rocks.

Triassic magmatism was demonstrated both by a meta-rhyolite from the northwestern Pelagonian Zone as well as by the intrusion age of felsic rocks that were later deformed to mylonites from the eastern Pelago-

nian Zone. Triassic metamorphism appears to have affected the U–Pb system of zircons in several samples, resulting in sporadic Triassic ages of individual grains.

The Upper Jurassic/Lower Cretaceous age obtained for an orthogneiss in the area south of Veria is to our knowledge the first zircon age of this age range reported from the Pelagonian Zone. Tentatively, this orthogneiss is assigned an Almopias Zone origin (i.e. western part of the Vardar Zone).

Tertiary magmatism in the Pelagonian Zone is of minor significance.

In conclusion, the results of the present study clearly demonstrate that the major crust-forming events in the Pelagonian Zone are predominantly of pre-Alpine/Variscan age.

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Appendix: Analytical methods

For geochronology sample weights were between 8 and 12 kg. The rocks were crushed and sieved to a grain size smaller than 500 μm using standard procedures, followed by mineral separation using a Wilfley table, a Frantz magnetic separator and heavy liquids. In a final step, the zircons were handpicked under a binocular to avoid grains with visible inclusions.

Three different methods were used for zircon geochronology, namely the Pb–Pb evaporation method (Kober 1986, 1987), the conventional U–Pb method and SHRIMP (e.g. Compston et al. 1984; Compston 1999).

For zircon grains that were analysed using the Pb–Pb evaporation method, ages were calculated from the $^{207}\text{Pb}/^{206}\text{Pb}$ values after correction for common Pb using the values of Stacey and Kramers (1975). Sample ages were calculated as weighted averages, using Isoplot (Ludwig 2003).

The application of the single-zircon conventional U–Pb method is based on the low contamination method of Krogh (1973). Before dissolution, the zircons were washed in 7 N HNO_3 and a mixed ^{205}Pb – ^{235}U spike was added. The zircon grains were dissolved with HF in Teflon bombs at 200°C. Chemical separation of U and Pb with HBr chemistry followed, using 20 μl columns filled with anion-exchange resin. Some zircon

grains of sample V7 were analysed following the vapour digestion method of Wendt and Todt (1991), in which Pb and U are not chemically separated after dissolution but measured from the same Re filament. Pb and U were loaded on single Re filaments with silica gel. Thermal ionisation mass spectrometer (TIMS) measurements were performed on a Finnigan MAT 261 equipped with a secondary electron multiplier at the Max-Planck-Institut für Chemie, Mainz, Germany. After correction for fractionation, blank and common Pb (using the values of Stacey and Kramers 1975), ages were calculated using Isoplot (Ludwig 2003). Procedure blanks were < 40 pg Pb, the fractionation factor (3‰ per ΔAMU) was determined by repeated measurements of NBS 981 under the same conditions as the samples.

Three samples (PI54, PI16 and Ev4) were dated by sensitive high-resolution ion microprobe (SHRIMP) at the ANU, Canberra, Australia. For calibration of the Pb–U ratios the zircon standard FC1 (age 1,099 Ma; Paces and Miller 1993) was used. U concentrations were calibrated using the SL13 zircon standard. Two samples (PI37 and PI40) were dated by SHRIMP at the Centre of Isotopic Research, St. Petersburg, Russia. The TEMORA reference zircon (age 416.75 Ma; Black et al. 2003) was used for calibration of the Pb–U ratios and zircon standard 91500 for U concentration calibration (Wiedenbeck et al. 1995). Data reduction and age calculations were based on SQUID (Ludwig 2001). Concordia diagrams were drawn with Isoplot (Ludwig 2003). All ages are given either at 2σ or 95% confidence level.

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