Geol Rundsch (1996) 85:761–774

ORIGINAL PAPER

Th. Reischmann · G. Anthes

Geochronology of the mid-German crystalline rise west of the River Rhine

Received: 8 January 1996 / Accepted: 2 June 1996

Abstract The mid-German crystalline rise has its westernmost exposures at the western margin of the Rhine graben in the southern Pfalz and the northern Alsace. The outcrops are made up of granitoid rocks and minor volcano-sedimentary sequences. Radiometric ages obtained by U/Pb, Pb/Pb, Sm/Nd and Rb/Sr analyses of the igneous rocks from this area range from ~433 to ~325 Ma thus covering a time span from the Silurian to the end of the lower Carboniferous. Because the investigated rocks are – according to their chemical composition – largely related to subduction zone environments, the following three geodynamical scenarios are postulated, always taking subduction of oceanic crust beneath the mid-German crystalline rise into account: (a) subduction of the Rheic ocean during the Silurian from the north; (b) subduction of the Rhenohercynian ocean during the late Devonian (~369 Ma) from the north; (c) subduction of the Saxothuringian ocean during the lower Carboniferous (~334 Ma) from the south.

Key words Geochronology · Mid-German crystalline rise · Variscan orogeny, S-Pfalz, N-Alsace

Introduction

The westernmost outcrops of the mid-German crystalline rise (MGCR) are exposed along the escarpments of the western shoulder of the Rhine Graben in the southern Pfalz and northern Alsace (Fig. 1). These occurrences are part of the Saxothuringian zone of the Variscan basement and are made up of granitoid rocks, metasediments and minor metavolcanics. They are unconformably overlain by Permian volcanics and sediments followed by Mesozoic strata. The localities and rock types are from N to S the metasediments of Neustadt and Hambach, the granite of Edenkoben, the metasediments and granitic dikes of Burrweiler, the gneiss of Albersweiler, the granodiorite of Waldhambach, the metasediments and metavolcanics of Weiler and the granodiorite of Windstein.

Only few formation ages of this part of the MGCR are known. The only published radiometric data are K–Ar ages of 334 ± 15 Ma for biotite of the Albersweiler gneiss (Frenzel 1971, recalculated) and 340 Ma for the Windstein granodiorite (Montigny et al. 1983). The metasediments of Weiler were assumed to be lower Carboniferous according to plant fossils (Genser 1965; Münzing 1956). Similarly, the metagreywackes of Neustadt are considered as sediments of the early lower Carboniferous (Häntzschel 1972). To the west the age of the MGCR is known from the borehole Saar 1, in which mid-Devonian to Lower Carboniferous sediments overlie a granite with a U/Pb zircon age of 444 ± 22 Ma (Sommermann 1993). The E extension of the MGCR is exposed in the Odenwald with ages of 362–332 Ma in the Bergsträsser part and ages of 375 Ma and around 400 Ma in the Böllstein area (Lippolt 1986; Kirsch et al. 1988; Todt et al. 1995). Biotite cooling ages from the Odenwald are around 330 Ma (e.g. Hess and Schmidt 1989). Further to the east in the Spessart, approximate Silurian ages, such as 414 ± 18 Ma and 439 ± 15 Ma (Lippolt 1986; Nasir et al. 1991), and 418 ± 18 Ma and 410 ± 18 Ma (Dombrowski et al. 1995), are well established.

Thus, the formation ages of the MGCR appear to cover a time span of more than 100 Ma from the Ordovician/Silurian to the lower Carboniferous, but details on the evolution of the MGCR are still inadequate. This study focusses on the geochronology of the westernmost region of the MGCR. We have chosen the

Thomas Reischmann (✉) · Gerald Anthes
Institut für Geowissenschaften, Johannes Gutenberg-Universität, Becherweg 21, D-55099 Mainz, Germany
Fax: +06131 394769
e-mail: reischma@mzdmza.zdv.uni-mainz.de

Thomas Reischmann · Gerald Anthes
Max-Planck-Institut für Chemie, Abteilung Geochemie, Becherweg 27, D-55020 Mainz, Germany

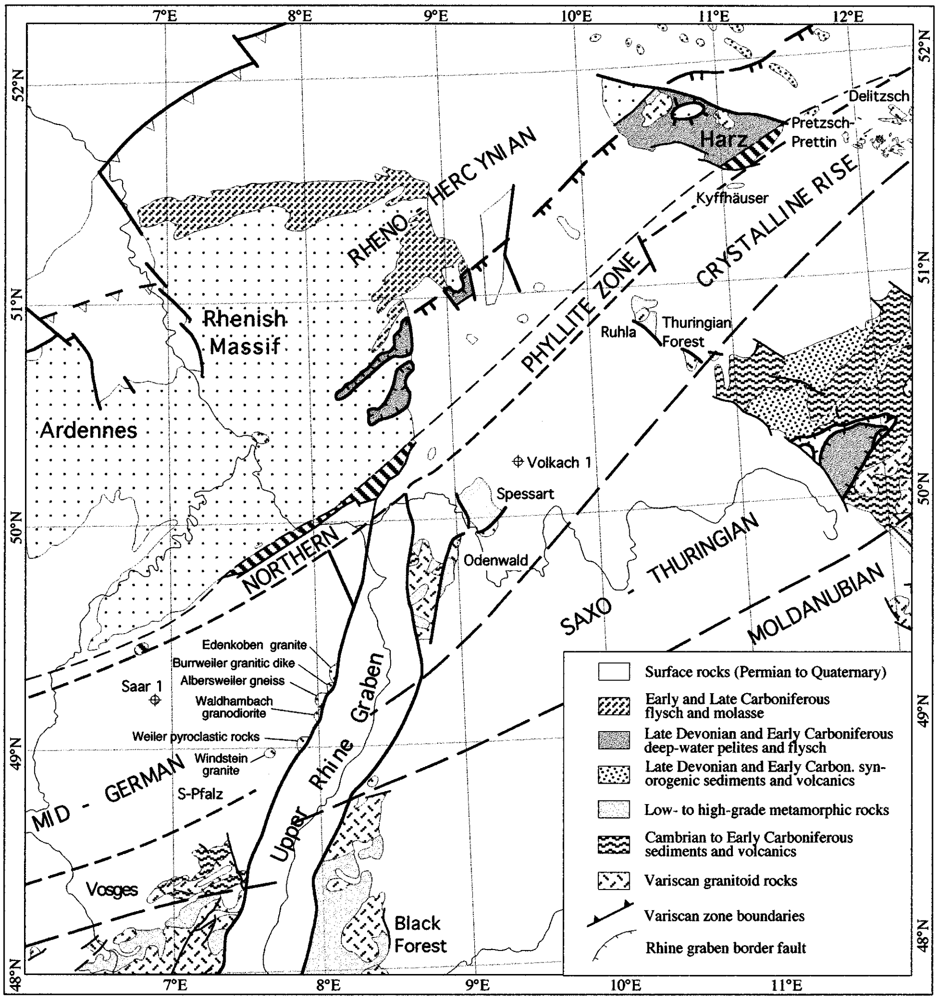

Fig. 1 Geological map of the mid-German crystalline rise. (Modified after Dallmeyer et al. 1995)

rocks of igneous origin from this area for radiometric age determination in order to acquire a profound database for the magmatic events of the MGCR as well as to better understand the role that the MGCR played within the evolution of the Variscan orogeny.

Samples and geological background

The sample localities are from a ca. 60-km-long SSW–NNE profile crossing the southern part of the MGCR along the western escarpments of the Rhine graben in the S-Pfalz and N-Alsace. The rock units analysed in this study are from N to S the granite of Edenkoben, the granitic dikes of Burrweiler, the granitoid gneiss of Albersweiler, the granodiorite of Waldhambach, the pyroclastic rocks of Weiler and the granodiorite of Windstein (Fig. 1).

The granite of Edenkoben

The Edenkoben granite is exposed in an area of ca. 0.5 km^2, 2 km west of Edenkoben in the Triefenbach valley. The country rock into which the granite intruded is not exposed. The granite itself is cut by thin aplitic and pegmatitic dikes as well as one lamprophyre dike. The granite is mainly undeformed with the exception of a weak foliation that was caused by the intrusion of the granite itself (Flöttmann and Oncken 1992). The granite is unconformably overlain by sandstones of the Lower Buntsandstein. The modal composition is plagioclase, K-feldspar, quartz, biotite, muscovite and opaques in decreasing order. Biotite is partially replaced by chlorite and the feldspars are cloudy in places. This indicates a weak low-temperature alteration, although a metamorphic overprint is not recognizable. The composition of the granite of Edenkoben ranges from 69.26 to 74.94% SiO_2. The rocks contain $Na_2O < K_2O$, and are very similar to S-type granites. They can further be classified as syn-collisional granite. Details are given in Laue and Reischmann (1994).

The granite dikes of Burrweiler

The granite dikes of Burrweiler which intruded into medium-grade metasediments are exposed in the Modenbach valley ca. 2 km NW of Burrweiler. The schists are mainly metapelites in which cordierite as relict of an early high temperature metamorphism could be identified (Flöttmann and Oncken 1992). One dike of ca. 0.5 m in width can be followed for a few metres. Others are preserved as small boudains within the schists. The basement is overlain by coarse lower Permian fanglomerates. The dikes are two mica granites according to their mineral assemblage with quartz, K-feldspar, plagioclase (An_{30}), biotite, muscovite and opaques. Biotite is partly altered to chlorite. Chemically, the Burrweiler dikes are typical S-type granites with, for example, high SiO_2 of 73.91% and $K_2O > Na_2O$. Similar to the Edenkoben granite, this composition is akin to that of syn-collisional granites. For further details the reader is referred to Laue and Reischmann (1994).

The granitic gneiss of Albersweiler

The granitoid gneiss of Albersweiler is well accessible at the NW margin of the village in the active northern quarry and the abandoned southern quarry. The gneiss is heterogeneous with darker and lighter varieties as well as differences according to the foliation. It is composed of quartz, plagioclase, K-feldspar, biotite and accessory minerals. E–W and N–S trending lamprophyre dikes cut through the gneiss complex which is unconformably covered by Permian sediments and volcanics (Löhr 1991; Flöttmannn and Oncken 1992). The SiO_2 composition ranges from 68.18 to 73.76% and K_2O is always less than Na_2O. The rocks belong to a sequence of calc-alkaline affinity and have the geochemical characteristics of I-type granites from a magmatic arc. Further information on the geochemistry is provided by Laue and Reischmann (1994).

The granodiorite of Waldhambach

The granodiorite of Waldhambach is exposed in an active quarry 2 km east of the village in the Kaiserbachtal. The largest part of the quarry is within the Permian volcanics which unconformably overlie the granodiorite. The granodiorite itself is accessible in the SE part of the quarry, where two NW–SE striking lamprohyre dikes cut through it. The rocks consist of plagioclase, quartz, alkali feldspar, biotite and accessories such as apatite, magnetite and zircon in decreasing order. Minor occurrences of gneisses and amphibolites are considered as remnants of the country rock into which the granodiorite intruded. The plutonic complex displays a magmatic foliation which is visible by the orientation of the numerous mafic to intermediate inclusions. Despite a minor brittle deformation, the granodiorite is well preserved without signs of metamorphism or alteration. Geochemically, the granodiorites investigated cover a narrow SiO_2-range of 69.38–71.03%. The Na_2O/K_2O is always >1, which supports the I-type character. The low Nb concentrations <10 ppm are also akin to the composition of volcanic arc granites (Laue and Reischmann 1994).

The pyroclastic rocks of Weiler

In Weiler, a village between Wissembourg/Alsace and the St. Germanshof/Pfalz, pre-Permian basement rocks are accessible. They can be found in the village, as well as in the Lauter valley and in the Buchbach valley, a small tributary. A recent investigation by Mühe (1992) identified pyroclastic rocks among metasediments of presumed lower Carboniferous age (Flöttmann and Oncken 1992). These metasediments and pyroclastics were intruded by numerous lamprophyre dikes and unconformably covered by Permotriassic sequences. Geochemically, the pyroclastics are similar to calc-alkaline volcanics generated in a subduction environment (Mühe 1992).

The granodiorite of Windstein

The granodiorite of Windstein is exposed in the valley of the Schwarzbach ca. 0.5 km SW of the ruins of Windstein castle. The pluton exposure is covered by lower Buntsandstein sediments. The rocks consist of plagioclase, quartz, K-feldspar, biotite and, in contrast to the previously described granitoids, also of hornblende. Apart from apatite, zircon and oxides, the mineral sphene occurs frequently as an accessory. The SiO_2 content ranges from 63.82 to 70.25%; only one aplitic dike is more differentiated containing 75.87% SiO_2 (Laue and Reischmann 1994). The rocks form a calc-alkaline suite with clear I-type characteristics and are therefore assumed to have formed in relation to a subduction zone.

Analytical methods

The $^{207}Pb/^{206}Pb$ single zircon evaporation technique was the preferred dating method for the granitoid rocks from Edenkoben, Waldhambach, Windstein and the Albersweiler gneiss. This method permits the precise analyses of individual zircon grains and has the additional advantage that inherited zircons can be recognized. In order to prove the suitability of this method for the studied rocks, we selected the granodiorite from Waldhambach for additional conventional U/Pb analyses as well as for single zircon vapour digestion U/Pb measurements. The metavolcanics from Weiler were dated by the Rb/Sr and Sm/Nd method. Rock types and sample locations are listed in Table 1.

The weight of the samples for zircon analyses ranged between 5 and 10 kg. They were crushed with a jaw crusher and a roller mill yielding a grain size of <0.5 mm. One part of this homogenized sample of 100 g was separated and powdered with an agate planet

Table 1 Rock types investigated and sample locations

Sample	Rock type	Locality	Coordinates
A-7	Granitic gneiss	Northern part of quarry at Albersweiler	R 3428770 / H 5454280
A-10	Granitic gneiss	Northern part of quarry at Albersweiler	R 3428900 / H 5454350
A-17	Granitic gneiss	Southern part of quarry at Albersweiler	R 3428540 / H 5454080
BUR-02	Granitic dike	Outcrop NW of Burrweilermühle, Modenbach valley	R 3432590 / H 5458480
EDE-02	Granite	Quarry in Triefenbach Valley, SW of Edenkoben	R 3433770 / H 5460950
EDE-03	Granite	Quarry in Triefenbach Valley, SW of Edenkoben	R 3434020 / H 5460870
EDE-04	Granite	Quarry in Triefenbach Valley, SW of Edenkoben	R 3434670 / H 5460950
EDE-05	Granite	Quarry in Triefenbach Valley, SW of Edenkoben	R 3434680 / H 5460980
K-11	Granodiorite	Southern part of quarry in Kaiserbach Valley	R 3427540 / H 5447320
PW-1	Granodiorite	Southern part of quarry in Kaiserbach Valley	R 3427510 / H 5447320
W-9	Granite	Outcrop NW of Petit-Muehlberg	R 3412050 / H 5427040
WEI-A	Dacitic ignimbrite	Outcrop at Buchbachtal near Weiler/Wissembourg	R 3419780 / H 5434620
WEI-B	Dacitic ignimbrite	Outcrop at Buchbachtal near Weiler/Wissembourg	R 3419780 / H 5434620
WEI-C	Andesitic–dacitic tuff	Outcrop at Buchbachtal near Weiler/Wissembourg	R 3419780 / H 5434620
WEI-D	Andesitic–dacitic tuff	Outcrop at Buchbachtal near Weiler/Wissembourg	R 3419780 / H 5434620

mill for further chemical analyses. The rest of the material was taken for heavy mineral concentration by using a Wilfley table. From the heavy fraction the non-magnetic material was extracted by a Frantz magnetic separator at 1 A current, with 12° forward tilt and 5° side tilt. Additional heavy mineral enrichment was attained by using heavy liquids such as bromoform (r = 2.8 g/cm^3) and methylene iodide (= 3.3 g/cm^3). The heavy mineral fraction was cleaned in 6 n HCl for 2–3 h before finally hand-picking the zircons under the binocular. The zircons selected for U/Pb measurements were additionally cleaned with 6 n HNO_3 and subsequently with 6 n HCl, each stage for 15 min in ultrasonic, immediately prior to dissolution.

^{207}Pb/^{206}Pb single zircon evaporation analyses

^{207}Pb/^{206}Pb single zircon ages were obtained by measuring the Pb-isotopes of evaporated zircons using a double Re-filament configuration. The principles of this method are described in Kober (1987) and Kröner et al. (1994). The evaporation temperatures ranged from 1432 to 1550°C. In each case the Pb isotopic composition was checked for changes at increasing temperatures. The heating was continued until no more changes in the Pb composition were recognized. Such a stable Pb isotopic composition was used for the measurement. The evaporated Pb condensed on the cold second Re filament which subsequently was heated to ionize the Pb condensate. Ionization temperatures were in the range of 1100–1200°C. The entire procedure was continued until all Pb had evaporated in order to check for the possibility of an older Pb component. In general, the zircons were single-domain zircons according to their Pb isotopic composition; only one composite grain could be identified.

The Pb isotopes of the zircons were analysed at the Max-Planck-Institut für Chemie in Mainz (Germany) using a Finnigan MAT261 mass spectrometer with a secondary electron multiplier (SEM) or ion counter, respectively. Results for both detector systems are identical within error. The measured ^{207}Pb/^{206}Pb were corrected for common Pb when necessary. Run precision and the error of the according individual ^{207}Pb/^{206}Pb age is given as 2σm. The age of each sample resulting from the weighted mean of the individual grains is quoted with the 2σm error. The single zircon ^{207}Pb/^{206}Pb data are shown in Table 2 and plotted in histograms in Fig. 2.

Conventional U/Pb zircon analyses

The zircons used for the conventional U/Pb analyses were dissolved in sealed Teflon bombs at a temperature of 220°C for 1 week using a mixture of concentrated HF–HNO_3. The spike applied is highly enriched in ^{233}U and ^{205}Pb. After chemical separation Pb and U were loaded on Re single filaments with silica gel. Isotope ratios were measured using a Finnigan MAT261 mass spectrometer with a multi-Faraday-cup configuration for Pb and a SEM for U. Data reduction includes corrections for mass fractionation, blank and common Pb after Stacey and Kramers (1976). The age calculation was performed by linear regression after York (1969) using the decay constants of Steiger and Jäger (1977). Errors are quoted at the 2σ level. The results are listed in Table 3 and visualized in Fig. 3.

Vapour digestion single zircon U/Pb analyses

Single zircon grain U/Pb analyses followed the procedures described in detail in Wendt and Todt (1991) and Kröner et al. (1994). The zircons were dissolved by the so-called vapour digestion technique and after dissolution at 220°C spiked with a ^{205}Pb–^{233}U enriched tracer. Without chemical separation the complete spiked sample was loaded with silica gel on an Re filament and measured with an SEM. Pb was measured at ca. 1200–1300°C. Subsequently, after heating the same filament

Table 2 Results of single zircon evaporation analyses

Sample		Temperature (°C)	Ratios	$^{207}Pb/^{206}Pb$	$2\sigma m$ *10e-6	Age (Ma)	$2\sigma m$	Average	$2\sigma m$	N
Edenkoben granite										
E3										
A	300, r, c, lp	1494	101	0.053125	263	334.1	11.3			
B	150, y, c, sp	1512	65	0.053179	66	336.4	2.8			
C[a]	200, y, c, sp	1540	95	0.053985	167	370.4	7.0			
			166	0.053146	210			335.0	9.0	2
Burrweiler granitic dike										
BUR-2										
A1[a]	250, b, t, lp	1446	77	0.053191	132	337.0	5.6			
A2[a]		1506	116	0.053037	63	330.4	2.7			
A mean			193	0.053098	65	333.0	2.8			
B	250, r, t, lp	1520	78	0.053133	196	334.5	8.4			
C	220, r, c, lp	1500	76	0.053050	211	330.9	9.0			
D	200, r, t, sp	1490	80	0.053109	213	333.5	9.1			
			427	0.053098	161			333.0	6.9	4
Albersweiler gneiss										
A7										
A	400, r, c, lp	1504	119	0.053840	62	364.4	2.6			
B	350, y, c, lp	1506	112	0.054040	112	372.7	3.5			
C	400, p, c, lp	1530	97	0.054038	86	372.6	3.6			
D	350, r, c, lp	1540	78	0.053160	202	335.6	8.6			
E	450, r-b, t	1530	158	0.054133	54	376.6	2.2			
A10										
A	250, y, c, lp	1450	117	0.053888	81	366.2	3.5			
A17										
A	250, y, c, lp	1518	158	0.053826	42	363.8	1.8			
B	220, y, t, lp	1494	98	0.053806	269	362.9	11.3			
C	150, y, c, lp	1465	212	0.053180	50	336.5	2.1			
F1[a]	150, y, t, lp	1432	40	0.053900	487	367.0	20.0			
F2[a]		1464	32	0.054782	194	403.0	8.0			
F3[a]		1546	154	0.055509	66	432.8	2.7			
			859	0.053942	169			368.6	7.1	7
			290	0.053175	113			336.3	4.8	2
Waldhambach granodiorite										
PW1										
A	200, p, c, lp	1456	192	0.053004	67	329.0	2.9			
B	200, p, c, lp	1500	54	0.053079	261	332.2	11.2			
C	200, w, c, sp	1498	116	0.053064	59	331.5	2.5			
D	250, p, c, lp	1500	49	0.053043	237	330.6	10.2			
E	200, p, c, lp	1510	297	0.053094	23	332.8	10.0			
F	500, p, c, lp	1512	135	0.053128	48	334.3	2.0			
G	450, p, c, lp	1515	156	0.053164	71	335.8	3.0			
H	520, p, c, lp	1440	250	0.053045	79	330.7	3.4			
I	500, p, c, lp	1540	192	0.053102	77	333.2	3.3			
J	200, w, c, lp	1500	217	0.053253	36	339.6	1.5			
K	250, p, c, lp	1512	285	0.053090	40	332.6	1.7			
			1943	0.053101	104			333.1	4.4	11
Windstein granodiorite										
W9										
A	320, y, c, lp	1500	152	0.053030	37	330.1	1.6			
B	300, y, c, lp	1550	115	0.053097	94	332.9	4.0			
C	200, y, c, lp	1493	159	0.053127	54	334.2	2.3			
D	200, p, c, lp	1550	160	0.053105	42	333.3	1.8			
E	200, p, c, lp	1550	140	0.053162	66	335.7	2.8			
F	200, y, c, lp	1460	154	0.053204	54	337.5	2.3			
G	150, y, c, sp	1492	160	0.053059	73	331.3	3.1			
H	150, w, c, lp	1510	116	0.053117	57	333.8	2.4			
I	250, w, c, lp	1507	74	0.053145	93	335.0	4.0			
J	300, y, c, sp	1550	56	0.053110	162	333.5	6.9			
			1286	0.053114	86			333.7	3.7	10
Igneous events										
Edenkoben		335.0			370.4					
Burrweiler		333.0								
Albersweiler					368.6			432.8		
Kaiserbachtal		333.1								
Windstein		333.7								
Mean		333.7			369.5			432.8		
2σ		1.8			2.5					

Abbreviations: c = clear, t = translucent, y = yellow, r = red, p = pink, b = brown, w = white (colourless), lp = long prismatic, sp = short prismatic,
[a] Not used for average calculation

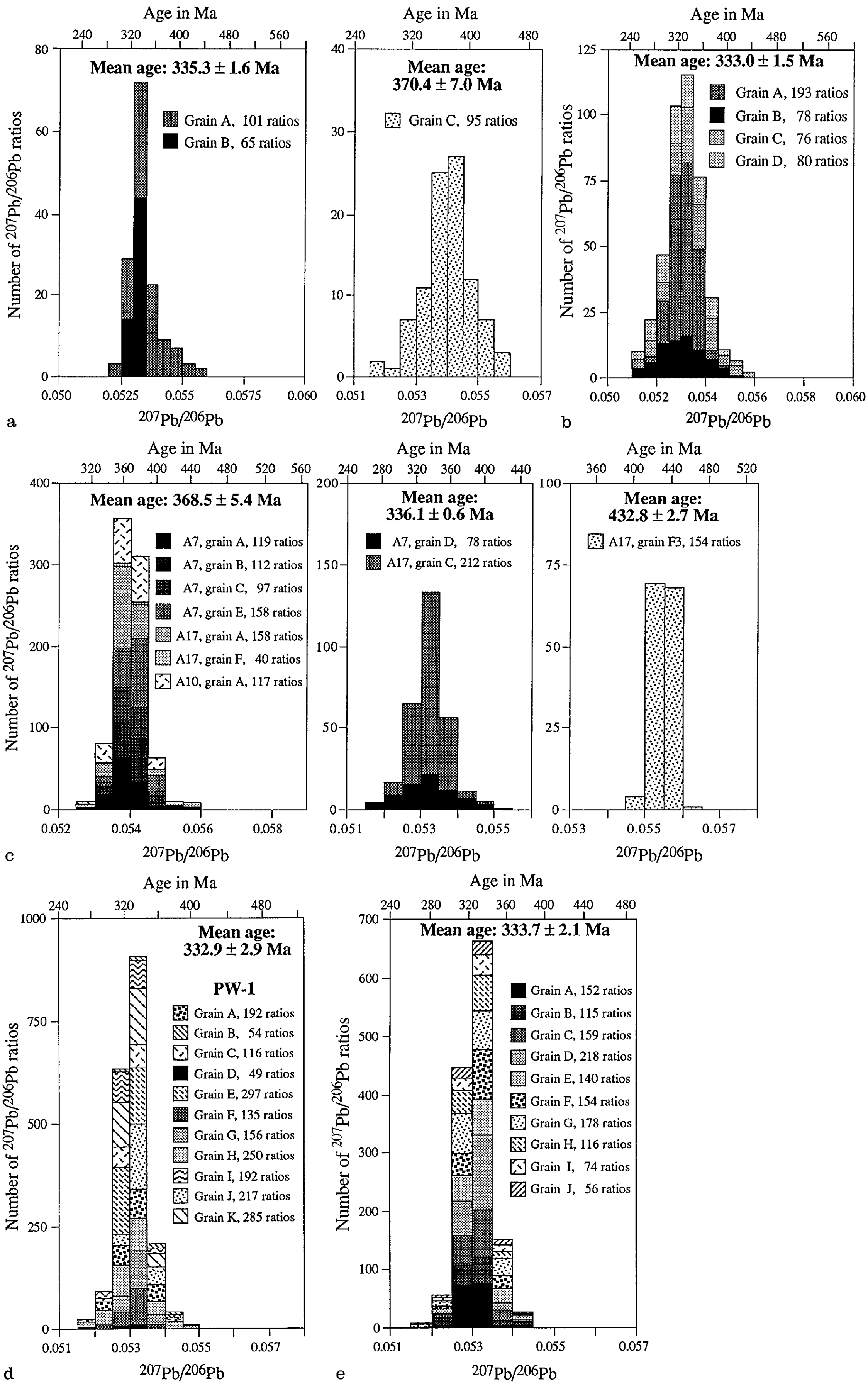

Fig. 2a–e Histograms showing the results of the $^{207}Pb/^{206}Pb$ single-grain zircon analyses. **a** Edenkoben granite; **b** Burrweiler granite dike; **c** Albersweiler gneiss; **d** Waldhambach granodiorite; **e** Windstein granodiorite

Table 3 U/Pb Analyses of the Granodiorite from Waldhambach

Sample no.	Weight (mg)	Size (μm)	U (ppm)	Pb (ppm)	Isotope ratios			Apparent ages			
					$^{206}Pb/^{204}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{238}U$	$^{207}/^{235}U$	$^{207}Pb/^{206}Pb$
1	1.446	<300	358.6	18.1	2128	0.04873	0.3572	0.05316	306.7	310.1	335.7
					36	0.00029	0.0032	0.00016	1.8	2.4	6.8
2	5.283	200–300	300.8	14.5	1519	0.04643	0.3403	0.05316	292.5	297.4	335.7
					67	0.00058	0.0072	0.00067	3.5	5.5	28.9
3	2.646	200–300	370.6	18.7	2578	0.04861	0.3566	0.05321	306.0	309.7	337.9
					74	0.00029	0.0035	0.00024	1.8	2.6	10.2
4	4.788	<200	428.2	20.6	1578	0.04650	0.3404	0.05309	293.0	297.5	332.7
					19	0.00033	0.0033	0.00021	2.0	2.5	8.8
5	2.525	<200	412.6	20.5	2391	0.04781	0.3509	0.05323	301.1	305.4	338.7
					55	0.00028	0.0033	0.00017	1.7	2.5	7.2
6	1 grain	400, c, y			1741	0.04796	0.3494	0.52842	302.0	304.3	322.0
					41	0.00071	0.0079	0.00046	4.4	6.0	19.7
7	1 grain	250, c, p			2673	0.04926	0.3601	0.05303	310.0	312.3	329.9
					66	0.00131	0.0129	0.00055	8.1	9.6	23.7
8	1 grain	400, c, y			2956	0.02901	0.2097	0.05242	184.4	193.3	303.9
					142	0.00084	0.0079	0.00050	5.3	6.7	21.9
9	1 grain	300, p, c			876	0.00433	0.0315	0.05269	27.9	31.5	315.5
					10	0.00003	0.0005	0.00043	0.2	0.5	18.7
10	1 grain	300, p, c			1033	0.04928	0.3577	0.52647	310.1	310.5	313.6
					17	0.00048	0.0065	0.00049	2.9	4.9	21.4

c = clear, p = pink, y = yellow

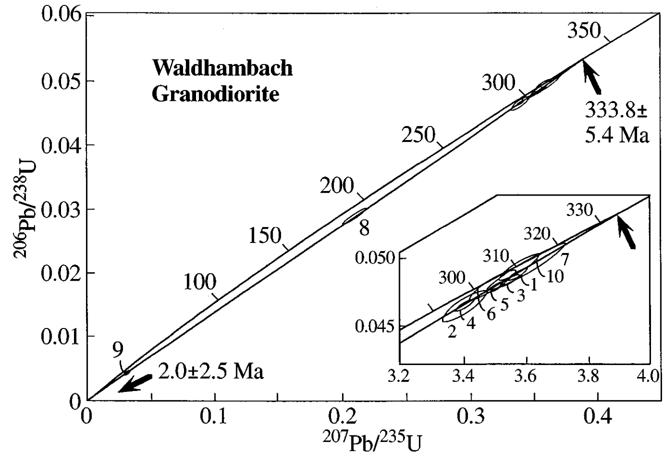

Fig. 3 Concordia diagram showing the data points for the granodiorite from Waldhambach

up to ca. 1350–1450°C, U was analysed, also using the SEM. Because the weight of the zircons is not known, the concentrations of U and Pb could not be calculated. However, because the U/Pb ratio can be determined, the data are plotted together with the conventional data in a concordia diagram (Fig. 3). The analytical data are listed in Table 3.

Rb/Sr and Sm/Nd analyses

Approximately 100 mg of each sample were spiked with mixed $^{84}Sr/^{85}Rb$ and $^{149}Sm/^{150}Nd$ tracers and dissolved by using HF and HNO_3 in a Teflon bomb at 220 °C for 4 days. Separation of Rb, Sr, Sm and Nd was achieved using the ion-exchange procedures as described by White and Patchett (1984). Isotope analysis was carried out by static mode with a multiple Faraday collector configuration. Sr was loaded with TaF_5 on single W-filaments. Rb, Sm and Nd were loaded and measured in a double Re filament configuration. Isotopic ratios for Sr were normalized to $^{86}Sr/^{88}Sr = 0.1194$. For NBS 987 a $^{87}Sr/^{86}Sr$-ratio of 0.710244 ± 20 was obtained on 44 runs during the course of this study. Nd isotopic compositions were normalized to $^{146}Nd/^{144}Nd = 0.7129$. The mean ratio for the La Jolla standard on 24 runs was 0.511844 ± 13. Total procedure blanks for Rb and Sr were less than 400 pg, and for Sm and Nd less than 45 pg, respectively, and thus are not significant for the samples under investigation.

The Rb/Sr and Sm/Nd data are presented in Tables 4 and 5 and shown as isochron diagrams in Fig. 4. Isochron regression followed York (1969) using the decay constants of Steiger and Jäger (1977). Errors on isochron ages are quoted on a 2σ level.

Results

The granite of Edenkoben

The geochronological investigation of this granite includes $^{207}Pb/^{206}Pb$ zircon evaporation analyses as well as Rb/Sr and Sm/Nd measurements. The zircons are of igneous habitus and mainly reddish or slightly yellow in colour. The prism planes prevail, whilst pyramids are generally smaller, but major (211) and minor (101) can also be well developed (Fig. 5a, b). The dominating zircon type is S2 with (110) > (100), a zircon morphology

Table 4 Sm/Nd data for rocks for the Edenkoben granite and the pyroclasic rocks from Weiler

Sample	Rock type	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{244}Nd$	$^{143}Nd/^{144}Nd$	$2\sigma_m$	-Nd	$^{143/144}Nd_i$	-Nd_T	T_{DM} (Ga)
Edenkoben										
EDE-02	Granite	2.37	13.21	0.10855	0.512270	±16	−7.2	0.512031	−3.41	1.32
EDE-03	Granite	4.32	26.15	0.09981	0.512253	± 4	−7.5	0.511990	−4.22	1.38
EDE-04	Granite	2.16	10.84	0.12055	0.512300	±15	−6.6	0.512034	−3.33	1.31
EDE-05	Granite	2.05	8.31	0.14901	0.512362	±14	−5.4	0.512035	−3.34	1.31
Age	335 Ma									
Weiler										
WEI-A	Ignimbrite	4.65	12.00	0.23397	0.512595	±17	−0.8	0.512095	−2.40	1.23
WEI-B	Ignimbrite	2.41	12.40	0.11759	0.512334	±12	−5.9	0.512083	−2.64	1.25
WEI-C	Tuff	2.89	13.38	0.13075	0.512388	±11	−4.9	0.512109	−2.13	1.21
WEI-D	Tuff	4.08	18.79	0.13130	0.512376	±11	−5.1	0.512096	−2.39	1.23
Age	326 Ma									

Table 5 Rb/Sr data for the pyroclastic rocks from Weiler

Sample	Rock type	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$2\sigma_m$	$^{87}Sr/^{86}Sr_i$	-Sr_T
Weiler								
WEI-A	Ignimbrite	183.8	36.3	14.7592	0.773229	±14	0.705520	19.44
WEI-B	Ignimbrite	182.1	90.7	5.8268	0.731674	±12	0.704638	7.33
WEI-C	Tuff	133.6	184.1	2.1021	0.714371	±13	0.704617	7.04
WEI-D	Tuff	150.3	228.5	1.9041	0.714350	±19	0.705515	19.79
Age	326 Ma							

typical for muscovite bearing leucogranites (Pupin and Turco 1975). Thus, the habitus of the most frequent zircons indicates crystallization from the granitic host magma. Three zircons were analysed, two yielding 335.0±9.0 Ma on average (Fig. 2a). The third grain has an age of 370.4±7.0 Ma. Although the 335 Ma age could be reproduced, it would be difficult to reach any geological conclusion from this data alone.

Fortunately, the zircon dating is independently supported by the Sm/Nd data. In Fig. 4a the four whole-rock samples of the Edenkoben granite form a linear array which fulfills isochron requirements (MSWD=0.07) and yields an age of 339±34 Ma (Ndt=–3.34).

Because the ~335 Ma age was obtained by two independent methods, we interpret this age as intrusion age of the granite. The 370-Ma-old grain is assumed to be an inherited zircon.

The granite dikes of Burrweiler

Single zircons from the Burrweiler samples were analysed by the $^{207}Pb/^{206}Pb$ evaporation technique. These zircons display a euhedral habitus of igneous origin with well-developed prism planes (Fig. 5c). Their prevailing morphology is of S2 type (Pupin and Turco 1975). The zircons are red or brown. Most of them are clear, but some are slightly transparent. The yield of zircons from the Burrweiler samples was poor; only a few grains with sizes >150 mm could be separated for analyses.

The $^{207}Pb/^{206}Pb$ ages of the four analysed grains are identical within error, resulting in an average age of 333.0±6.9 Ma (Fig. 2b). An older component could not be identified, even when different heating steps were measured as in grain A. We interpret the age as the crystallization age of the zircons and thus as the intrusion age of the granite dikes.

The granitic gneiss of Albersweiler

Three whole-rock samples were chosen for zircon separation. According to their prism-dominated habitus, the zircons are of igneous origin (Fig. 5d). Most of the zircons are long and prismatic, and correspond with the S19 type (Pupin and Turco 1975). Another zircon type has (100)>(110) and belongs to S4, sometimes with shorter prisms and better-developed pyramids. However, there was no difference between the three samples with respect to the zircon morphology.

The ages obtained for the Albersweiler gneiss are different (Fig. 2c). The most frequent age which could be recognized in all three samples was 368.6±7.1 Ma on average. In two of the samples we found 336.3±4.8 Ma, and in one sample (A17F) a distinctly older age of 432.8±2.7 Ma could be identified.

Taking into account that the gneiss has a metamorphic history which is not visible in the other igneous rocks from the studied area, it has to be concluded that the intrusion age of the granite from which the gneiss originated is older than ~336 Ma. Furthermore, the K/Ar age of 334±15 Ma cited in Frenzel (1971; recalcu-

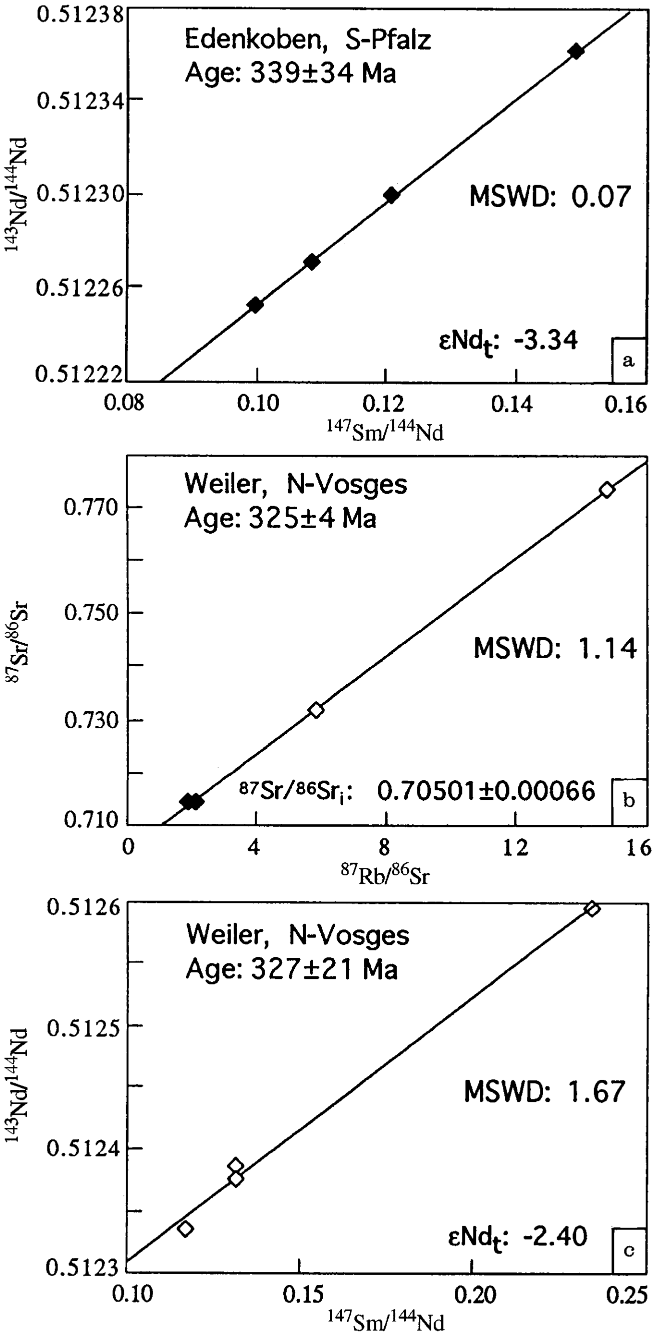

Fig. 4a–c Sm/Nd and Rb/Sr isochron diagrams. **a** Edenkoben granite; **b**, **c** pyroclastic rocks from Weiler

lated with new decay constant) for biotite of the gneiss indicate that the complex had already passed through the biotite closure temperature of K/Ar isotopic system at that time.

In this age distribution the ~336 Ma age is likely to reflect the metamorphism, whereas the ~369 Ma can be taken as age of the granite intrusion. The latter age is not very precise. The data can also be taken as a bimodal distribution with one age clustering around 364 Ma and the other around 374 Ma. However, because both ages were observed within the zircon population of one sample, we are not able to differentiate between the age data and therefore keep the average of ~369 Ma as the best approximation of the intrusion age.

In grain A17F we found different Pb isotopic composition at various heating steps. Although the first heating steps did not produce a strong and stable beam which could be used for precise dating, the results indicate an age of 367 ± 20 Ma at the lowest temperature and 403 ± 8 Ma at intermediate temperature. These ages might reflect mixtures of various parts of this composite grain. The most stable part of the zircon was evaporated at the highest temperature. Consequently, the 432.8 ± 2.7 Ma age has to be interpreted as the crystallization age of an inherited grain.

The Granodiorite from Waldhambach

The sample of the Waldhambach granodiorite was rich in zircons, and we therefore chose this sample for comparison of the evaporation method with conventional U/Pb dating as well as with the single zircon vapour digestion technique (Wendt and Todt 1991). The zircon grains are clear, euhedral and mainly pink, subordinate yellow or brown in colour. The prevailing mineral shape is long and prismatic of S19 type (Pupin and Turco 1975) as shown in Fig. 5e and f, suggesting an igneous origin.

The individual ages obtained by evaporation range from 329.0 to 339.6 Ma. The average of all ages is 333.1 ± 4.4 Ma (Fig. 2d). Despite all analytical uncertainties, correction for common Pb and the possibilities of inherited Pb, as well as Pb loss during metamorphism, weathering and laboratory treatment, the spread of the resulting single zircon ages is less than 11 Ma.

Concentrations of U in conventionally analysed zircons range from 300 to 428 ppm, and the Pb is between 14.5 and 20.6 ppm. The $^{206}Pb/^{204}Pb$ ratio varies from 1519 to 2578 for the conventional measurements and 876 to 2956 for the vapour digestion data. The conventional U/Pb data of zircon fractions and the vapour digestion single-grain data are combined in one concordia diagram (Fig. 3). Regression of the data gives an upper intercept at 333.8 ± 5.4 Ma and a lower intercept at 2.0 ± 2.5 Ma (MSWD = 0.93).

Most of the samples plot close below the concordia with U/Pb ages between 292.5 and 312.2 Ma and corresponding $^{207}Pb/^{206}Pb$ ages between 303.9 and 338.7 Ma. Two single-grain samples are distinctly discordant indicating severe Pb loss. This Pb loss obviously occurred during recent processes probably during acid treatment in the laboratory, because they point to the origin as lower intercept. Taking the discordance of the size fractions into account it can be assumed that such individuals that lost Pb also occur among these fractions, but are largely masked by the high number of grains.

In summary, all methods of zircon analyses applied for the Waldhambach granodiorite yield the same ages

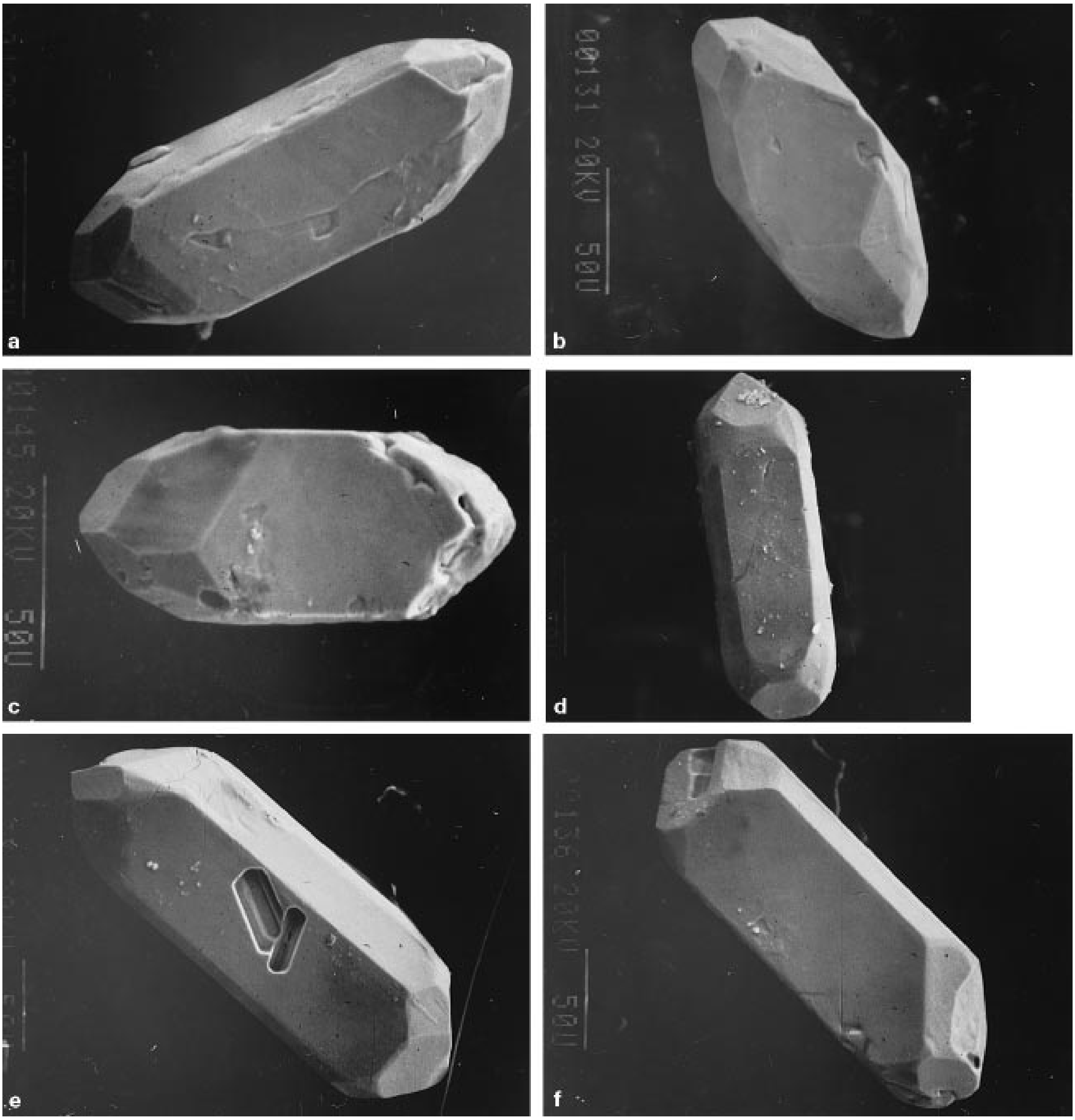

Fig. 5a–f SEM photographs of typical zircons. **a, b** Edenkoben granite; **c** Burrweiler granite dike; **d** Albersweiler gneiss; **e, f** Waldhambach granodiorite

within error. The U/Pb age from the concordia regression differs from the one obtained by zircon evaporation by less than 0.3%. This coincidence demonstrates that both methods reached the same results. We take 333.1 ± 4.4 Ma as the best estimate of the intrusion age of the granodiorite.

This study shows furthermore the advantages and disadvantages of the various methods. The advantages of the conventional U/Pb analysis is the possibility to determine the concentrations of the two elements and its good precision depending on the amount of zircons processed and based on the fact that Faraday cups can be used in a static mode because of the strong ion beam. However, inherited grains and zircons affected by Pb loss cannot be detected within the size fractions. The identification of such grains is an advantage of the vapour digestion technique, because it allows a single grain to be measured. Compared with conventional techniques, the concentrations of U and Pb are not known and the precision is decreased by a factor of 2–3 on average. The single-grain evaporation allows the determination of precise and accurate $^{207}Pb/^{206}Pb$ ages and the identification of complex zircon populations. Although the U/Pb ratio and the concentrations of the two elements cannot be analysed by this method, it has proven to be very useful for the rocks of this study.

The pyroclastic rocks of Weiler

From the pyroclastic rocks of Weiler we analysed the four whole-rock samples which were investigated for major and trace elements by Mühe (1992). For age determination we applied the Sm/Nd and the Rb/Sr system (Tables 4 and 5).

The Rb concentrations are between 134 and 183 ppm, and the Sr content is between 37 and 228 ppm, giving a large spread in the Rb/Sr ratio. The Sm/Nd ratio also has a considerable spread according to the concentrations of 2.4–4.7 ppm for Sm and 12.0–18.8 ppm for Nd.

Both methods yield within error identical results of 325 ± 4 Ma (MSWD = 1.14) for the Rb/Sr and 327 ± 21 Ma (MSWD = 1.67) for the Sm/Nd system (Fig. 4). The initial isotopic compositions are $^{87}Sr/^{86}Sr = 0.70501$ and eNdt = –2.4. The precision of the Rb/Sr age is enhanced by the larger spread in the Rb/Sr ratio and the faster decay of ^{87}Rb. We take this age as the best approximation of the age of the volcanic activity which produced the pyroclastic rocks of Weiler.

The granodiorite of Windstein

The Windstein granodiorite was dated by zircon evaporation. Similar to the Waldhambach granodiorite, the zircons have a typical long prismatic, euhedral morphology which is characteristic of igneous zircons. The prevailing morphology is S19 (Pupin and Turco 1975) and therefore very similar to the population found in the Waldhambach granodiorite. The analysed grains are clear, colourless or slightly yellow or brownish in colour. The resulting ages of the 10 grains analysed have a very small variation from 330.1 to 337.5 Ma. They yield on average an age of 333.7 ± 3.7 Ma (Fig. 2e). Because the isotopic composition of zircons documents only one event, and because there is no geological evidence for a complex history, we adopt this age as the age of intrusion.

Discussion and conclusions

Age distribution in the western MGCR

The ages determined in this study for the western part of the MGCR range from ~433 to ~325 Ma, thus covering a time span of ca. 100 Ma from the lower Silurian to the upper Carboniferous (Fig. 6). The major peak of igneous activity was around ~334 Ma, an age which is found at all localities of this study. This age is interpreted as the intrusion age of the granites of Edenkoben and Burrweiler, as well as the age of the granodiorites from Waldhambach and Windstein. The previously published age of the Windstein granodiorite of 340 Ma (Montigny et al. 1983) is slightly older. But because the quality of this K/Ar age is not mentioned, it is not possible to decide whether there is a significant difference in the age of this study or whether both results are identical within error.

Taking the 330–340 Ma ages of the studied intrusions as one group, the coincidence is surprising. The average age of the four occurrences is 333.7 ± 1.8 Ma. This clearly proves a short-lived but major igneous event at the end of the lower Carboniferous. The metavolcanics of Weiler appear to be slightly younger by a few Ma, although a clear distinction between the various igneous events is difficult to make.

Older ages are found in the Edenkoben granite and the Albersweiler gneiss. In the case of the Edenkoben granite we interpret the ~370 Ma as the age of an inherited grain because the intrusion age of ~335 Ma is independently constrained by the Sm–Nd isochron age of 339 ± 29 Ma. The age information obtained from the zircons of the Albersweiler gneiss is more complex. We found ages of ~336 Ma, ~369 Ma and, in one case, ~433 Ma. Previously obtained biotite K/Ar ages of 334 ± 15 Ma (Frenzel 1971, recalculated with the decay constant of Steiger and Jäger 1977) indicate that here the temperature already reached the closure temperature of biotite of ~300°C after intrusion and metamorphism. Further cooling and uplift must have occurred within the next few Ma because the intrusion of the lamprophyre dikes is dated at 318 ± 6 and 330 ± 15 Ma (Frenzel 1971, recalculated). It therefore appears necessary to assume that the intrusion of the granitoid precursor must have taken place considerably before ~336 Ma. We therefore interpret the most frequent $^{207}Pb/^{206}Pb$ age around 369 Ma as the age of intrusion, and the age of ~336 Ma as the age of metamorphic overprint. It is interesting to note that morphology and colour of the zircons do not provide any means to distinguish between the various ages. Even the complex Pb isotopic composition found in grain A17F cannot be related to morphological structures visible under the microscope. Nevertheless, this ~433-Ma-old grain documents the Silurian age of an inherited component despite Pb loss or zircon overgrowth during intrusion and later metamorphism.

Regional variation and geodynamical implications

In order to evaluate the geochronological data of the MGCR it appears convenient to apply the concept of microcontinents or terranes to the Variscan areas discussed in this paper. We follow Franke (1995) and take the Rhenohercynian zone of the Variscan belt as the

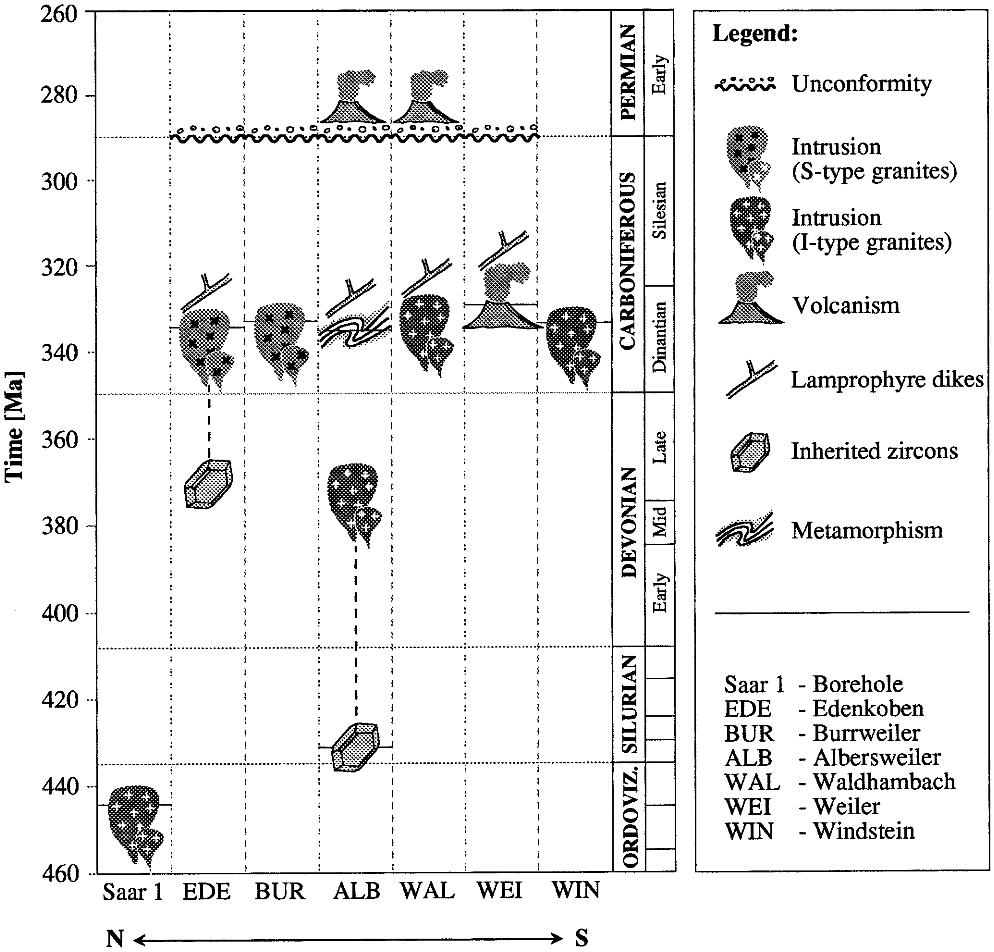

Fig. 6 Major igneous events and synthesis of the evolution of the western part of the MGCR. (For details see text)

eastern part of Avalonia. The MGCR is part of Armorica and the Moldanubian is consequently equivalent to Gondwana. According to palaeogeographic reconstructions the oceans between Armorica and Avalonia would be the Rheic ocean in Ordovician/Silurian times and the Rhenohercyian ocean in the Devonian. The Saxothuringian basin has to be considered as the ocean separating Gondwana from the continental terranes to the north.

Silurian

The ages in this study from 433 to 325 Ma are equivalent to those known from other regions of the MGCR and adjacent areas. The Silurian age that is identified as an inherited component in one grain of the Albersweiler gneiss is similar to the granite of Saar 1 borehole ca. 70 km to the west (444 ± 22 Ma; Sommermann 1993). Silurian ages are also well documented from the Böllsteiner Odenwald (Lippolt 1986) and 120 km further east from the Spessart with ages between 410 ± 18 and 439 ± 15 Ma as mentioned above. Additional Ordovician/Silurian ages of igneous rocks from the phyllite zone of 426 + 14/-15 Ma and 442 ± 22 Ma, and from the Krausaue of 434 + 34/-22 Ma, have been reported by Sommermann et al. (1992, 1994). Obviously, such Ordovician/Silurian ages are found in the northern part or at the northern margin of the MGCR. In the south of the MGCR and in the southeastern part of the Saxothuringian zone igneous rocks with these formation ages are not known. In the southern part of the area of this study, south of Albersweiler, no zircons with such ages could be identified, although numerous single-grain analyses were performed which implies that such Silurian or older zircons are missing or at least are very rare. Further to the south in the northern Vosges, Silurian granitoids were also not reported.

According to their geochemical composition these rocks of approximate Silurian age are generally considered to be related to subduction zones (Altenberger et al. 1990; Altenberger and Besch 1993; Dombrowski et al. 1995; Meisl 1990). If it is justified to take the MGCR as a distinct terrane within the Variscan plate assemblage, the most plausible scenario is that of a south-dipping subduction zone at the northern margin of the MGCR during the Silurian. The oceanic crust consumed by these subduction processes would be identical to those of the Rheic ocean, which separated Avalonia from Armorica. This is well in agreement with recent palaeomagnetic reconstructions (Bachtadse et al. 1995). The suture of this ocean is now hidden within the tectonic collage of the northern phyllite zone, camouflaged by later Variscan collisional processes (see e.g. Franke et al. 1995).

Devonian

The intrusion age of the Albersweiler granitoid is similar to ages known from the Odenwald. In the Böllsteiner Odenwald, Todt et al. (1995) found metamorphic ages of ~375 Ma. In the northern part of the Bergsträsser Odenwald magmatism of the Frankenstein gabbro is dated at 362±7 Ma (Kirsch et al. 1988). We are not able to conclude from the obtained data whether the ages found in Albersweiler represent two distinct groups, one close to 364 Ma, the other close to 374 Ma. Therefore, we cannot deduce which event in the Odenwald relates to the formation of the Albersweiler granitoids. The Frankenstein gabbro was not subjected to pervasive metamorphism since 362 Ma, whereas other parts of the MGCR including the Albersweiler gneiss had been severely affected. On the database now available we are not able to answer such questions about this late stage of Devonian magmatism, e.g. concerning the different degree of deformation and metamorphism. Nevertheless, the chemical composition of the granitoids concerned is that of I-type, which requires the relation to a subduction zone in the late Devonian. The subducted oceanic crust probably was that of the small Rhenohercynian ocean between Avalonia in the North and Armorica in the South, which opened and closed in a relatively short time span from the early to late Devonian. Because the remnants of this oceanic crust (e.g. Giessen nappes) became obducted onto the Rhenohercynian, the phyllite zone is a plausible locality for the suture of that ocean. This suture, however, did not exactly follow the suture of the Rheic ocean, although it lies in the vicinity (see discussion in Franke and Oncken 1995). We thus favour the idea of a subduction zone dipping beneath the MGCR from the north in Devonian time.

Carboniferous

The ages of the plutonic rocks of the studied area, except from Albersweiler, cluster closely around 334 Ma. This indicates a major period of igneous activity during that period of time. The ~334-Ma-old event is obviously the most important in the MGCR and widespread in many parts of the Variscan orogen. In the northern Vosges, north of the border to the Moldanubian zone, numerous I-type granitoids intruded at 320–340 Ma (see Hess et al. 1995 for a recent evaluation). To the east of the studied area, in the southern Bergsträsser Odenwald, ages reflecting metamorphism at approximately 330 Ma are also reported (e.g. Todt et al. 1995). The pyroclastic rocks from Weiler are slightly younger, but almost contemporaneous. They have geochemical characteristics of a subduction zone volcanism and Mühe (1992) therefore postulated such a geodynamical setting for the formation of the Weiler pyroclastics. Further arguments for a subduction zone can be taken from distribution of various granite types in the study area. In the south of the working area the granodiorites of Windstein and Waldhambach have the composition of I-type granitoides, whereas in the north in Edenkoben and Burrweiler the granites are classified as S-type (Laue and Reischmann 1994). This indicates a higher incorporation of continental material in the source rock in this region. This polarity can be interpreted as the result of a north-dipping subduction zone below the MGCR at the end of lower Carboniferous.

The missing I-type granitoids and subduction-related volcanics of that age in the northern Moldanubian zone is a further support for such an interpretation. If the Moldanubian zone was a Cordillerian type continental margin in the early Carboniferous as suggested by Flöttmann und Oncken (1992), it should be expected to find numerous subduction-related granitoids in the Schwarzwald and central Vosges. This has not been observed; instead, S-type granites occur frequently (e.g. Liew and Hofmann 1988). However, the big number of such I-type granitoids in the working area and in the northern Vosges is in agreement with the formation at an active continental margin at the southern margin of the MGCR, which has to be interpreted as the consequence of the north-dipping subduction of a Saxothuringian ocean basin. This interpretation is a priori based on our geochronological and geochemical data, and also is in agreement with the palaeomagnetic data which revealed an approximately 50° latitudinal distance between Armorica and Gondwana in the early Carboniferous (Bachtadse et al. 1995). The north-dipping subduction of such a large Saxothuringian ocean between the two terranes would explain the voluminous I-type granitoids in the Saxothuringian zone.

To summarize, three major conclusions arose from this study of the western part of the MGCR:

1. The Silurian subduction beneath the MGCR from the north led to the formation of a magmatic arc in the northern part of the MGCR. The closure of the Rheic ocean between Rhenohercynian basement (Avalonia) and the MGCR (Armorica) is the most probable geodynamical reason for this subduction.
2. Late Devonian (~369 Ma) magmatism occurred in the central part of the MGCR. The geodynamical setting is probably related to the closure of a Rhenohercynian ocean and subduction under the MGCR from the north.
3. Magmatism in the lower Carboniferous which reached its climax at ~334 Ma in the southern part of the MGCR is related to a north-dipping subduction zone at the southern margin of the MGCR. This igneous activity accompanies the closure of the Saxothuringian ocean between the MGCR (Armorica) and the Moldanubian (Gondwana) in the South.

Acknowledgements P. Jaeckel, A. Kröner and W. Todt are thanked for numerous advices and discussions on the single zircon dating techniques applied. R. Mühe kindly provided the samples from Weiler. This work was supported by the DFG (Re 772/3).

References

Altenberger U, Besch T (1993) The Böllstein Odenwald: evidence for pre- to Early Variscan plate convergence in the Central European Variscides. Geol Rundsch 82:475–488

Altenberger U, Besch T, Mocek B, Zaipeng Y, Yong S (1990) Geochemie und Geodynamik des Böllsteiner Odenwaldes. Mainzer Geowiss Mitt 19:183–200

Bachtadse V, Torsvik TH, Tait JA, Soffel HC (1995) Paleomagnetic constraints on the paleogeographic evolution of Europe during the Paleozoic. In: Dallmeyer et al. (eds) Pre-Permian geology of Central and Eastern Europe. Springer, Berlin Heidelberg New York, pp 567–578

Dallmeyer RD, Franke W, Weber K (1995) Pre-Permian geology of Central and Eastern Europe. Springer, Berlin Heidelberg New York

Dombrowsky A, Henjes-Kunst R, Höhndorf A, Kröner A, Okrusch M, Richter P (1995) Orthogneisses in the Spessart crystalline complex, north-west Bavaria: Silurian granitoid magmatism at an active continental margin. Geol Rundsch 84:399–411

Flöttmann T, Oncken O (1992) Constraints on the evolution of the mid-German crystalline rise: a study of outcrops west of the river Rhine. Geol Rundsch 81:515–543

Franke W, Oncken O (1995) Zur prä-devonischen Geschichte des Rhenohercynischen Beckens. Nova Acta Leopoldina NF 71:53–72

Franke W, Dallmeyer RD, Weber K (1995) Geodynamic evolution. In: Dallmeyer et al. (eds) Pre-Permian geology of Central and Eastern Europe. Springer, Berlin Heidelberg New York, 579–593

Frenzel G (1971) Die Mineralparagenese der Albersweiler Lamprophyre (Südpfalz). N Jb Miner Abh 115:164–191

Genser H (1965) Fossilfunde aus den Schiefern von Weiler bei Weissenburg/Elsass Jber Mitt oberrh geol Ver 47:153–157

Häntzschel W (1972) Lebensspuren in den Kulm-Tonschiefern von Neustadt a. d. Weinstrasse. Oberrhein Geol Abh 21:107–115

Hess JC, Schmidt G (1989) Zur Alterstellung der Kataklasite im Bereich der Otzberg-Zone, Odenwald. Geol Jb Hessen 117:69–77

Hess JC, Lippolt HJ, Kober B (1995) The age of the Kragenfels granite (northern Vosges) and its bearing on the intrusion scheme of late Variscan granitoids. Geol Rundsch 84:568–577

Kirsch H, Kober B, Lippolt HJ (1988) Age of intrusion and rapid cooling of the Frankenstein gabbro (Odenwald, SW-Germany) evidenced by $^{40}Ar/^{39}Ar$ and single zircon $^{207}Pb/^{206}Pb$ measurements. Geol Rundsch 77:693–711

Kober B (1987) Single-zircon evaporation combined with Pb+emitter-bedding for $^{207}Pb/^{206}Pb$-age investigations using thermal ion mass spectrometry, and implications to zirconology. Contrib Mineral Petrol 96:63–71

Kröner A, Jaeckel P, Williams IS (1994) Pb-loss patterns in zircons from a high-grade metamorphic terrain as revealed by different dating methods: U–Pb and Pb–Pb ages for igneous and metamorphic zircons from northern Sri Lanka. Precambrian Res 66:151–181

Laue S, Reischmann T (1994) Petrographie und Geochemie variscischer Intrusiva der westlichen Rheingrabenschulter. Mitt Pollichia 81:195–214

Lippolt HJ (1986) Nachweis altpaläozoischer Primäralter (Rb–Sr) und karbonischer Abkühlungsalter (K–Ar) der Muskovit-Biotit-Gneise des Spessarts und der Biotit-Gneise des Böllsteiner Odenwaldes. Geol Rundsch 75:569–583

Liew TC, Hofmann AW (1988) Precambrian crustal components, plutonic associations, plate environment of the Hercynian fold belt in central Europe: indications from an Nd and Sr isotopic study. Contrib Mineral Petrol 98:129–138

Löhr P (1991) Zur Petrographie und Geochemie der Lamprophyre der nordwestlichen Rheingrabenrandschulter, Südpfalz und nördliches Elsass. Diplomarbeit, Universität Mainz, 123 pp

Meisl S (1990) Metavolcanic rocks in the "Northern Phyllite Zone" at the southern margin of the Rhenohercynian belt. In: Franke W (ed) Int Conf Palaeozoic Orogens in Central Europe. Field guide mid-German crystalline rise and Rheinisches Schiefergebirge, Giessen–Göttingen, pp 25–42

Montigny R, Schneider C, Royer JY, Thuizat R (1983) K–Ar dating of some plutonic rocks of the Vosges. Terra Cognita 3:201

Mühe R (1992) Ignimbrit- und Tuff-Horizonte in den Metasedimenten von Weiler/Wissembourg (Elsass): Hinweise für orogenen Kalk-Alkali-Vulkanismus im Bereich des Saxothuringikums. N Jb geol Paläont Mh 7:435–447

Münzing K (1956) Geologische Beobachtungen im Pfälzerwald. Pfälzer Heimat 7:14–16

Nasir S, Okrusch M, Kreuzer H, Lenz H, Höhndorf A (1991) Geochronology of the Spessart crystalline complex, mid-German crystalline rise. Mineral Petrol 44:39–55

Odin GS (1994) Geological time scale (1994). C R Acad Sci Paris 318:59–71

Pupin JP, Turco G (1975) Typologie de zircon accessoire dans les roches plutonique dioritiques, granitiques et syénitiques. Facteures essentiels déterminant les variations typologiques. Pétrologie 1:139–156

Sommermann AE (1993) Zirkonalter aus dem Granit der Bohrung Saar 1. Beih Europ J Mineral 5:145

Sommermann AE, Meisl S, Todt W (1992) Zirkonalter von drei verschiedenen Metavulkaniten aus dem Südtaunus. Geol Jb Hessen 120:67–76

Sommermann AE, Anderle HJ, Todt W (1994) Das Alter des Quarzkeratophyrs der Krausaue bei Rüdesheim am Rhein (Bl. 6013 Bingen, Rheinisches Schiefergebirge). Geol Jb Hessen 122:143–157

Stacey JS, Kramers JD (1976) Approximation of terrestrial lead isotope evolution by a two-stage model. Earth Planet Sci Lett 26:207–221

Steiger RH, Jäger E (1977) Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. Earth Planet Sci Lett 36:359–362

Todt WA, Altenberger U, Raumer JF von (1995) U–Pb data on zircons for the thermal peak of metamorphism in the Variscan Odenwald, Germany. Geol Rundsch 84:466–472

Wendt IJ, Todt W (1991) A vapour digestion method for dating single zircons by direct measurement of U and Pb without chemical separation. Terra Abstr 3:507-508

White WM, Patchett PJ (1984) Hf–Nd–Sr isotopes and incompatible element abundances in island arcs: implications for magma origins and crust-mantle evolution. Earth Planet Sci Lett 67:167–185

York D (1969) Least squares fitting of a straight line with correlated errors. Earth Planet Sci Lett 5:320–324