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ORIGINAL PAPER

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Late-Variscan magmatism revisited: new implications from Pb-evaporation zircon ages on the emplacement of redwitzites and granites in NE Bavaria

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Abstract Pb-evaporation zircon analyses coupled with a detailed cathodoluminescence (CL) study on the complete series of granitoids from the northern Oberpfalz, NE Bavaria, provide new evidence for the commencement and timing of late-Variscan magmatism. All granitoids analysed in this study were dated before by Rb–Sr and/or K–Ar methods. Investigated samples comprise medium-grained, I-type dioritic rocks (redwitzites), I/S-type granites (Leuchtenberg, Marktredwitz (G1), Zainhammer) and S-type granites (Falkenberg, Liebenstein, Mitterteich, Friedenfels, Steinwald, Flossenbürg, Bärnau). The zircon evaporation technique reveals three groups of $^{207}Pb/^{206}Pb$ ages which are interpreted to represent magmatic crystallisation: (1) ages of 324–321 Ma are found in all analysed redwitzites and in almost all I/S-type granites; (2) the granites of Falkenberg and Liebenstein yield ages of ~315 Ma; (3) ages between 312 and 310 Ma are recorded in the Mitterteich, Friedenfels, Steinwald and Flossenbürg granites. Titanite crystals from different redwitzite bodies yield conventional U–Pb ages of 325–322 Ma, identical to the Pb-evaporation zircon data of these rocks. The S-type granites of groups 2 and 3 contain zircons with relict cores but only a small number of them yield older ages, indicating that some of the cores must have lost their radiogenic Pb. From the geochronological data, we infer that metamorphic conditions of the Variscan crust produced different granite types at different times. The data support a model involving an early period of mantle-related magmatism which postdates the final convergence stage of the Variscan orogen. This magmatic activity was at the same time as the thermal peak of regional metamorphism and is followed by a late period of crustal anatexis, which is probably related to post-collisional extension of the thickened Variscan crust.

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Introduction and aims of investigation

Over the last 30 years numerous attempts have been undertaken to determine the emplacement ages and to refine the intrusion sequence of the late-Variscan granitoids in the northern Oberpfalz, SE Germany (e.g. Köhler et al. 1974; Köhler and Müller-Sohnius 1976; Wendt et al. 1986, 1988; Holl et al. 1989; Wendt et al. 1992, 1994; Siebel 1995a, 1995b). From existing data it was concluded that magmatism took place in two major pulses at ~325 Ma and between 315–310 Ma (Siebel et al. 1997). The methods of choice in most of these investigations were Rb–Sr whole-rock and K–Ar mineral dating. So far, these methods could not provide reliable age constraints for the intrusion of intermediate rocks (local name used throughout the text is *redwitzite*) associated with some of the granites, although a late-Variscan age is widely cited for these rocks (e.g. Troll 1968; Fischer et al. 1968; Holl et al. 1989; Köhler et al. 1989; Taubald 2000). Questions still pending are when granitic magmatism began and which rocks intruded first. The latter point is important when discussing whether heat and melt input from the mantle caused melting of the crust or whether intracrustal melting triggered crustal weakening and intrusion of magmas from the mantle. To discriminate between these petrogenetic models, the relative timing between the redwitzites and the granites is of major importance. Another controversial issue in previous geochronology concerns zircon ages older than 330 Ma reported from the Falkenberg and Leuchtenberg granites (Carl et al. 1989; Köhler and Hölzl 1996), which suggest old emplacement ages.

In this study we present a comprehensive set of geochronological data on all major granitoids from the northern Oberpfalz, including the Steinwald and the southern Fichtelgebirge (Marktredwitz area). The single-zircon Pb-evaporation method developed by Kober

(1986, 1987) was applied to all these units, whereas conventional U–Pb titanite analyses were carried out on the redwitzites. Internal morphology of the zircons was imaged by cathodoluminescence (CL) investigations. Changes in CL intensity in zircon are attributed to variations in the concentrations of a range of trace- and rare-earth elements (Hanchar and Miller 1993). CL intensity also depends on the amount of lattice defects caused by radiation damage induced by decay of U and Th (Poller et al. 1997; Geisler and Pidgeon 2001), and thus gives information about the distribution of these elements in zircon. It is shown that zircons from granitoids differing in age can be distinguished by their internal morphology and degree of inheritance. Most grains are coreless and yield concordant ages for different evaporation steps resulting in analytical uncertainties of generally 2–3 Ma. Different zircon grains from the same sample yield Pb-evaporation zircon ages generally reproducible within 1–6 Ma, and therefore thought to be suitable to define precise granitoid emplacement events. In addition, we demonstrate that zircons with visible cores do not necessarily yield older ages and the reasons for this are discussed.

Geological background

Granitoids are represented in the northern Oberpfalz by a number of small- to medium-size (~10–150 km^2) intrusive bodies with circular-, crescent-, tongue- or teardrop-shaped surface expressions (Fig. 1). The granitoids intruded discordantly to the regional penetrative foliation of the country rocks. The Oberpfalz region (including the Steinwald and the southern Fichtelgebirge, i.e. Marktredwitz area) comprises at least four, spatially unconnected redwitzite occurrences and about ten individual granite intrusions (Fig. 1). The redwitzites account for volumetrically minor amounts among the igneous rocks in NE Bavaria. They belong to a group of peculiar late-Variscan igneous rocks (Fischer 1965; Troll 1968). The name was originally given to unusual textured igneous rocks of largely dioritic and granodioritic composition in NE Bavaria (Willmann 1920). The redwitzites are fine- to medium-grained, generally non-porphyritic and show considerable petrographical variation. In detail, they range from quartz gabbro through tonalite to quartz monzodiorite. A hydrous mineralogy consisting of amphibole and biotite (both Mg-rich but notably low in Al), plagioclase (An_{40}–An_{30}), minor amounts of quartz, K-feldspar, pyroxene, titanite, and apatite as well as early post-magmatic Ca–Al alteration minerals is typical (Troll 1968; Freiberger et al. 2001). Compared to the granites, the redwitzites have low SiO_2 (53–63 wt%), low mol% $Al_2O_3/CaO+Na_2O+K_2O$ (<1.05), high TiO_2 (0.8–1.7 wt%) and low Rb/Ba ratios (<0.18). Nd and Sr isotope ratios of the redwitzites are in the range of enriched mantle values (εNd=1 to 4, $^{87}Sr/^{86}Sr_{325\ Ma}$=0.706–0.708). Fischer (1965), Troll (1968) and Holl et al. (1989) regarded the redwitzites as older than the associated granites. The contact between granite and redwitzite varies from sharp to poorly defined. Enclaves of dioritic rocks are frequently found in the granites. Chill zones are not observed, suggesting that the temperature contrast between both magmas was moderate. In this study, redwitzites from four separate intrusive centres were investigated. 1. A large intrusive body NE of Marktredwitz, southern Fichtelgebirge which covers a 7×4 km area. Redwitzites from this intrusion coexist with a porphyritic granite (here referred to as G1 from Marktredwitz) which is considered as part of the Falkenberg pluton (Stettner, personal communication 2001) or the Weißenstadt-Marktleuthen (G1) pluton in the Fichtelgebirge (Troll 1968; Holl et al. 1989). 2. An elongated body in the axial zone of the northern Leuchtenberg granite exposed over a strike length of ca. 8 km with maximum width of 1.0–1.5 km (Wurz-Ilsenbach body). 3. Small occurrences interfingering with the Zainhammer granite in the southern Steinwald (Reuth-Erbendorf body). 4. Isolated outcrops, interpreted as dikes or sills in the region between Tirschenreuth and Mähring.

Accounts on petrography, geochemistry and field relations of the granites sensu stricto have been given elsewhere (Voll 1960; Fischer 1965; Köhler et al. 1974; Madel 1975; Wendt et al. 1986; Richter and Stettner 1987; Wendt et al. 1988, 1992, 1994; Siebel 1995a, 1995b; Siebel et al. 1997). Only a brief description is given here. The granites vary from coarse-grained, strongly porphyritic (i.e. megacrystic K-feldspar and plagioclase), mildly peraluminous biotite and biotite–muscovite granites (Falkenberg, Leuchtenberg, Marktredwitz) to weakly porphyritic or medium- to fine-grained, strongly peraluminous biotite–muscovite and muscovite granites (Liebenstein, Mitterteich, Friedenfels, Steinwald, Flossenbürg, Bärnau). On the basis of chemical and isotopic composition the granites of Leuchtenberg, G1 from Marktredwitz and Zainhammer, are transitional between S- and I-type (εNd_T=2 to 4, $^{87}Sr/^{86}Sr_T$=0.707–0.708) whereas those of Falkenberg, Liebenstein, Mitterteich, Friedenfels, Steinwald, Flossenbürg and Bärnau are S-type granites (εNd_T=4 to 8, $^{87}Sr/^{86}Sr$=0.710–0.720). Most intrusions display chemical characteristics which can be explained by fractional crystallisation processes (Madel 1975; Richter and Stettner 1987; Wendt et al. 1994; Siebel et al. 1997).

The granitoids are exposed in different terranes comprising Moldanubia, Saxo-Thuringia and part of Bohemia (i.e. Zone of Erbendorf-Vohenstrauß). These units experienced polyphase metamorphism and deformation during pre-Variscan and Variscan orogenic cycles resulting in a wide spectrum of metamorphic grades. All of these units and also part of their contact zones are cut by granitoids. The basement was exposed to a final high-temperature, low-pressure (HT–LP) metamorphic event which is recorded between 326 and 322 Ma (e.g. Kalt et al. 2000).

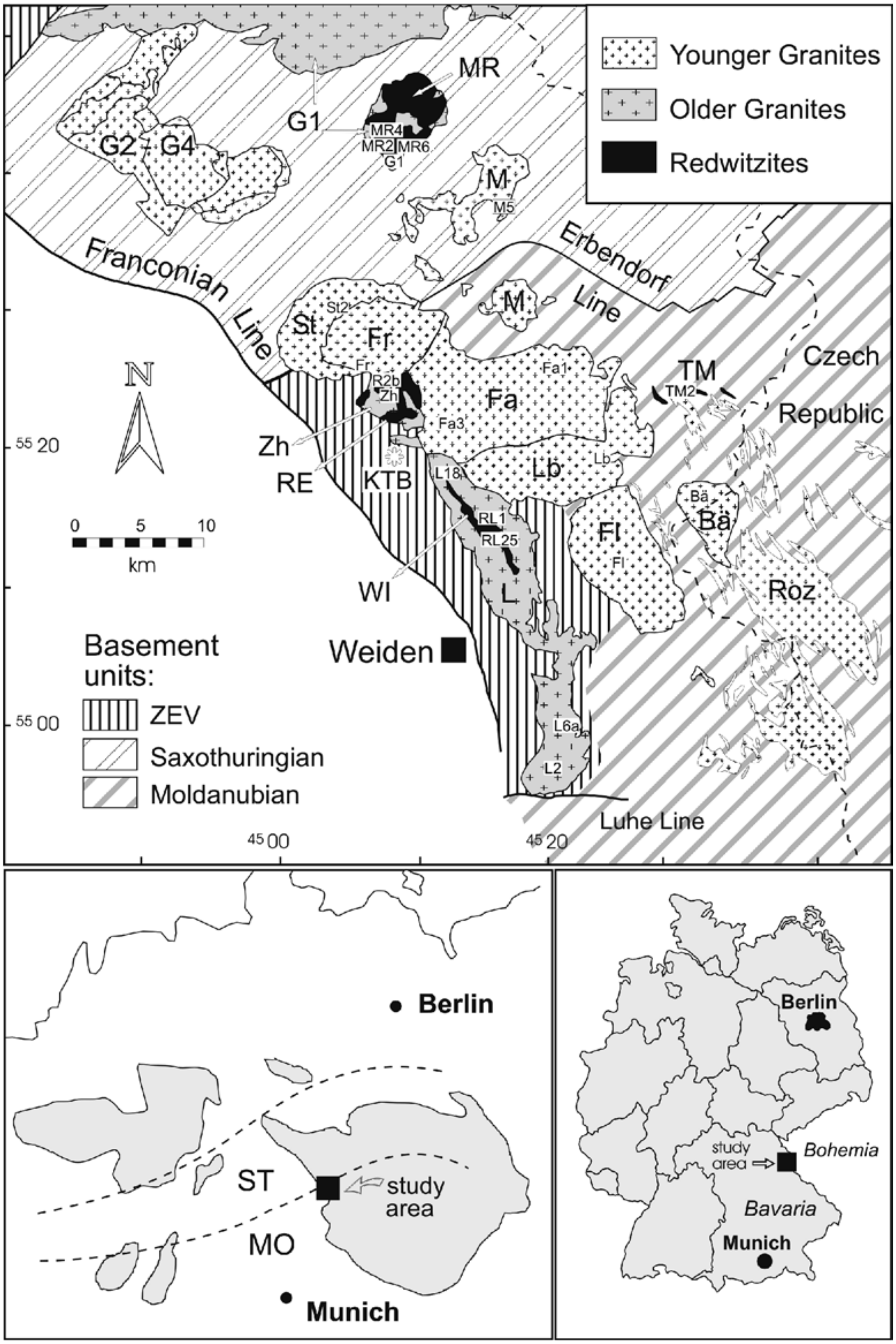

Fig 1 Simplified geological map of the crystalline basement of NE Bavaria showing granitoid distribution and sample locations. Abbreviations: *Bä* Bärnau, *Fa* Falkenberg, *G1* Weißenstadt-Marktleuthen, *Fl* Flossenbürg, *Fr* Friedenfels, *L* Leuchtenberg, *Lb* Liebenstein, *M* Mitterteich, *MR* Marktredwitz, *RE* Reuth-Erbendorf, *St* Steinwald, *WI* Wurz-Ilsenbach, *Zh* Zainhammer, *G2–G4* younger granite series from the Fichtelgebirge, *Roz* Rozvadov granidoids (not discussed in this paper), *KTB* locality of the German continental deep-drilling project, *ZEV* Zone of Erbendorf-Vohenstrauß

Previous geochronology

In earlier studies different geochronological techniques were applied to the granitoids analysed in this study. Isotopic data on the redwitzites are complex. Rb–Sr whole-rock analyses yielded dates between 545 and 415 Ma (Holl et al. 1989; Siebel 1994), interpreted to represent incomplete homogenisation of Sr isotopes due to magma mixing during petrogenesis. A recent study attributed Upper Carboniferous ages for redwitzitic rocks from the Fichtelgebirge (Taubald 2000). Amphiboles and biotites from the Reuth-Erbendorf and Wurz-Ilsenbach redwitzites vary in K–Ar and Rb–Sr ages between 320 and 300 Ma and were probably influenced by later thermal reheating (Siebel 1994). Ar–Ar age spectra of amphiboles from the Wurz-Ilsenbach body are largely disturbed but the high-temperature heating steps of these minerals indicate ages of 342–346 Ma (Siebel et al. 1998). K–Ar dates for the Marktredwitz intrusive suite vary in an inconsistent fashion between 344–304 Ma for amphibole and 350–327 Ma for biotite (Holl 1988).

Based on Rb–Sr and K–Ar geochronology, it is possible to distinguish two groups of granites. The older group (326–320 Ma) includes the Leuchtenberg, Zainhammer and Weißenstadt-Marktleuthen granites. The latter granite, which is also referred to as G1, is the main intrusive body in the Fichtelgebirge (Richter and Stettner 1979; Hecht et al. 1997). The Leuchtenberg granite gave a Rb–Sr whole-rock date of 326±2 Ma for the main intrusive body. This age was supported by K–Ar muscovite and biotite data from the southern part of the pluton ranging between 326 and 323 Ma (Siebel 1995b). K–Ar and Ar–Ar mica ages of ca. 325 Ma were also found at some localities around the Leuchtenberg granite (Kreuzer et al. 1989, 1993; Henjes-Kunst, personal communication) and were attributed to the contact metamorphic overprint. The northern Leuchtenberg granite and the associated redwitzites show a northward decrease of the K–Ar biotite and amphibole ages from ~325 to ~300 Ma within a distance of ca. 10 km. Reasons for this are either rejuvenation caused by the intrusion of the younger granites, or higher inherent temperatures (Siebel 1995b). The northern lobe of the Leuchtenberg granite is interpreted as the deepest level of the former magma chamber whereas the southern sector represents an upper portion (Stettner, personal communication). Conventional U–Pb zircon analyses on a sample from the northern half of the granite gave an upper intercept age of 333±5 Ma (Abdullah et al. 1994). Conventional U–Pb multigrain dating of six zircon fractions from the southern half of the Leuchtenberg granite provided an upper intersection with the concordia at 342±6 Ma in the Tera-Wasserburg diagram (Köhler and Hölzl 1996). However, the data points are discordant and do not fit well along a chord. This was discussed in terms of Pb-loss by Grauert et al. (1996). These authors proposed another discordia-fit in the Tera-Wasserburg diagram (including additional zircon data) resulting in a lower intercept age of ca. 322 Ma for the Leuchtenberg granite. The porphyritic granite from Marktredwitz has so far not been dated by Rb–Sr or U–Pb methods but similar rocks from the Fichtelgebirge G1 intrusion yielded a Rb–Sr whole-rock age of 326±2 Ma (Carl and Wendt 1993). The southern Steinwald contains a small granite body referred to as Zainhammer granite (Wendt et al. 1988) which suffered later thermal reheating. The oldest ^{40}Ar–^{39}Ar mica plateau age of about 317 Ma is regarded as a minimum age for this granite (Wendt et al. 1992).

The younger group of post-tectonic S-type granites clearly postdate the LP–HT metamorphic event. Apart from the Liebenstein granite, the intrusion ages of these granites were constrained by the Rb–Sr whole-rock method at 311±4 Ma (Falkenberg granite, Wendt et al. 1986), 310±3 Ma (Mitterteich granite, Siebel 1995a), 310±2 Ma (Friedenfels granite, Wendt et al. 1992), 310±1 Ma (Steinwald granite, Wendt et al. 1988), 312±2 Ma (Flossenbürg granite, Wendt et al. 1994), and 313±2 Ma (Bärnau granite, Wendt et al. 1994). K–Ar and Rb–Sr muscovite ages are equal or slightly younger than the Rb–Sr whole-rock isochron ages, indicating that crystallisation was followed by rapid cooling below the blocking temperatures of muscovite in the Upper Carboniferous. However, zircons from the Falkenberg granite gave Pb-evaporation zircon ages between 370 and 320 Ma (Carl et al. 1989). The older ages were attributed to the presence of inherited components in the zircons.

Analytical techniques

Zircon and titanite were isolated from the granitoids by standard mineral separation techniques and were finally handpicked under a binocular microscope. Individual zircon grains were selected on the basis of size (~80–200 µm) and crystal quality (i.e. euhedral morphology, lack of overgrowth and visible inclusions). For cathodoluminescence (CL) studies, zircons were mounted in epoxy resin and polished down to expose the grain centres. CL images were obtained by electron microprobe using the JEOL JXA-8900RL, working with an accelerating voltage of 15 kV and a beam current of 15 nA.

The titanite fractions used for U–Pb analyses were cleaned with 0.1 N HCl and ultrapure H_2O, and a mixed ^{205}Pb–^{235}U tracer solution was added to the grains prior to dissolution in 22 N HF. Separation and purification of U and Pb were performed in Teflon columns filled with a 40-µl bed of AG1-X8 (100–200 mesh) anion exchange resin. The technique used for separation of U and Pb is that outlined in Poller et al. (1997), and further details on U–Pb analytical techniques are given in Chen et al. (2000). All isotopic measurements were carried out on a Finnigan MAT 262 multicollector mass spectrometer. Pb and U were loaded on separate Re filaments using SiGel and 1 N HNO_3 respectively. A factor of 1‰ per mass unit for instrumental mass fractionation was applied to the Pb analyses, using NBS SRM 981 as reference material. Total procedure blanks were <50 pg for Pb and <10 pg for U. Initial common Pb remaining after correction for tracer and blank was corrected using values from the Stacey and Kramers (1975) model. U–Pb discordia intercepts were calculated using the Isoplot program (Ludwig 1999).

For single-zircon Pb-evaporation, chemically untreated, whole zircon grains or fragments were analysed using a double Re filament configuration. Note that the evaporated zircons are not those taken for CL analyses. However, they are supposed to be representative of those investigated by CL. Principles of the evaporation method are described in Kober (1986, 1987), Kröner and Todt (1988), Cocherie et al. (1992) and Klötzli (1997). The zircons were embedded in a Re evaporation filament which was fixed in front of a second Re ionisation filament. A slow increase in the evaporation temperature to about 1,390 °C (temperature was monitored with a Keller pyrometer) for 5 to 10 min evaporated common and radiogenic Pb hosted in less stable phases, e.g. in crystal domains affected by radiation damage which have low activation energies (Kober 1986). The temperature of the evaporation filament was then turned down and the temperature of the ionisation filament was raised to about 1,650 °C for a few seconds to remove the Pb from this filament. The cold ionisation filament then received Pb from the first heating stage at about 1,400 °C for about 15 min. The temperature of the evaporation filament was then again turned down, followed by an increase in the temperature of the ionisation filament at 1,060–1,160 °C. Within this temperature range the most stable Pb ion-beams were obtained. In our experiments temperatures of the evaporation filament were gradually increased in 20 or 30 °C steps during repeated evaporation-deposit cycles. Only data with high intensities, generally 40.000–250.000 counts per second for ^{206}Pb, and with no changes in the Pb isotope ratios were considered for evaluation. With the exception of analyses from Marktredwitz-G1 and Mitterteich, only data with high radiogenic Pb component (^{204}Pb/^{206}Pb<2×10^{-4}) were used for evaluation. This ensures that the effect of varying initial common Pb isotopic composition on the resulting age calculation is negligible. Data acquisition was performed by peak switching using a MasCom secondary electron multiplier with the mass sequence 206–207–204–206– 207–208. One grain from redwitzite sample R2b yielded very high Pb intensities, and masses 206, 207 and 208 were simultaneously measured in Faraday cups. All ^{207}Pb/^{206}Pb ratios were corrected for common Pb according to Cocherie et al. (1992), following the two-stage growth model for the evolution of Pb isotopic ratios of Stacey and Kramers (1975). We note the similarity of the Stacey and Kramers (1975) Pb ratios and measured feldspar Pb isotope composition of the granites (Friese 1990 and own data). No correction was made for mass fractionation.

The common Pb corrected ^{207}Pb/^{206}Pb ratios normally define a Gaussian distribution and the mean of the ^{207}Pb/^{206}Pb ratios was derived from this distribution. The error for a single zircon age was calculated according to the formula

$$\Delta_{age} = \sqrt{\left(\frac{2\sigma}{\sqrt{n}}^{2} + \Delta f^{2}\right)}$$

where n is the number of ^{207}Pb/^{206}Pb isotope ratio scans (generally between ~50 and ~600 per grain), 2σ is the 2sigma standard error of the Gaussian distribution function, and Δf an assumed error of 0.1% which includes potential bias caused by mass fractionation of Pb isotopes and uncertainty in linearity of the multiplier signal. The age for several zircons from the same sample are given as weighted average, and the error refers to the 95% confidence level (Isoplot, Ludwig 1999). Repeated measurements on natural zircons from the Phalaborwa igneous complex, South-Africa, and from zircon standard 91500 (Wiedenbeck et al. 1995) were performed for geologically realistic age and error treatment and the results are published in Chen et al. (2002a). ^{207}Pb/^{206}Pb evaporation ages obtained for Phalaborwa yielded an average age of 2,054±1.9 Ma, similar to the age of 2,051.8±0.4 Ma reported by Kröner and Willner (1998). Repeated analysis of zircon 91500 gave Pb-evaporation ages of 1,062.7±2.2 Ma, consistent with the reported conventional U–Pb age of 1,065.4±0.3 Ma obtained in different laboratories (Wiedenbeck et al. 1995).

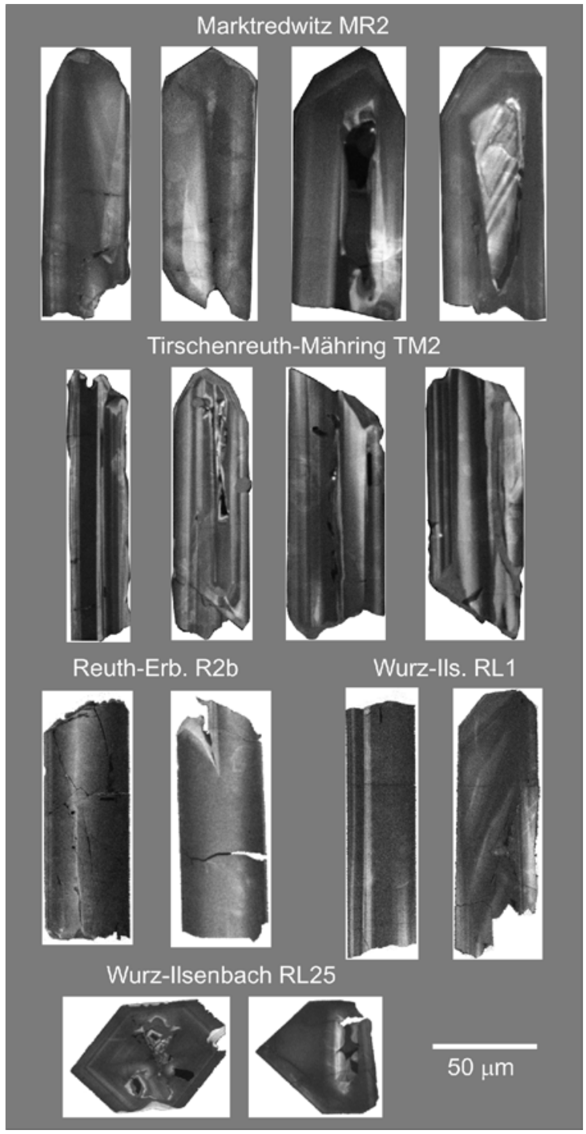

Fig 2 Cathodoluminescence images of typical zircons from redwitzites

Sample description and analytical results

Redwitzites

Zircons from samples RL1 and R2b (for further analytical data of these samples, see Siebel 1993, 1994) have needle-like shapes with very high aspect ratios. Most of the needles have been broken during separation of the crystals. The CL images in Fig. 2 display faintly zoned

Table 1 Isotope data for single-grain $^{207}Pb/^{206}Pb$ evaporation analyses of zircons from the redwitzites (* measured with Faraday detector, – not measured)

Sample/grain	No. of ratios	$^{204}Pb/^{206}Pb$	$^{206}Pb/^{208}Pb$	$^{206}Pb/^{208}Pb$	Age (Ma)
Redwitzite Tirschenreuth-Mähring					
TM2/1	278	0.000044	4.7	0.052824±0.000045	321.3±3.0
TM2/2	241	0.000148	4.9	0.052851±0.000033	322.4±2.7
TM2/3	228	0.000056	5.3	0.052905±0.000025	324.8±2.5
Weighted average					323.0±4.5
Redwitzite Marktredwitz					
MR2/1	179	0.000014	6.6	0.052841±0.000037	322.0±2.8
MR2/2	325	0.000051	6.3	0.052753±0.000035	318.2±2.7
MR2/3	144	0.000006	7.6	0.052911±0.000035	325.0±2.7
MR2/4	161	0.000016	4.1	0.052816±0.000058	320.9±3.4
Weighted average					321.6±4.7
Redwitzite Reuth-Erbendorf					
R2b/1	342	0.000031	4.3	0.052840±0.000038	322.0±2.9
R2b/2	357	0.000033	2.8	0.052867±0.000017	323.1±2.4
R2b/3	262	0.000015	2.3	0.052911±0.000015	325.0±2.4
R2b/3*	333	0.000013	2.3	0.052915±0.000021	325.2±2.5
Weighted average					323.5±3.7
Redwitzite Wurz-Ilsenbach					
RL1/1	510	0.000146	5.0	0.052894±0.000032	324.3±2.7
RL1/2	607	0.000007	3.5	0.052857±0.000019	322.7±2.4
RL1/3	280	0.000042	4.7	0.052852±0.000029	322.5±2.6
Weighted average					323.1±1.4
RL25/1	409	0.000016	–	0.052894±0.000025	324.3±2.5
RL25/2	252	0.000026	–	0.052831±0.000039	321.6±2.9
RL25/3	261	0.000005	3.0	0.052839±0.000027	321.9±2.6
Weighted average					322.7±3.7

or essentially unzoned zircons. Although unzoned crystals can be the result of recrystallisation of zoned crystals accompanied by loss of U, Th, and Pb (Pidgeon 1992), we believe that the zircons were formed during a one-stage magmatic crystallisation history. Sample RL25 (for whole-rock and mineral data, see Siebel 1993, 1994) contains zircons with distinct morphology (Fig. 2). None of the grains are needle-like but they are equant with 1:1 aspect ratios and show stubby crystal habit. Some grains have well-developed tetragonal prisms. Despite their different morphology, all crystals from samples RL1 and RL25 gave Pb-evaporation ages between 324 and 322 Ma with mean ages of 323.1±1.4 Ma (RL1) and 322.7±3.7 Ma (RL25; Table 1). Similar results (ages between 325 and 322 Ma, mean of 323.5±3.7 Ma, Fig. 3) were obtained for three crystals from sample R2b.

Sample MR2 is a medium-grained diorite and comes from north-east of Marktredwitz. The zircons from this sample are similar to those of samples RL1 and R2b. However, at least one zircon (out of eight grains analysed by CL) has a higher reflectance, wedge-shaped core with relic zonation (Fig. 2). Zircons with cores have been reported from the Marktredwitz intrusion (Hecht, personal communication). Four zircons analysed provided ages between 325 and 318 Ma with a mean of 321.6±4.7 Ma (Fig. 3). Another redwitzite sample which was analysed comes from a dike intrusion between Tirschenreuth and Mähring (TM2). It is a fine-grained diorite, containing long-prismatic zircons. Three grains yielded $^{207}Pb/^{206}Pb$ ages between 325 and 321 Ma with a mean age of 323.0±4.5 Ma (Fig. 3).

An independent estimate for the age of the redwitzites was attempted by the U–Pb dating of titanite. Results obtained for six titanite fractions from three different samples (R2b, MR4 and MR6) are presented in Table 2 and displayed graphically on a concordia diagram in Fig. 4. Data from three fractions of sample R2b plot slightly below the concordia curve. Unforced regression yields upper and lower discordia intercept ages of 322±4 Ma and –3±130 Ma (e.g. zero) respectively, with a mean square of weighted deviates (MSWD) value of 0.3. The titanite fraction from sample MR4 yields a concordant data point with $^{238}U/^{206}Pb$ and $^{235}U/^{207}Pb$ ages of 326±3 and 325±5 Ma respectively. The two titanite fractions of sample MR6 are slightly reverse discordant. When forced through the 0-Ma intercept, an age of 323±6 Ma (MSWD=0.1) is obtained. If all data points would be combined and fitted to a chord through the origin in the concordia diagram, the intercept age would be at 322±4 Ma (MSWD=0.3).

Marktredwitz (G1) granite

The G1 sample was collected from a new outcrop close to the motorway 93, NE of Marktredwitz. The distribution of G1 granite in redwitzites is irregular and makes up only 5–10% of the outcrop area. Zircons from G1 are

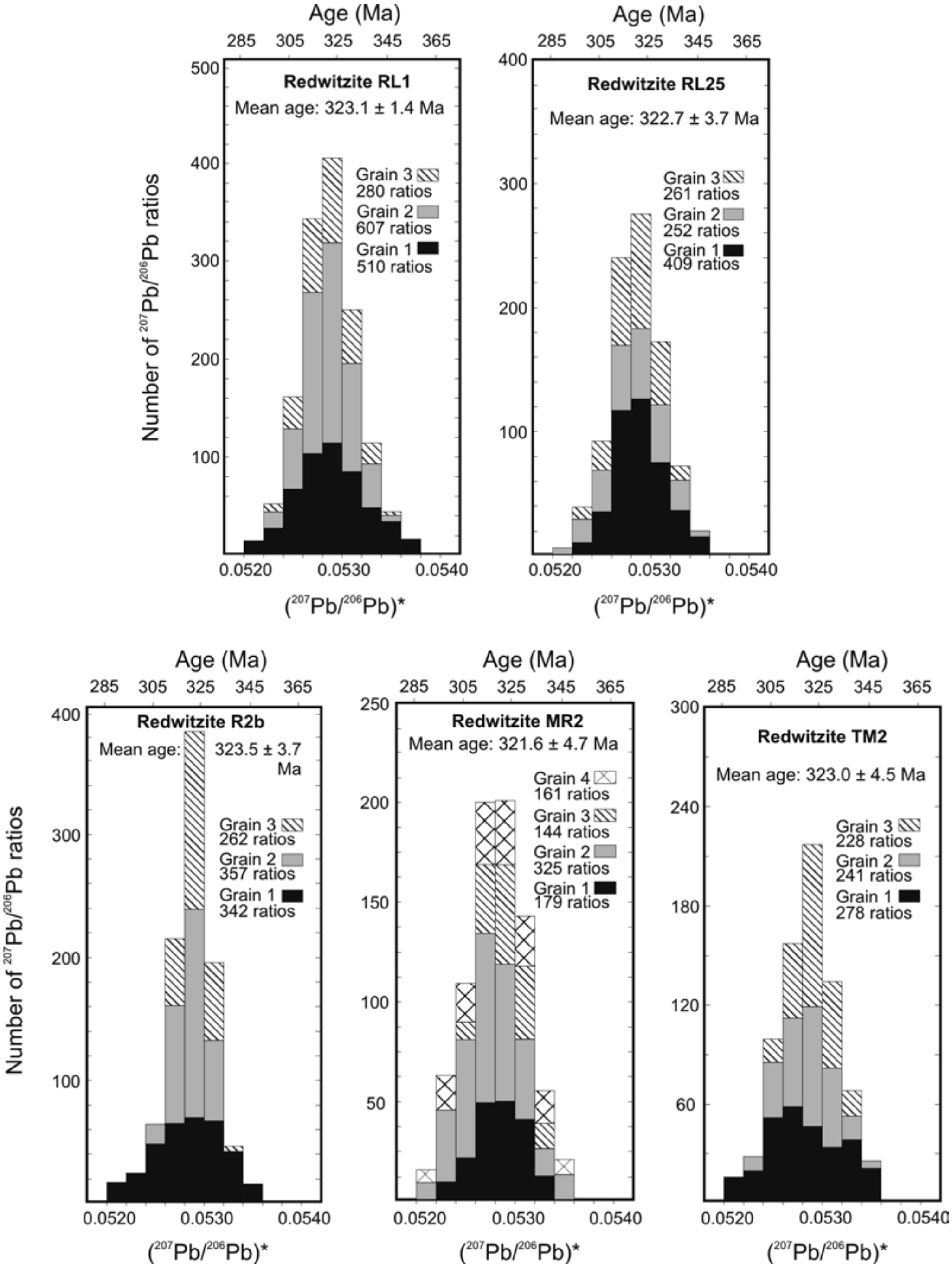

Fig 3 Histograms showing the distribution of radiogenic $^{207}Pb/^{206}Pb$ ratios obtained from evaporation of single zircon grains from redwitzites

Table 2 U–Pb analytical data for titanite from NE Bavarian redwitzites

		Atomic ratios			Model ages (Ma)		
Fraction	$^{206}Pb/^{204}Pb$	$^{206}Pb^{a}/^{238}U$	$^{207}Pb^{a}/^{235}U$	$^{207}Pb^{a}/^{206}Pb^{a}$	$^{206}Pb^{a}/^{238}U$	$^{207}Pb^{a}/^{235}U$	$^{207}Pb^{a}/^{206}Pb^{a}$
R2b/1	222.0±0.5	0.04940±0.00121	0.3605±0.0093	0.05293±0.00023	310.0±7.5	312.6±7.0	325.7±10.0
R2b/2	222.3±0.4	0.05021±0.00086	0.3657±0.0066	0.05282±0.00022	315.8±5.3	316.4±4.9	321.0±9.3
R2b/3	221.8±0.5	0.04963±0.00185	0.3612±0.0137	0.05278±0.00023	312.3±11.3	313.1±10.2	319.3±9.3.
MR4	133.0±0.5	0.05185±0.00046	0.3768±0.0062	0.05270±0.00048	325.9±2.8	324.7±4.5	316.0±21.0
MR6/1	307.4±1.5	0.05292±0.00046	0.3855±0.0046	0.05283±0.00026	332.4±2.8	331.0±3.4	321.5±11.3
MR6/2	243.0±0.7	0.05363±0.00069	0.3909±0.0057	0.05287±0.00019	336.7±4.2	335.0±4.2	323.0±8.2

[a] Radiogenic Pb. $^{206}/Pb/^{204}Pb$ is corrected for tracer and fractionation. Atomic ratios are corrected for tracer, fractionation, blank and Stacey-Kramers common Pb. Decay constants for U are from Jaffey et al. (1971). All errors are 2σ absolute uncertainties

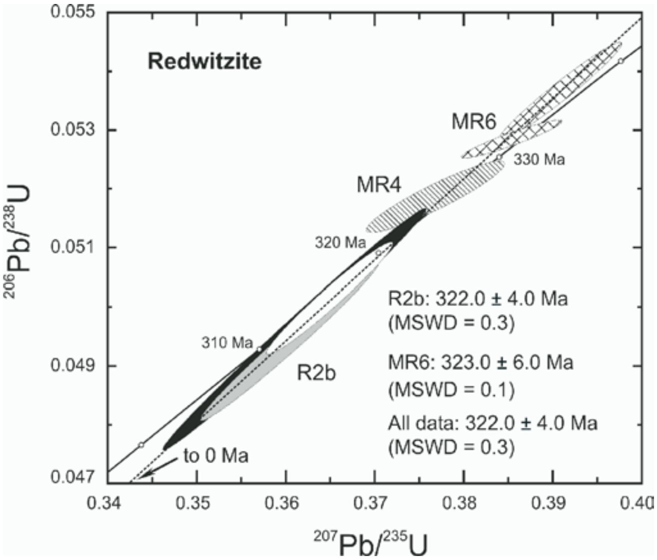

Fig 4 U–Pb concordia diagram showing the analyses for titanite from three different redwitzite samples (R2b from Reuth-Erbendorf, MR4 and MR6 from Marktredwitz)

slightly elongated and prismatic with concentric, oscillatory zoning in CL images (Fig. 5). The inner area consists of a light luminescent region with dark embayments or inclusions. The inner core is partially resorbed, a process often linked to recrystallisation. The grains are characterised by high $^{204}Pb/^{206}Pb$ ratios (4.2×10^4 to 2.4×10^4, Table 3) which could result from the resorption process through diffusional loss of radiogenic Pb. Other possibilities for high $^{204}Pb/^{206}Pb$ ratios are inclusions of common Pb-rich minerals, low U concentrations, infiltration or inheritance of common Pb. Since there is an inevitable uncertainty about the isotopic character of the common Pb, the corrected $^{207}Pb/^{206}Pb$ ratios, i.e. age estimates, are more unreliable when the measured $^{204}Pb/^{206}Pb$ ratios are high ($>2\times10^{-4}$). Notwithstanding these potential problems, Pb-evaporation from three grains yields similar $^{207}Pb/^{206}Pb$ ages between 325 and 322 Ma with a mean age of 324.2±4.2 Ma (Fig. 6).

Leuchtenberg granite

Three samples (L2, L6a, L18; for geochemical and isotope data on whole rocks and major minerals, see Siebel 1993, 1995b) were taken from this granite. Samples L2 and L6a come from the southern lobe of the granite outcrops whereas sample L18 comes from the northern lobe and was collected from a point adjacent to the Wurz-Ilsenbach redwitzite. As seen from the CL images (Fig. 5), zircons from samples L6a and L18 have developed compositional zonation reflecting growth during crystallisation from magma. Zircons from the more fractionated sample L2 show only weak zonation pattern. $^{207}Pb/^{206}Pb$ ages of zircons from sample L6a are between 327 and 328 Ma with a mean age of 327.6±1.2 Ma. Five zircon

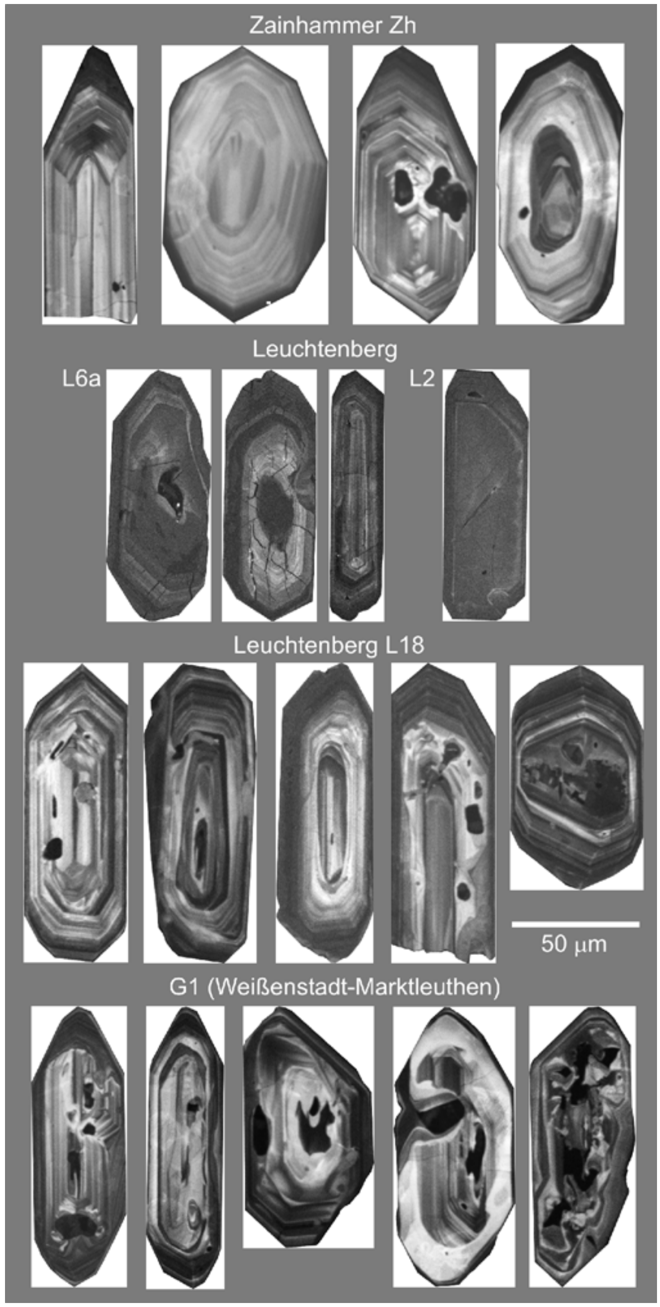

Fig 5 Cathodoluminescence images of typical zircons from the granites of Marktredwitz (G1), Leuchtenberg and Zainhammer

ages from sample L2 vary between 327 and 322 Ma with a mean age of 323.9±2.8 Ma. Three grains from sample L18 yielded Pb-evaporation ages between 324 and 322 Ma with a mean age of 322.6±1.4 Ma (Fig. 6). The two heating steps carried out on another zircon from this sample gave significantly older ages of ~340 Ma (Table 3), indicating that this grain, or a major part of it, had formed prior to emplacement.

Table 3 Isotope data for single-grain $^{207}Pb/^{206}Pb$ evaporation analyses of zircons from the granites of G1 from Marktredwitz, Leuchtenberg and Zainhammer (– not measured)

Sample/grain	No. of ratios	$^{204}Pb/^{206}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{206}Pb$	Age (Ma)
Zainhammer granite					
Zh/1	301	0.000009	11.8	0.052831±0.000023	321.6±2.5
Zh/2	290	0.000020	14.6	0.052801±0.000023	320.3±2.5
Zh/3	185	0.000014	20.9	0.052830±0.000045	321.5±3.0
Zh/4	258	0.000017	15.2	0.052816±0.000031	321.0±2.6
Zh/5	138	0.000014	29.0	0.052827±0.000038	321.4±2.8
Weighted average					321.1±1.2
Leuchtenberg granite					
L18/1	374	0.000020	32.0	0.052875±0.000025	323.5±2.5
L18/2	377	0.000111	23.0	0.052858±0.000025	322.7±2.5
L18/3	419	0.000172	9.6	0.052829±0.000033	321.5±2.7
One grain with apparent $^{207}Pb/^{206}Pb$ age of ~340 Ma					
Weighted average grains 1–3					322.6±1.4
L2/1	287	0.000029	–	0.052951±0.000039	326.7±2.9
L2/2	188	0.000011	44.0	0.052831±0.000034	321.6±2.7
L2/3	138	0.000053	11.5	0.052916±0.000052	325.2±3.2
L2/4	145	0.000016	43.0	0.052854±0.000046	322.6±3.0
L2/5	44	0.000111	–	0.052880±0.000088	323.7±4.5
Weighted average					323.9±2.8
L6a/1	451	0.000127	14.7	0.052948±0.000035	326.6±2.7
L6a/2	441	0.000094	20.7	0.052978±0.000019	327.9±2.4
L6a/3	389	0.000102	15.2	0.052975±0.000024	327.8±2.5
L6a/4	226	0.000074	15.5	0.052977±0.000025	327.8±2.5
Weighted average					327.6±1.2
Marktredwitz (G1) granite					
G1/1	394	0.000238	12.1	0.052919±0.000023	325.3±2.5
G1/2	253	0.000412	9.3	0.052901±0.000035	324.6±2.7
G1/3	213	0.000337	5.8	0.052837±0.000056	321.8±3.3
Weighted average					324.2±4.2

Zainhammer granite

Sample Zh comes from an abandoned quarry SW of Zainhammer lodge, close to outcrops of the Reuth-Erbendorf redwitzite. This sample was taken from the same locality as samples 2478 and 2759 investigated by Wendt et al. (1988, 1992). Zircons from sample Zh exhibit homogeneous magmatic oscillatory zoning and the intensity of the CL signal is quite constant (Fig. 5), indicating that the chemical conditions during crystallisation remained fairly stable. With one exception (fourth grain of first line in Fig. 5), inherited cores were not detected by CL. Final stages of zircon growth are revealed by darker rims. Pb-evaporation data from five grains which were analysed yielded almost the same age, with a mean value of 321.1±1.2 Ma (Table 3, Fig. 6).

Falkenberg granite

Two porphyritic biotite–muscovite granites samples (Fa1 and Fa3) were collected from the Falkenberg granite. Zircons from each of these rocks show several growth stages revealed in CL images (Fig. 7). Sample Fa1 comes from a road cut east of Falkenberg. In this sample, unzoned or weakly zoned cores, interpreted as representing pre-emplacement zircon growth, are overgrown by several stages of oscillatory zoned material, interpreted as syn- to post-emplacement structures. In some grains, replacement of the cores occurs along small, embayment-like chemical reaction fronts which proceed towards the interior of the core. The second Falkenberg sample, Fa3, comes from a new road cut at the motorway A93. Most of the zircons of this sample are characterised by purely magmatic growth zonation.

Three grains of sample Fa1 gave ages between 314 and 317 Ma with a weighted mean age of 315.5±3.7 Ma (Table 4, Fig. 8). Several grains from this sample show variation of the measured $^{207}Pb/^{206}Pb$ ratios due to the presence of more than one age component. As such, no definite age could be obtained from these grains. Two of them yielded ages of ~333 and ~338 Ma. The oldest age obtained for a high-temperature evaporation step of a third grain was around ~475 Ma. This analysis was probably influenced by a zircon core domain which may indicate an inherited Caledonian or older age. It should be recalled that zircons from the Falkenberg granite investigated by Carl et al. (1989) yielded old Pb-evaporation ages of 336, 346 and 368 Ma, suggesting a contribution from relict cores.

The second Falkenberg sample, Fa3, gave similar $^{207}Pb/^{206}Pb$ ages between 315 and 314 Ma with a mean

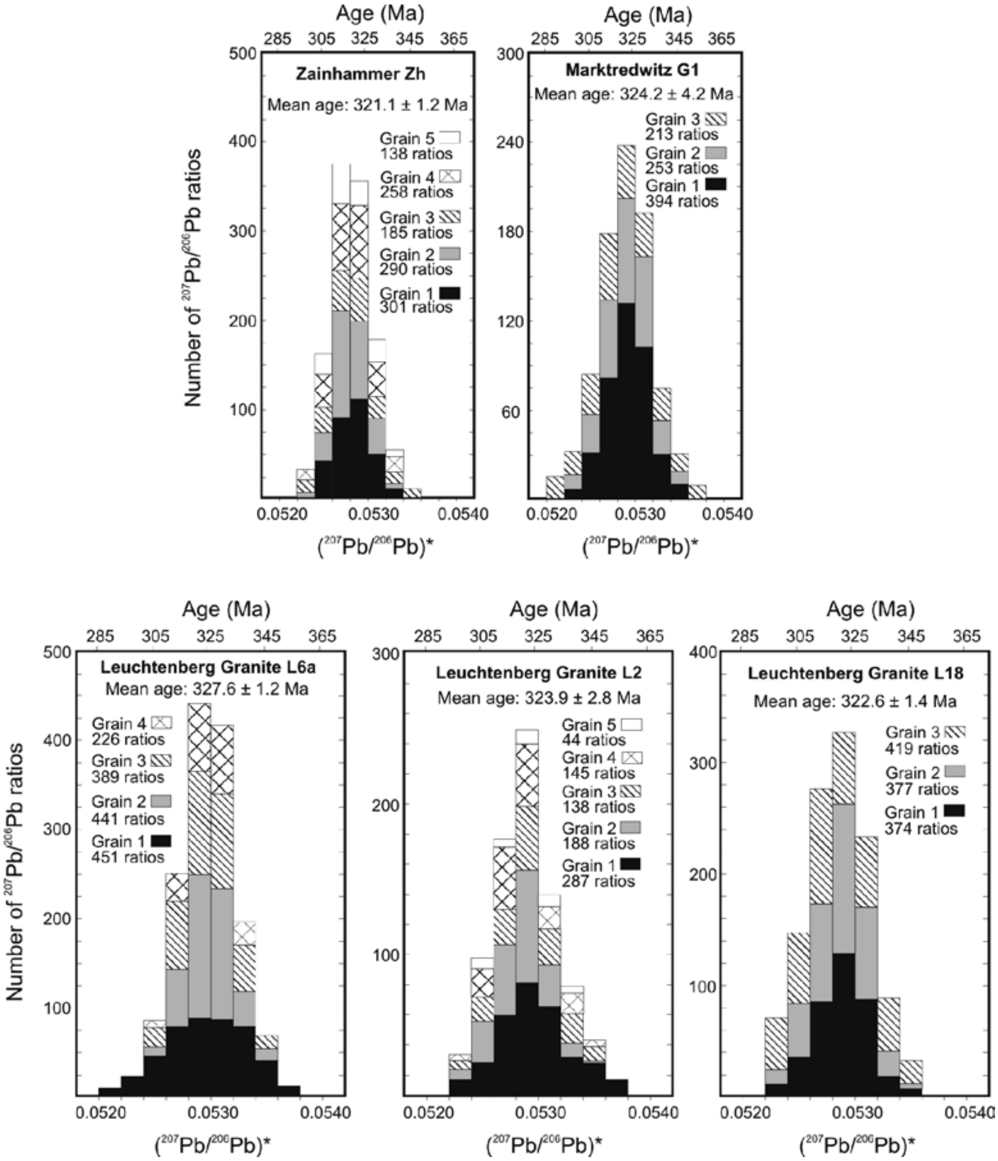

Fig 6 Histograms showing the distribution of radiogenic $^{207}Pb/^{206}Pb$ ratios obtained from evaporation of zircons from the granites of Marktredwitz (G1), Leuchtenberg and Zainhammer

Table 4 Isotope data for single-grain $^{207}Pb/^{206}Pb$ evaporation analyses of zircons from the granites of Falkenberg and Liebenstein

Sample/grain	No. of ratios	$^{204}Pb/^{206}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{206}Pb$	Age (Ma)
Liebenstein granite					
Lb/1	335	0.000024	9.6	0.052554±0.000020	309.6±2.5
Lb/2	550	0.000156	15.6	0.052681±0.000019	315.1±2.4
Lb/3	135	0.000056	26	0.052676±0.000037	314.9±2.8
Lb/4	291	0.000131	68	0.052717±0.000029	316.7±2.6
Lb/5	407	0.000090	19	0.052644±0.000015	313.5±2.4
Weighted average grains 2–5					315.0±1.2
Falkenberg granite					
Fa1/1	289	0.000060	17	0.052648±0.000028	313.7±2.6
Fa1/2	223	0.000015	39	0.052716±0.000019	316.6±2.4
Fa1/3	194	0.000060	19	0.052690±0.000035	315.5±2.7
Grains with apparent $^{207}Pb/^{206}Pb$ ages of ~333, ~338 and 359–475 Ma					
Weighted average grains 1–3					315.3±3.7
Fa3/1	263	0.000077	25	0.052683±0.000012	315.2±2.4
Fa3/2	332	0.000062	44	0.052663±0.000030	314.4±2.6
Fa3/3	172	0.000055	25	0.052651±0.000045	313.8±3.0
Weighted average					314.6±1.5

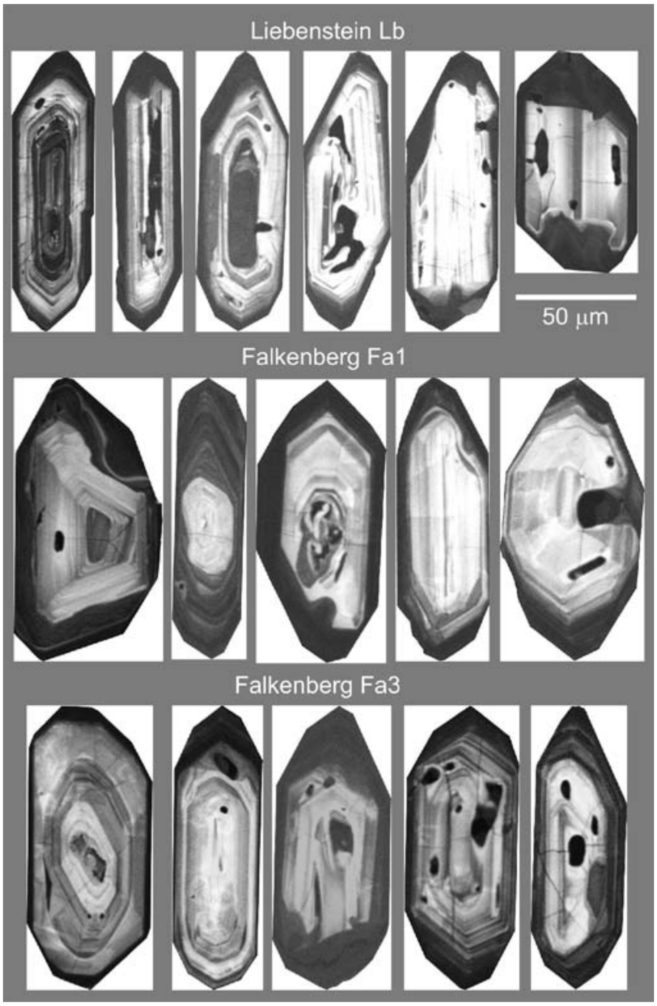

Fig 7 Cathodoluminescence images of typical zircons from the granites of Falkenberg and Liebenstein

age of 314.6±1.5 Ma, identical to the zircon ages from sample Fa1. No grains with older age information were detected in this sample.

Liebenstein granite

A sample from this granite (Lb) was taken from the Liebenstein reservoir. CL investigations reveal long-prismatic zircons with oscillatory zoning (Fig. 7). Replacement of the core occurs along curved chemical reaction fronts which proceed from the surface towards the interior of the zircon. As in the zircons from the Falkenberg granite, subsequent growth stages can by distinguished by their darker CL colour. From five grains analysed, four yielded similar data with a mean age of 315.0±1.2 Ma (Table 4, Fig. 8). These ages are consistent within analytical uncertainty with most age data from the Falkenberg granite and are therefore interpreted as the most realistic age estimate for the Falkenberg/Liebenstein granite. The two different temperature steps of grain Lb/1 yielded ages around ~310 Ma (mean: 309.6±2.5 Ma) which is, within error limits, identical to the average K–Ar muscovite ages from this granite (306.7±1.4 Ma, Wendt et al. 1986). If the young zircon age would indicate crystallisation, then all other grains from the Liebenstein granite would have the same degree of discordance, a case which seems very unlikely. We therefore think that the young Lb/1 zircon age may be caused by loss of Pb during a subsequent stage.

Mitterteich granite

Sample M5 was collected from a quarry close to Großbüchlberg and comes from the same locality as samples M5a–c analysed in Siebel (1995a). It is a coarse-grained biotite–muscovite granite. The majority of the zircons from this sample show homogeneous magmatic zonation or sector zoning (Fig. 9). In two of the grains shown in Fig. 9, a diffuse contact between the bright core and the dull grey rim can be seen. This feature suggests that earlier zircon of igneous origin was resorbed prior to crystallisation of the outer growth zones. The grains are characterised by high $^{204}Pb/^{206}Pb$ ratios (7.1×10^4 to 3.8×10^4, Table 5), making it difficult to achieve high-precision evaporation ages. Common Pb correction results in larger age uncertainties and in a slightly over-dispersed $^{207}Pb/^{206}Pb$ frequency distribution when compared to other samples (Fig. 10). Four zircons from sample M5 were dated and ages range from 315 to 306 Ma with a mean of 309.5±6.2 Ma, matching the Rb–Sr whole-rock and K–Ar mica ages of this granite (Siebel 1995a). Two grains yielded older ages of ~331 Ma (one temperature step analysis) and ~364 to ~430 Ma (low- and high-temperature step analyses of same grain), suggesting involvement of a relict core. The $^{207}Pb/^{206}Pb$ ratios were corrected using Stacey-Kramers common Pb of 310 Ma ($^{206}Pb/^{204}Pb$=18.22, $^{207}Pb/^{204}Pb$=15.60). We also determined the Pb isotope composition of a K-feldspar concentrate from this sample, which gave $^{206}Pb/^{204}Pb$=18.18 and $^{207}Pb/^{204}Pb$=15.63. Correction of zircon data with Pb from the K-feldspar would result in a small decrease (ca. 0.3–0.5%) of the ages.

Friedenfels granite

Sample Fr comes from the same locality as samples 2752 investigated by Wendt et al. (1992). All zircon grains consist of magmatic overgrowths with weak zoning and bright, irregularly shaped and partly resorbed inherited cores (Fig. 9). Six zircons from this sample were analysed and gave Upper Carboniferous ages between 316 and 307 Ma (weighted average age=311.8±3.8 Ma, Fig. 10). The average Pb-evaporation zircon age is only slightly older than the K–Ar muscovite age of 309.4±1.5 Ma from sample 2752 (Wendt et al. 1992). No constant $^{207}Pb/^{206}Pb$ ratios could be obtained from three other zircon grains, due to the presence of different age

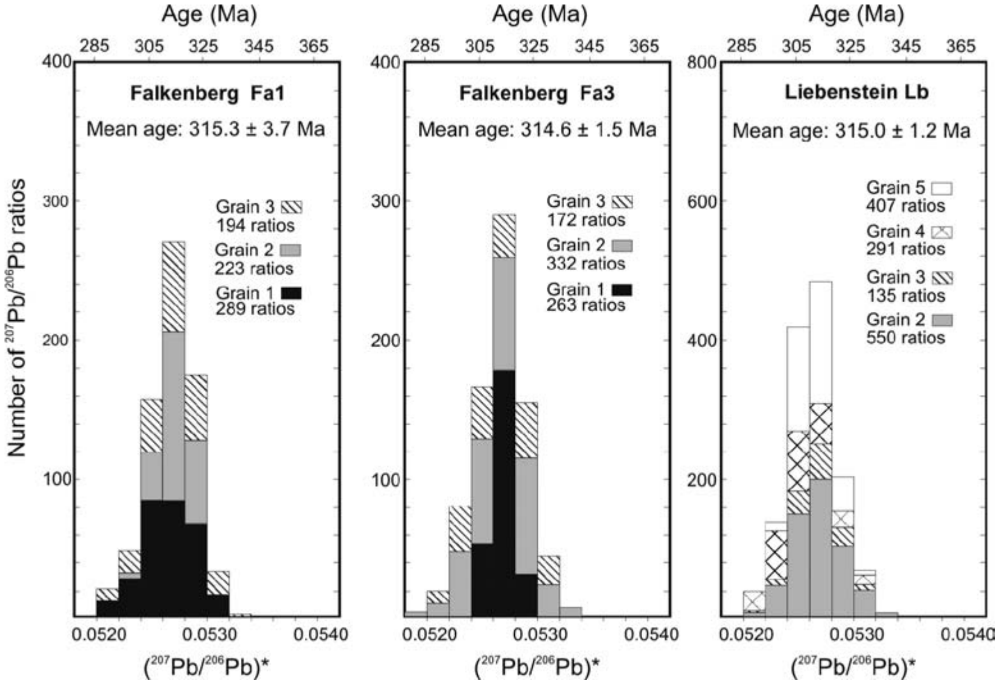

Fig 8 Histograms showing the distribution of radiogenic $^{207}Pb/^{206}Pb$ ratios obtained from evaporation of zircons from Falkenberg and Liebenstein

Table 5 Isotope data for single-grain $^{207}Pb/^{206}Pb$ evaporation analyses of zircons from the granites of Mitterteich, Friedenfels, Steinwald, Flossenbürg and Bärnau

Sample/grain	No. of ratios	$^{204}Pb/^{206}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{206}Pb$	Age (Ma)
Bärnau granite					
Grains with apparent $^{207}Pb/^{206}Pb$ ages of ~317, ~320, 329–422, ~448 and 1,300–1,430 Ma					
Flossenbürg granite					
Fl/1	262	0.000005	42	0.052553±0.000011	309.6±2.4
Fl/2	337	0.000009	26	0.052617±0.000011	312.3±2.4
Fl/3	105	0.000006	34	0.052554±0.000018	309.6±2.4
Fl/4	173	0.000010	52	0.052515±0.000019	307.9±2.4
Grains with apparent $^{207}Pb/^{206}Pb$ ages of ~317 and ~325 Ma					
Weighted average grains 1–4					309.9±2.9
Steinwald granite					
St2/1	372	0.000026	95	0.052586±0.000017	311.0±2.4
St2/2	340	0.000012	111	0.052628±0.000018	312.8±2.4
St2/3	263	0.000015	58	0.052666±0.000021	314.5±2.5
St2/4	180	0.000009	148	0.052613±0.000053	312.2±3.3
St2/5	187	0.000008	65	0.052646±0.000032	313.6±2.7
St2/6	342	0.000076	10.4	0.052518±0.000032	308.1±2.7
Grains with apparent $^{207}Pb/^{206}Pb$ ages of ~334 and ~340 Ma					
Weighted average grains 1–6					312.1±2.4
Friedenfels granite					
Fr/1	355	0.000108	33	0.052484±0.000033	306.6±2.7
Fr/2	254	0.000027	146	0.052640±0.000026	313.3±2.5
Fr/3	471	0.000075	26	0.052521±0.000015	308.2±2.4
Fr/4	151	0.000012	49	0.052618±0.000035	312.4±2.7
Fr/5	399	0.000050	88	0.052698±0.000018	315.9±2.4
Fr/6	67	0.000039	22	0.052652±0.000060	313.9±2.6
Grains with apparent $^{207}Pb/^{206}Pb$ ages of ~318, ~332, 328–340 and ~540 Ma					
Weighted average grains 1–6					311.8±3.8
Mitterteich granite					
M5/1	167	0.000720	11.2	0.052525±0.000084	308.4±4.4
M5/2	116	0.000631	6.4	0.052675±0.000064	314.9±3.6
M5/3	128	0.000464	5.4	0.052530±0.000065	308.6±3.6
M5/4	154	0.000377	16.4	0.052475±0.000058	306.2±3.4
One grain with apparent $^{207}Pb/^{206}Pb$ age of ~331 and ~364–430 Ma					
Weighted average grains 1–4					309.5±6.2

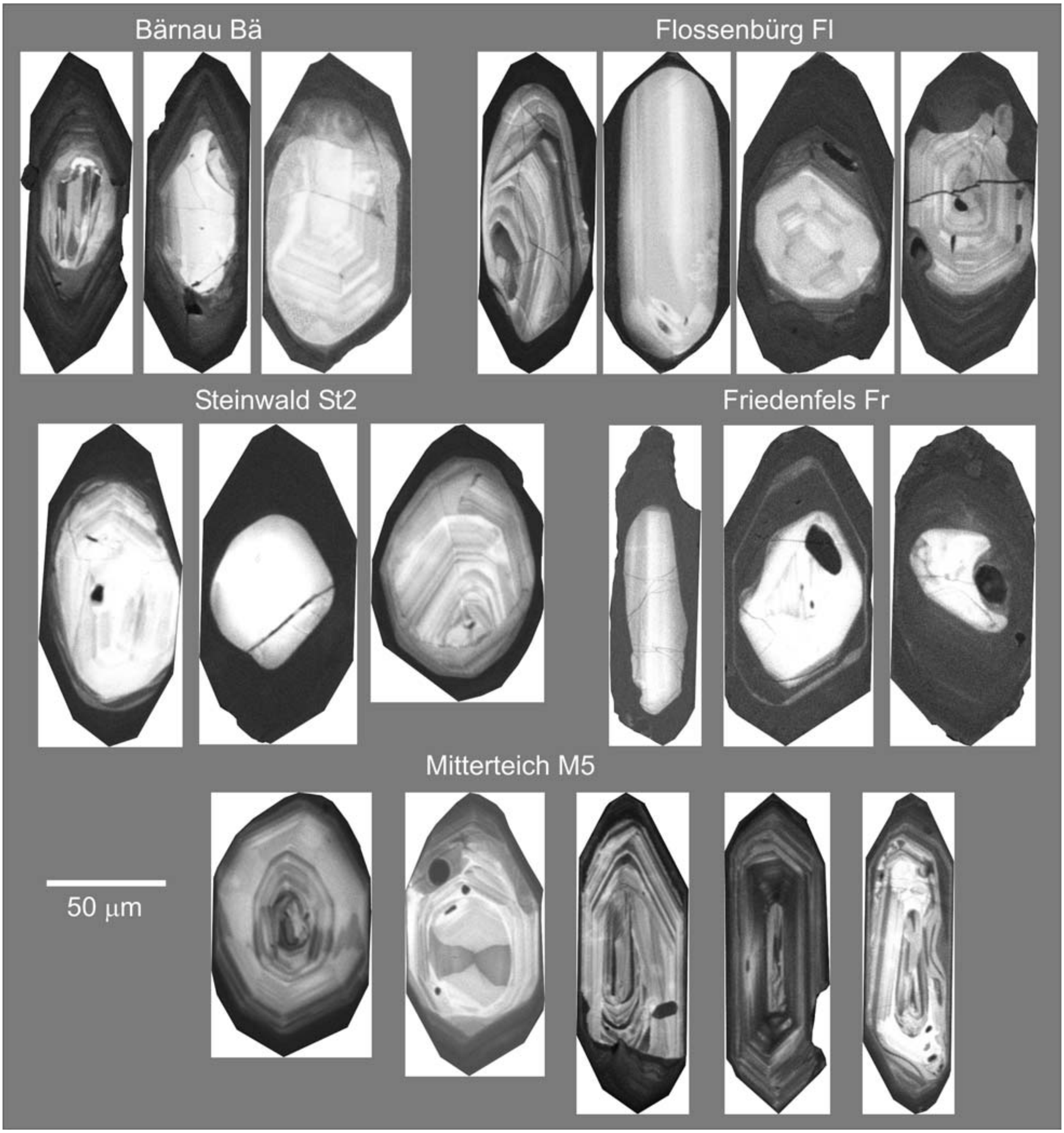

Fig 9 Cathodoluminescence images of typical zircons from the granites of Mitterteich, Friedenfels, Steinwald, Flossenbürg and Bärnau

domains in the crystal. The youngest $^{207}Pb/^{206}Pb$ ages were obtained for the lowest evaporation temperature steps of these grains and are ~318, ~332, ~328–340 and ~540 Ma (Table 5). We interpret them as reflecting various mixtures between Variscan and older (?Caledonian, ?pan-African) components.

Steinwald granite

Sample St2 comes from a small abandoned quarry, Hohes Saubad. CL imaging reveals essentially two distinct zircon generations for all crystals (Fig. 9). The inner parts consist of partly oscillatory zoned zircon with generally high CL intensity, whereas the outer domains are characterised by low CL intensity. The cores are well rounded and may have been formed either by abrasion during transport prior to sedimentation or by chemical corrosion in the Steinwald magma. Six grains have ages between 315 and 308 Ma, producing a mean age of 312.1±2.4 Ma (Table 5, Fig. 10) which we interpret to reflect the time of granite formation. The Pb-evaporation

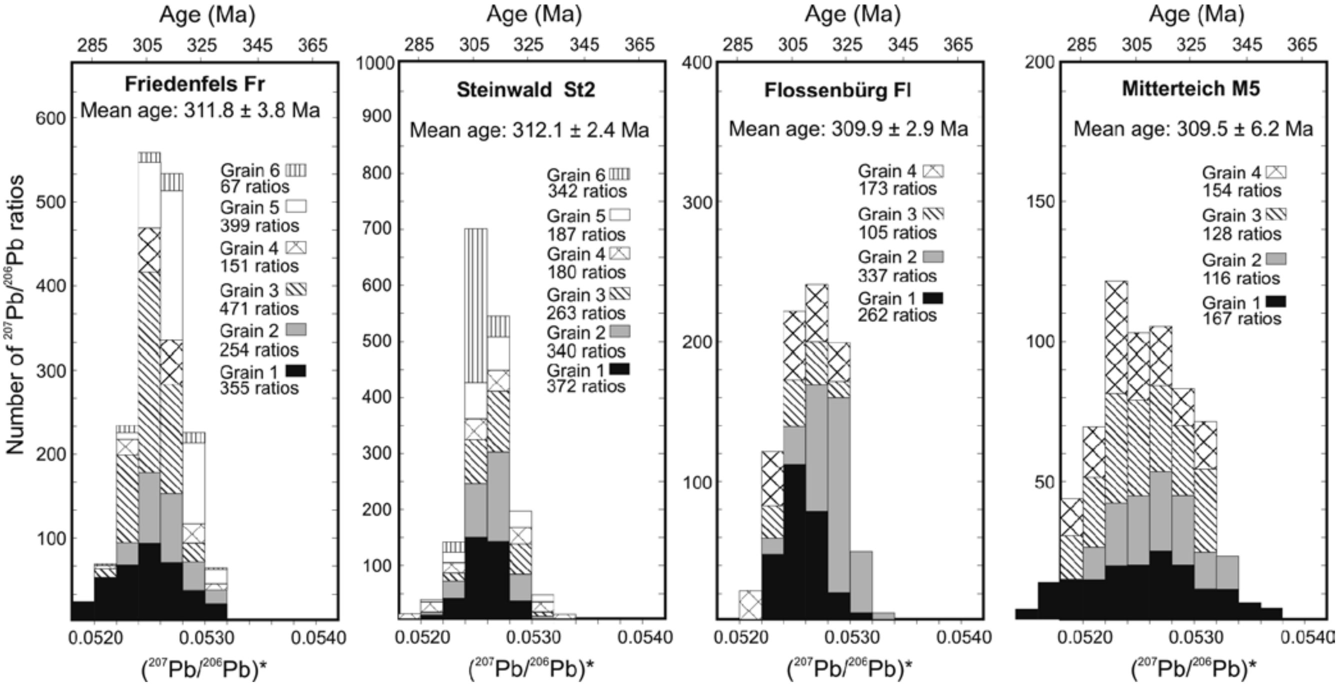

Fig 10 Histograms showing the distribution of radiogenic $^{207}Pb/^{206}Pb$ ratios obtained from evaporation of zircons from Mitterteich, Friedenfels, Steinwald and Flossenbürg

ages are equal within error with the age of the Friedenfels granite. All grains from the Steinwald and Friedenfels granite are characterised by very high $^{206}Pb/^{208}Pb$ ratios (Steinwald: 58–148, Friedenfels: 22–146), indicating that the melt from which the zircons crystallised had very high U/Th ratios. Whole-rock data show that Th is strongly depleted in the Friedenfels and Steinwald granites (Richter and Stettner 1987). Two grains from the Steinwald granite yield older ages of ~334 Ma (one temperature step analysis) and ~340 Ma (high-temperature step of grain St2/3), which we interpret as core material inherited from source rocks.

Flossenbürg granite

The granite quarry from which the sample was collected is located about 1 km WNW of Flossenbürg. The zircon population of this sample displays complex internal structures with core and rim domains (Fig. 9). Some cores show well-preserved magmatic growth zoning; others are homogeneous and dominate the major part of the crystal; a third type of core shows corrosion features. Six grains were analysed and four of them have ages between 312 and 308 Ma, giving a mean age of 309.9±2.9 Ma (Table 5, Fig. 10). Two grains have older ages of ~317 and ~325 Ma (one temperature step analyses), probably reflecting the presence of inherited core material. One age is identical to the age of the Leuchtenberg granite whereas the other age corresponds to that of the Falkenberg/Liebenstein granites.

Bärnau granite

During stepwise Pb-evaporation of zircons from the Bärnau granite, zones with different $^{207}Pb/^{206}Pb$ ratios were removed from the crystal, i.e. no constant ages for different temperature steps were obtained. An increase of the evaporation temperature resulted in successively older ages. This implies that the sample from the Bärnau granite was derived from a source which contained a significant proportion of older crustal material. As seen from CL images in Fig. 9, the zircon population of the Bärnau granite contains inherited cores mantled by magmatic rims with faint oscillatory zoning. Some measured evaporation ages of the Bärnau granite are between ~329 and 422 Ma and at ~448 Ma (Table 5). These ages may be explained by mixing between Caledonian or older and Variscan rocks. For another grain the high-temperature evaporation step gave exceptionally high $^{207}Pb/^{206}Pb$ ratios, corresponding to ages in the range 1,300–1,430 Ma. This age is in the range of the Nd model ages for the Bärnau granite (1,500–1,600 Ma, Siebel et al. 1995) and may indicate a mid-Proterozoic crust forming event. The youngest $^{207}Pb/^{206}Pb$ zircon ages obtained (for low-temperature steps only) are ca. 317 and 320 Ma. If the Bärnau granite emplacement age is 313±2 Ma, as indicated by Rb–Sr whole-rock analyses (Wendt et al. 1994), then even those grains are characterised by some inheritance.

Discussion

Geochronology of the NE Bavarian granitoids

A first order result of this study is that Pb-evaporation zircon ages concurrently point to an emplacement age of 324–322 Ma for the redwitzites. Age replication for all evaporation steps of a single grain indicates that a single component has been dated, as it is unlikely that several age components were repeatedly mixed in identical proportions (e.g. Dougherty-Page and Bartlett 1999). In none of the 16 zircon grains analysed were an old Pb component or a complex age pattern found. For a few exceptions, no cores were detected by CL imaging. Zircons from the redwitzites form a morphologically distinct group and the grains are further characterised by lower average $^{206}Pb/^{208}Pb$ ratios (2.3–7.6, Table 1), compared to the zircons from the granites (5.4–148, Tables 3, 4 and 5). Zircons from the redwitzites can be interpreted as primary minerals which have crystallised directly from the magma. Pb-evaporation zircon ages of the redwitzites are corroborated by conventional U–Pb titanite ages of 325–322 Ma. Thus, the isotopic ages are considered as time of intrusion for the redwitzites. All titanite age data of the redwitzites are indistinguishable within error from zircon ages, implying rapid cooling from temperatures >850 to 700 °C (the latter temperature being an estimate for U–Pb titanite closure temperature published in the literature, e.g. Scott and St-Onge 1995). K–Ar mineral ages older than 325 Ma (Holl 1988) and excessively old amphibole ages calculated from high-temperature Ar–Ar steps (Siebel et al. 1998) can no longer be regarded as cooling ages of the redwitzites and raise new questions. A possible explanation is that argon was occluded in these minerals, when magma mixing and subsequent recrystallisation of the amphibole occurred.

The granites of Marktredwitz, Leuchtenberg and Zainhammer yielded very similar age results. The large number of Pb-evaporation zircon ages clustering between 325 and 321 Ma strongly suggests that granite intrusion occurred at that time. Pb-evaporation zircon ages from the southern lobe of the Leuchtenberg granite (L6a: 327.6 Ma, L2 323.9 Ma) are slightly older than those from the northern lobe (L18: 322.6 Ma) and further north in the Zainhammer granite (321.1 Ma). The southern Leuchtenberg granite has also yielded the oldest K–Ar muscovite and biotite ages among the granites in the northern Oberpfalz (326–323 Ma, Siebel 1993, 1995b). This gives reason to suspect that the southern lobe of the Leuchtenberg granite represents the earliest crystallised magma pulse in the northern Oberpfalz, whereas samples from the northern lobe crystallised some million years later, simultaneously with the redwitzites. Zircons from the Leuchtenberg granite are very different in external morphology and typology. It is well known that the development of a distinct crystal shape of an accessory zircon is strongly influenced by the chemical composition and physical conditions of the magma (Pupin 1980; Vavra 1990; Benisek and Finger 1993). Köhler (1970) interpreted the typological variation of the zircons from the Leuchtenberg granite as reflecting chemical evolution of the magma through a fractional crystallisation process. The zircons thus have acted as recorders of the compositional evolution of the Leuchtenberg magma.

Pb-evaporation zircon ages for the three samples from the Leuchtenberg granite (328 to 323 Ma) are significantly younger than the U–Pb upper intercept age of 342±5 Ma reported by Köhler and Hölzl (1996). This discrepancy is not surprising as the latter date is in conflict with K–Ar mineral ages of ca. 325 Ma for contact metamorphism (Henjes-Kunst, personal communication). The older age of Köhler and Hölzl (1996) obtained by conventional analyses could have been caused by the influence of metamict zones (see discussion in Grauert et al. 1996). The consistency between Pb–Pb zircon, Rb–Sr whole-rock and K–Ar mineral ages can be used as an argument for its chronological significance. Thus, the 328–323 Ma ages are considered the best estimate for the actual emplacement and crystallisation period of the Leuchtenberg granite.

The Falkenberg and Liebenstein granites are distinctly younger than the Leuchtenberg, Marktredwitz (G1), and Zainhammer granites but older than all other leucogranites from the northern Oberpfalz. A time gap of ca. 5 Ma between Pb-evaporation zircon ages and K–Ar mineral ages in the Falkenberg and Liebenstein granite is thus found (for summary of K–Ar mineral data, see Siebel et al. 1997). Pb-evaporation ages of ca. 315 Ma for both granites, K–Ar muscovite ages of 309.8±0.6 Ma (Falkenberg) and 306.7±1.4 Ma (Liebenstein), and K–Ar biotite ages of 299.2±0.6 Ma (Falkenberg) and 301.1±1.4 Ma (Liebenstein) suggest a slow cooling scenario for the Falkenberg/Liebenstein complex. This is in accordance with an intrusion depth of more than 9 km, as postulated by Maier and Stöckhert (1992).

The ca. 312–309 Ma zircon ages of the granites of Mitterteich, Friedenfels, Steinwald and Flossenbürg are largely compatible with the Rb–Sr whole-rock and K–Ar muscovite ages from these granites, and are taken as dating magmatic crystallisation. It is well known that the Rb–Sr whole-rock system can easily be disturbed when the rocks interact with a fluid phase. Good agreement between Pb-evaporation zircon ages and Rb–Sr whole-rock isochron ages therefore shows that the Rb–Sr system of these granites remained largely undisturbed since crystallisation. In instances where relict cores in the zircons caused a serious dating problem, like in the Bärnau granite, more reliable age information is then probably provided by the Rb–Sr whole-rock system. For the younger granites the $^{207}Pb/^{206}Pb$ zircon ages are not significantly older than the K–Ar mica ages from the same sample or granite. This indicates that crystallisation was followed by rapid cooling. In contrast to the older granites and the Falkenberg/Liebenstein complex, the younger granites probably intruded at higher levels (e.g. 2–4 km as estimated by Matthes (1951) for the Steinwald granite) and cooled rapidly below the blocking temperature of the micas.

Implications from zircon geochronology on magma geneses

Zircon is a unique geochronometer, insofar as its closure temperature (1,000 °C, Cherniak and Watson 2000) is higher than the temperatures under which the mineral can form in a granitic melt. Therefore, a U–Pb zircon age dates the time when the magma cooled below its saturation temperature and new magmatic zircons can nucleate. Uncertainties in age, however, arise from zircon inheritance, i.e. relict cores. Such zircons can enter the melt as (1) residual material inherited from the source, (2) material entrained by the ascending magma, or (3) material taken by wall-rock assimilation during intrusion. We are aware that the Pb-evaporation technique is not the best method to study inheritance, and only in-situ U–Pb measurements would really help to characterise and date the inherited cores. Combined with the CL images, however, the evaporation results allow some general statements about zircon inheritance. As mentioned above, inheritance of older grains is largely absent in the zircons from the redwitzites and the older granites. From the 36 individual Pb-evaporation analyses of these rocks, inheritance is documented only in one grain from sample L18. Scarcity of inheritance of older zircon is consistent with CL images which, in general, do not show visible cores (Figs. 2 and 5). The older granitoids are either of I-type or transitional I/S-type. In zircons from the younger granites the amount of inherited grains is larger. These granites exclusively have S-type geochemical characteristics. Among these, it is only in the Liebenstein granite that older ages were not detected by the Pb-evaporation method, although inheritance is documented in some of the zircon CL images from this granite (Fig. 7). CL images give the impression that almost all younger granites contain inherited zircon cores. In the case of the Bärnau granite, CL images seem to be supported by Pb-evaporation data, insofar as all grains analysed in this study gave older $^{207}Pb/^{206}Pb$ ages. In the other S-type granites, older zircon ages were found only in a limited number of grains. This misfit between CL images suggesting older cores and Pb-evaporation data may be explained by complete Pb-loss from the zircon cores during formation of the melts. In fact, Nasdala et al. (2001) found that zircon cores with high radionuclide content or higher degree of radiation damage of the crystal lattice can lose their radiogenic Pb completely. Alternatively, most of the inherited zircons may be only slightly older than those matching the accepted ages of the granites. This explanation is supported by the finding that in some zircons with cores, the "age" for the highest evaporation step was not remarkably older than the crystallisation age of the granite (see data for Flossenbürg granite). It seems possible that the cores of these zircons were formed during an earlier melting event related to the formation of the older granites. However, a combination of the two reasons given above may be the most likely explanation for the enigmatic relationship between CL and Pb-evaporation results.

The solubility of zircon in a silicate melt is a function of temperature and the composition of that melt (Watson and Harrison 1983). If the zircon saturation temperature was exceeded by inherent temperatures of the melt, complete zircon dissolution may have occurred, followed by cooling during ascent and magmatic crystallisation. According to the calibration curves of Watson and Harrison (1983), the NE Bavarian granitoids have low zircon saturation temperatures (redwitzites/older granites <860 °C, younger granites <750 °C). For I-type tonalitic melts, high liquid temperatures of 1,100–850 °C can be assumed. Such conditions may have prevailed in the mantle or in deeper crustal levels of a thickened crust. Thus, it seems possible that zircon was completely dissolved in the melts which produced the redwitzites and probably also the older, I/S-type granites. Generation of larger amounts of S-type melts during crustal anatexis requires temperatures between 850 and 700 °C (e.g. Clarke 1992). Intrusion temperatures of about 780 °C were inferred for the Falkenberg/Liebenstein granite (Maier and Stöckhert 1992). At these temperatures zircon xenocrysts may have been retained in the melt. Even if the temperature of the melt was higher than the zircon saturation temperature, it could be argued that there was some chemical disequilibrium between zircon and melt during anatexis, so that the older grains were not completely dissolved.

Based on the zircon type (inheritance or not), we believe that magma-generating processes were different for the older granitoids (redwitzites and older granites) and the two groups of younger granites. Nd isotopic characteristics (Siebel et al. 1997) of the older granitoids (εNd=+1 to −4, $^{87}Sr/^{86}Sr_T$=0.706–0.708) suggest a higher degree of contribution from the mantle than in the younger granites (εNd=−4 to −8, $^{87}Sr/^{86}Sr_T$=>0.710). Zircon inheritance is rare in mantle-derived magmas. Mantle input could have played a larger role during the genesis of the older granitoids than was presumed in earlier studies. The Nd and Sr isotope composition of the older granitoids is not in conflict with this idea, given the presence of enriched mantle and its crustal signatures below the Bohemian Massif (Janoušek et al. 1995; Gerdes et al. 2000).

Conclusions

Single-zircon Pb-evaporation geochronology in NE Bavaria shows unequivocal evidence for simultaneous intrusion of redwitzites and the spatially associated older granites of Leuchtenberg, Marktredwitz (G1) and Zainhammer. From this finding, the NE Bavarian redwitzite suite cannot be considered any longer as precursor intrusion but as temporal equivalents of the older granites. The coexistence of the redwitzites and the older granites as contemporaneous but contrasting magmas may suggest that there was also a link between melt extraction from the mantle, heat input into the crust, and the generation of heterogeneous hybrid (redwitzites) and larger amounts of well-mixed homogeneous (older granites) melts.

The now existing dataset of Pb-evaporation ages reflects a multistage history of magmatic events ranging from 328 to 321 Ma (redwitzites and older granites), ~315 Ma (Falkenberg, Liebenstein) and from 312 to 310 Ma (Flossenbürg, Friedenfels, Mitterteich, Steinwald, i.e. younger granites). The general agreement of the zircon evaporation data with pre-existing Rb–Sr whole-rock data implies that, apart from the redwitzites, most granite bodies achieved isotopic equilibrium at the whole-rock scale during the melting process. When U–Pb zircon data from granitoids of adjacent regions in Bavaria are considered (southern Oberpfalz, Bavarian Forest), which mainly range from 330 to 312 Ma (Propach et al. 2000, Chen et al. 2002b, 2003), it can be concluded that magmatism in Bavaria occurred over a time span of at least 15 Ma. Geochronological data imply that the first pulse of magmatism in NE Bavaria was coequal with late-Variscan LP–HT regional-scale metamorphism (e.g. Kalt et al. 2000), and part of the southern lobe of the Leuchtenberg granite could had been affected by this metamorphic event (Voll 1960). Formation of the younger granites marks the time when pure, intracrustal, acidic S-type magmas were produced. This magmatism occurred in a different geotectonic environment and was probably related to the late- and post-Variscan extensional tectonics of the thickened Variscan crust.

Relict cores in zircons are largely absent in the redwitzites, and seem to be very rare in the older granites as opposed to the younger granites. This difference in internal morphology allows us to use zircon as a recorder for magma generation processes. It can be argued that the older granitoids (i.e. redwitzites and older granites) were mainly extracted from a lithospheric mantle reservoir, implying that their generation caused juvenile magma input into the late-Variscan crust. An alternative explanation for the older granites sensu stricto is that any older zircons were completely redissolved in the magma, or that the melts from which these rocks were formed were produced in a crustal section where very high temperatures probably caused by mantle heat source prevailed. The large amount of zircons with cores observed in the younger granites relative to the low zircon saturation temperatures of these rocks is interpreted as being consistent with melting in a pure crustal section, with the zircons not having undergone complete equilibration with the bulk rock during melting.

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