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Inferences about magma mixing and thermal events from isotopic variations in redwitzites near the KTB site

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Abstract. Two bodies of redwitzite, one of which was previously examined by Holl et al. (1989), have been analyzed for Sr and Ar isotopes. Rb-Sr whole-rock systems yield aberrantly old isotopic ages of 538 ± 22 Ma for the Reuth-Erbendorf body (including data obtained by Holl et at. 1989) and 415 ± 20 Ma for the Wurz-Ilsenbach body. Samples show systematic variation in $(^{87}Sr/^{86}Sr)_{325Ma}$ ratios, which fall in the range 0.705 – 0.708. Three-dimensional, planar regression of the data according to Wendt (1993) yields Variscan ages and reduces the amount of scatter relative to conventional evaluation. Therefore, the aberrantly old ages achieved by two-dimensional regression are best explained in terms of Variscan magma mixing.

K-Ar dates of amphiboles and biotites consistently decrease northwestwards through the investigated area from 320 Ma to 300 Ma, with the youngest ages occurring in the Reuth-Erbendorf redwitzites. Models proposed to explain the observed K-Ar age trend invoke: a) sequential cooling due to differential uplift and b) contact-metamorphic reheating due to subsequent granite intrusion.

Geological and isotopic background

The two bodies of redwitzite under discussion crop out adjacent to the KTB drilling site (Fig. 3). The Wurz-Ilsenbach redwitzites are exposed as an elongate, NW–SE-trending 'inlier' in the central zone of the northern Leuchtenberg granite (Siebel 1993a). The Reuth-Erbendorf redwitzites form a mass in contact with the Friedenfels and Falkenberg granites. This body was disrupted by the intrusion of the Zainhammer granite (Wendt et al. 1988). Field relations indicate emplacement of the redwitzitic melts prior to, or contemporaneous with the granites. Moreover, rock textures confirm that the redwitzites intruded after the peak of Variscan regional metamorphism.

The redwitzites comprise dioritic to tonalitic rock types with calc-alkali, metaluminous compositions (Table 1). Compared to the granites, the rocks reveal enrichment in Ba, Co, Cr, Ni, Sc, Sr, and V and low values for Cs, Pb, Rb, Ta, and U. Heterogeneity in initial Nd-isotopic ratios has been well documented and suggests that the redwitzites were generated by incorporation of extant crust by a sub-crustal component (Holl et al. 1989, Siebel et al. 1995).

In earlier studies on the NE Bavarian redwitzites (Holl et al. 1989) these rocks were found to yield aberrantly old Rb-Sr whole-rock ages of 468 ± 9 Ma (Marktredwitz), 470 ± 33 Ma (Tirschenreuth-Mähring), and 545 ± 16 Ma (Reuth-Erbendorf). These 'ages' were interpreted by Holl et al. (1989) to reflect an inherited Caledonian anatectic event. Rb-Sr biotite dates are concordant within the Marktredwitz and Tirschenreuth-Mähring redwitzites, averaging 319 Ma, but give discrepant dates of 303 Ma, 316 Ma, and 319 Ma within the Reuth-Erbendorf redwitzites. K-Ar dates, so far available only for Marktredwitz, are largely inconsistent: amphiboles 304 – 344 Ma, biotites 327 – 350 Ma (Holl 1988).

Table 1: Bulk chemical analyses and normative mineral compositions (according to Müller 1982) of representative redwitzite samples from Wurz-Ilsenbach (RL-samples) and Reuth-Erbendorf (R-samples). Main element concentrations are given in wt%, trace elements in ppm.

Sample	RL25	RL11	RL1	RL10	RL24	RL23	R2A	R1	R2B	R4A	R3
	Wurz-Ilsenbach redwitzites						*Reuth-Erbendorf redwitzites*				
SiO_2	54.66	56.52	57.07	58.10	60.10	62.46	54.89	55.19	55.21	55.25	56.16
TiO_2	1.198	1.141	1.187	1.131	1.205	1.097	1.556	1.350	1.521	1.462	1.612
Al_2O_3	16.62	16.92	16.19	17.13	16.70	16.77	17.77	17.56	17.39	17.94	17.69
Fe_2O_3	7.18	6.52	7.09	6.29	5.86	5.27	7.24	6.97	7.21	8.06	7.32
MnO	0.114	0.108	0.106	0.101	0.101	0.079	0.116	0.120	0.121	0.119	0.108
MgO	5.55	4.70	5.07	3.63	2.55	1.67	3.19	3.54	3.22	4.13	3.49
CaO	6.88	6.33	5.46	5.75	4.56	3.43	6.80	7.32	6.60	5.98	5.63
Na_2O	2.94	2.88	2.76	3.06	3.35	3.88	2.84	2.59	2.87	2.73	2.98
K_2O	2.71	2.89	3.28	3.04	3.82	3.49	3.06	2.87	3.35	2.01	2.68
P_2O_5	0.33	0.32	0.37	0.31	0.40	0.36	0.46	0.36	0.47	0.31	0.30
LOI	1.33	1.39	1.02	0.95	0.93	0.85	1.40	1.44	1.37	1.45	1.45
$\sum$	99.51	99.72	99.60	99.49	99.58	99.36	99.32	99.31	99.33	99.44	99.42
Ba	960	1114	1140	941	1346	1311	1179	1033	1188	513	742
Ce	70	73	113	80	113	127	108	105	154	96	89
Co	28	25	26	23	13	13	25	24	22	35	38
Cr	197	122	123	107	61	38	107	165	111	148	94
Cs	9	7	10	12	9	10		15	6.4	5.2	4.7
Ga	17	23	17	24	20	23	30	29	30	30	29
Hf	3.3		3.5		2.5			0.8	1.1	0.6	0.9
La	48	51	62	57	86	84		77	45	41	46
Nb	21	19	18	19	21	18	27	26	27	23	20
Ni	51	26	32	19	11	7	16	22	20	45	27
Pb	19	17	22	22	31	24	11	11	21	11	12
Rb	95	110	124	127	154	170	116	114	119	84	106
Sc	21	22	22	19	19	12		30	23	24	22
Sr	482	399	375	356	347	300	588	539	591	390	397
Ta	1.0		1.0		1.1			1.4	1.7	1.3	1.3
Th	22	36	29	26	22	25	12	13	14	8	11
U	3.7		3.5		3.1			2.0	2.7	1.5	2.0
V	119	135	130	117	89	78	171	169	175	183	157
Y	16	22	27	24	28	23	24	22	26	11	14
Zn	63	73	78	71	84	74	80	72	79	102	89
Zr	246	248	244	265	188	371	318	275	322	160	212
qz	7.46	11.96	14.87	14.43	15.53	18.94	9.84	9.62	8.74	15.46	16.46
alk	10.11	9.15	7.22	9.78	16.03	10.76	13.68	14.94	17.26	0.00	1.80
plg	43.03	46.49	45.03	49.69	48.29	51.14	48.55	44.93	45.12	54.16	55.88
hbl	25.04	15.21	8.96	8.53	3.53	0.00	13.81	20.26	16.82	0.00	0.00
bio	10.25	13.36	19.79	13.83	12.73	11.34	9.24	5.89	7.21	14.88	20.21
ms	0.00	0.00	0.00	0.00	0.00	4.30	0.00	0.00	0.00	4.18	1.05
ap	0.70	0.68	0.79	0.66	0.85	0.77	0.99	0.78	1.01	0.67	0.65
il	1.70	1.62	1.69	1.61	1.71	1.56	2.24	1.94	2.19	2.11	2.32
cr	0.03	0.02	0.02	0.02	0.01	0.01	0.02	0.03	0.02	0.02	0.02
mt	1.63	1.47	1.61	1.41	1.27	1.14	1.56	1.54	1.56	1.81	1.57
zir	0.03	0.03	0.03	0.03	0.02	0.05	0.04	0.04	0.04	0.02	0.03
An in Plg	37.84	43.34	43.43	43.66	38.26	30.03	47.33	48.94	44.00	53.21	48.49

Methods: ICP-MS (Cs, Hf, Ta, U), XRF (remaining elements)

Isotopic results

Rb-Sr whole-rock data

Rb–Sr isotope ratios have been determined for six Reuth-Erbendorf samples and seven Wurz-Ilsenbach samples. In addition to the new data (Table 2), Figures 1 and 2 include earlier data for six Reuth-Erbendorf samples from Holl et al. (1989). The new samples from Reuth-Erbendorf have a very limited range of Rb/Sr ratios, which fall on the lower side of those of Holl et al. (1989). A 'true' isochron cannot be fitted to the data points. The MSWD for all twelve data points is 7.1, i.e. no firm confidence can be placed on the 538 ± 22 Ma age obtained from this fit. If the two samples with the largest deviation from this line are omitted (samples R4A, R4B), a least square fit to ten points gives an apparent age of 575 ± 23 Ma, and the MSWD decreases markedly to 2.1. However, exclusion of these samples is somewhat arbitrary because they do not show strong alteration. Both samples have been analysed twice and consistently fall above the regression line so that the deviations are believed to be real.

Table 2: Rb-Sr isotopic data of the whole-rock samples from the redwitzites of Reuth-Erbendorf and Wurz-Ilsenbach.

Sample no.	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$ ($1\sigma = \pm 1\%$)	$^{87}Sr/^{86}Sr$ ($1\sigma = \pm 0.3‰$)	$1/^{86}Sr$ (μmol^{-1})	$(^{87}Sr/^{86}Sr)_{325Ma}$
Wurz-Ilsenbach						
RL25	98	508	0.5571	0.70807	1.75	0.70549
RL11	114	414	0.7950	0.70967	2.17	0.70599
RL1	126	401	0.9124	0.71072	2.22	0.70650
RL10	129	385	0.9709	0.71062	2.31	0.70613
RL20	135	315	1.2448	0.71259	2.82	0.70683
RL24	154	372	1.1972	0.71193	2.39	0.70639
RL23	168	324	1.5043	0.71363	2.75	0.70667
Reuth-Erbendorf						
R2B	120	611	0.5690	0.70790	1.46	0.70527
R2A	116	610	0.5485	0.70812	1.46	0.70558
R1	113	560	0.5864	0.70824	1.59	0.70553
R3	108	412	0.7586	0.70994	2.16	0.70643
R4A	83	404	0.5969	0.70998	2.20	0.70722
R4B	94	391	0.6934	0.71039	2.28	0.70718

Suffixes A and B refer to different rock types from the same exposure

The whole-rock samples from the Wurz-Ilsenbach redwitzites have a similar range of Rb/Sr ratios to those of Reuth-Erbendorf. The seven analytical data points are relatively well correlated and have a slope equivalent to an age of 415 ± 20 Ma with MSWD = 1.2.

Rb-Sr data added here support Holl's findings that the total rock isochrons for the redwitzites yield 'ages' significantly older than their true crystallization age. Inferences from the present results can be explored by plotting the data on a more convenient three-dimensional evaluation diagram developed by Wendt (1993) where the z-axis represents the reciprocal ^{86}Sr concentration (Fig. 2). Intersections of the three-dimensional best-fit plane with the $^{87}Sr/^{86}Sr$, $^{87}Rb/^{86}Sr$ isochron plane yield reduced ages of 378 ± 30 Ma for Reuth-Erbendorf, 327 ± 56 Ma for Wurz-Ilsenbach, and 292 ± 23 Ma for the pooled data. The MSWD is improved from 7.1 to 3.6 (Reuth-Erbendorf), from 1.2 to 0.7 (Wurz-Ilsenbach), and from 8.7 to 6.5 (pooled data).

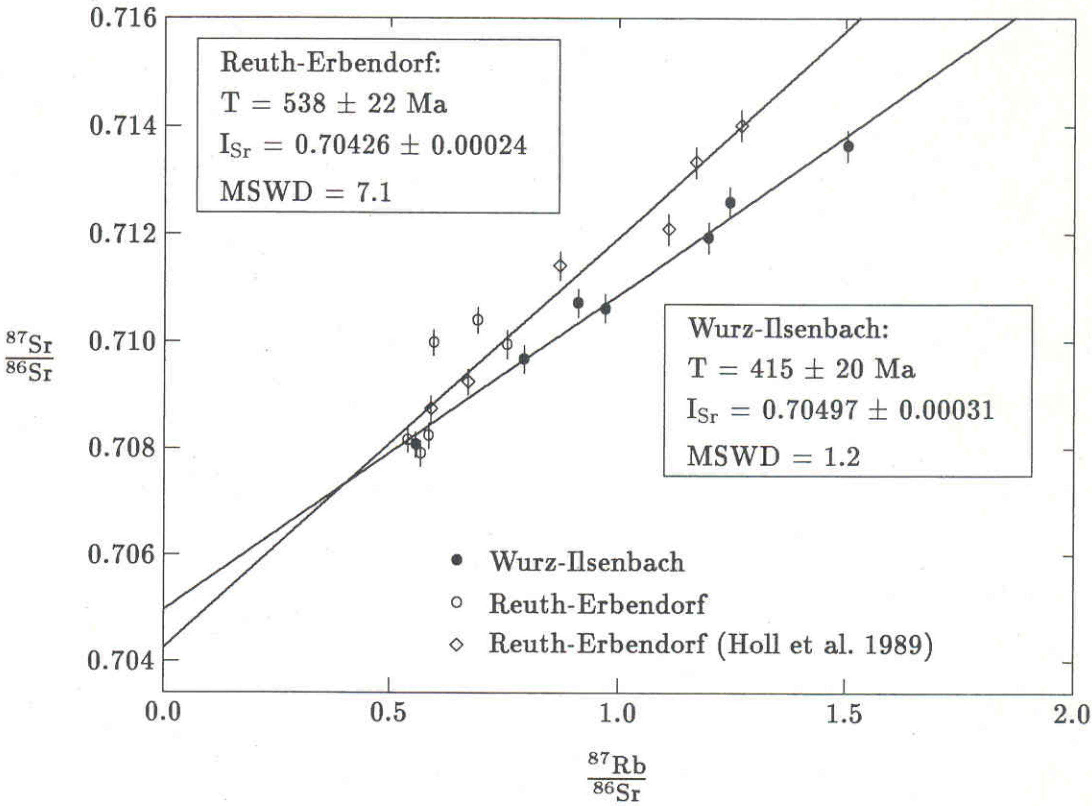

Fig. 1: Plot of $^{87}Sr/^{86}Sr$ ratios *versus* $^{87}Rb/^{86}Sr$ for redwitzite samples from the Wurz-Ilsenbach and Reuth-Erbendorf intrusions. Error bars are 1σ. The two regression lines shown are fittet to all of the data points of Reuth-Erbendorf (open symbols) and Wurz-Ilsenbach (closed symbols). Isochron calculation according to Wendt (1986).

Also shown in Figure 2 are the values of $(^{87}Sr/^{86}Sr)_{325Ma}$ versus the present-day $^{87}Rb/^{86}Sr$ and $1/^{86}Sr$ ratios. From this figure it is apparent that the late Variscan Sr ratios display an overall increase with increasing Rb/Sr and $1/^{86}Sr$ ratios.

K-Ar mineral data

Rock samples selected for mineral separation have yielded concentrates of biotite and amphibole (actinolitic hornblende), thereby poviding two mineral indicators with different closure temperatures within the same rock. K-Ar dating was performed to derive age limits for the intrusion and cooling history of the redwitzites.

The apparent ages decrease from 320 Ma to 300 Ma towards the NW, reaching the lowest and more scattered values in the Reuth-Erbendorf redwitzites (Fig. 3). Note that the hornblende K-Ar ages are, in general, not significantly older than those of the biotites from the same rock sample. A K-Ar age trend for biotites which conforms to that of the Wurz-Ilsenbach redwitzites is documented within the northern lobe of the Leuchtenberg granite (Siebel 1993b).

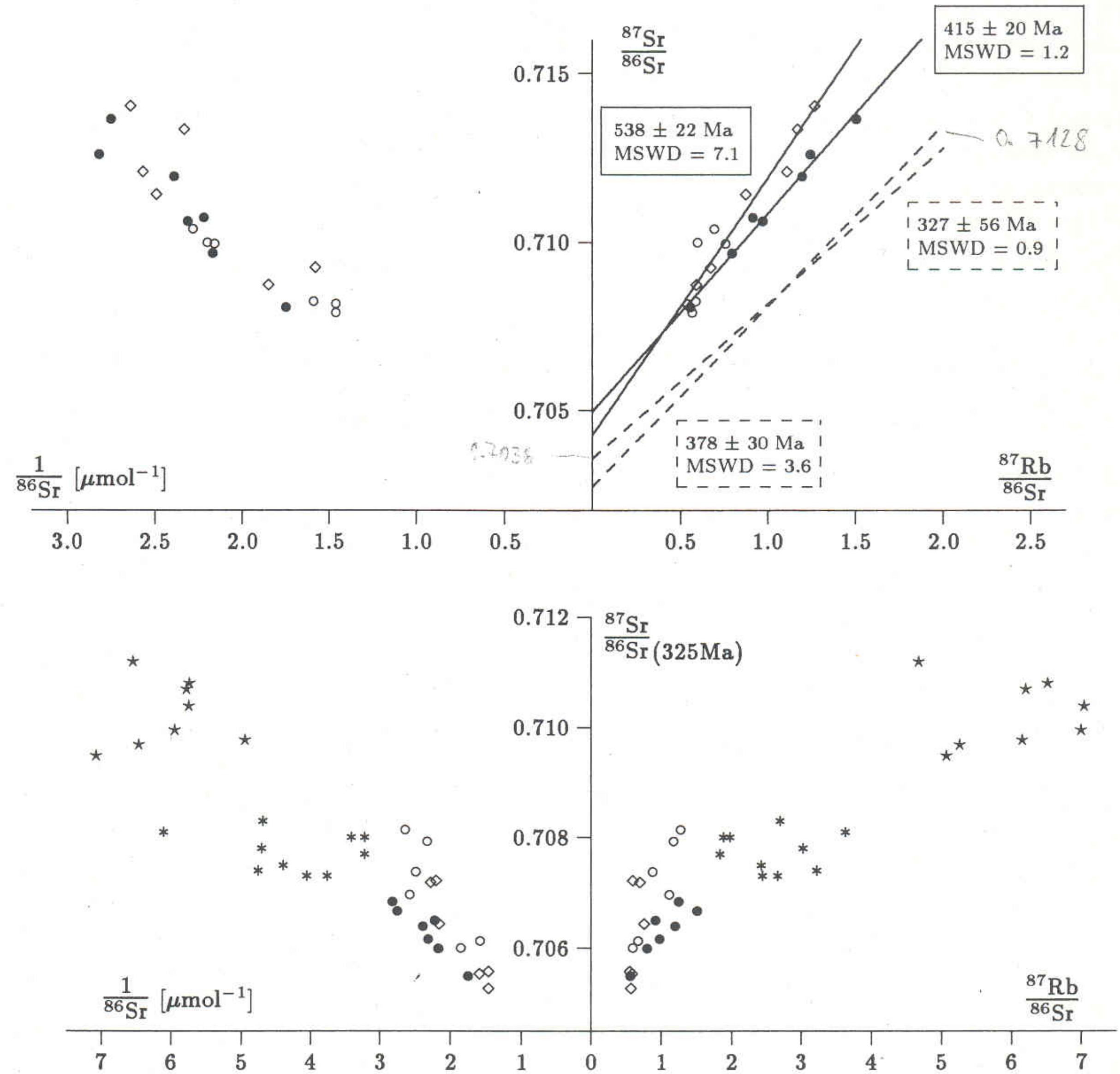

Fig. 2: Upper panel: data evaluation according to the three-dimensional model of Wendt (1993). Projections of the calculated plane parameters in the $^{87}Sr/^{86}Sr$, $^{87}Rb/^{86}Sr$ plane yield reduced ages of 378 ± 30 Ma (Reuth-Erbendorf) and 327 ± 56 Ma (Wurz-Ilsenbach). Lower panel: range of $^{87}Sr/^{86}Sr_{(325\,Ma)}$ ratios *vs.* $^{87}Rb/^{86}Sr$ and *vs.* $1/^{86}Sr$. This figure shows that linear arrangements between these parameters were present in the rocks 325 Ma ago. ∗ = Leuchtenberg granites, ⋆ = Liebenstein/Zainhammer granites, other symbols as in Figure 1.

Discussion and conclusions

Rb-Sr data

Holl et al. (1989) based their petrogenetic model on the presence of Caledonian Rb-Sr ages and assumed that the rocks were already affected by a Caledonian anatectic event. This interpretation implies that the redwitzites retained their Caledonian isotopic identities throughout the Variscan cycle. However, despite the uncertainties, the Variscan ages derived by three-dimensional evaluation reported here support the contention, that the Caledonian ages are likely to be artificial, simply reflecting magma mixing during Variscan times. Mixing could have been caused by the incorporation of varying amounts of ^{87}Sr-enriched sialic material by a less fractionated magma probably on its way through the earth's crust. The isotopic disequilibrium may be explained by a rapid rate of ascent and crystallization. As can be seen in hand-specimen (Siebel 1993a), magma formation was insufficient to completely mix the different melts and hence to destroy source rock heterogeneities. Taken together, all redwitzite occurrences show a significant spread in Rb-Sr whole-rock ages ranging from 415 Ma to 538 Ma; thus it is reasonable to suppose that mixing has not involved exactly the same end-member compositions. From Figure 2 one would expect values of about 0.705 for the initial Sr parameters in the uncontaminated magma. This is in accordance with derivation from an upper mantle source. The crustal material incorporated would have to have $(^{87}Sr/^{86}Sr)_{325Ma} > 0.707$ and $^{87}Rb/^{86}Sr > 2.5$. A crustal component with the isotopic properties of the associated granites of Leuchtenberg, Liebenstein, and Zainhammer would represent an acceptable contaminant (Fig. 2, below).

Table 3: K-Ar mineral data of the redwitzites from Wurz-Ilsenbach and Reuth-Erbendorf.

Sample no.	Mesh Fraction (μm)	K (%)	$Ar_{rad.}$[1] (nl/g STP)	$Ar_{atm.}$[2] (nl/g STP)	K-Ar-Date (Ma)
Reuth-Erbendorf					
Hbl-R2B	200–112	0.466	6.20	0.28	301.8 ± 2.3
	112–063	0.425	5.48	0.20	304.6 ± 2.3
Bi-R2B	500–400	7.53	96.5	1.8	303.0 ± 1.6
	315–250	7.62	97.4	1.9	302.3 ± 1.6
Bi-R1	500–400	7.25	92.3	1.1	301.1 ± 1.5
	400–315	7.28	92.6	1.6	300.9 ± 1.5
Bi-R3	500–400	7.58	98.4	1.7	306.4 ± 1.6
	315–250	7.56	98.9	1.6	308.8 ± 1.6
Bi-R4A	500–400	7.35	96.1	2.2	308.4 ± 1.6
	400–315	7.44	96.9	1.6	307.6 ± 1.6
Wurz-Ilsenbach					
Bi-RL27	500–400	7.57	98.5	1.9	307.1 ± 1.2
	400–315	7.56	98.8	2.3	308.2 ± 1.2
Hbl-RL1	200–112	0.354	4.73	0.24	316.7 ± 2.5
Bi-RL1	1000–800	7.72	103.6	2.2	315.3 ± 1.1
	630–500	7.69	101.6	2.1	311.5 ± 1.6
	400–315	7.65	100.0	1.6	308.4 ± 1.1
Hbl-RL25	200–112	0.378	5.13	0.20	319.6 ± 2.6
Bi-RL25	500–400	7.62	100.7	1.8	311.6 ± 1.6
	400–315	7.61	101.1	1.6	313.0 ± 1.6
Bi-RL24	630–500	7.63	103.7	2.2	319.2 ± 1.4
	400–315	7.67	102.4	1.7	315.2 ± 1.1

[1] rad = radiogenic; [2] atm = atmospheric; Bi = biotite; Hbl = hornblende
Constants given in Steiger and Jäger (1977) have been applied to all the dates, quoted errors are 1σ

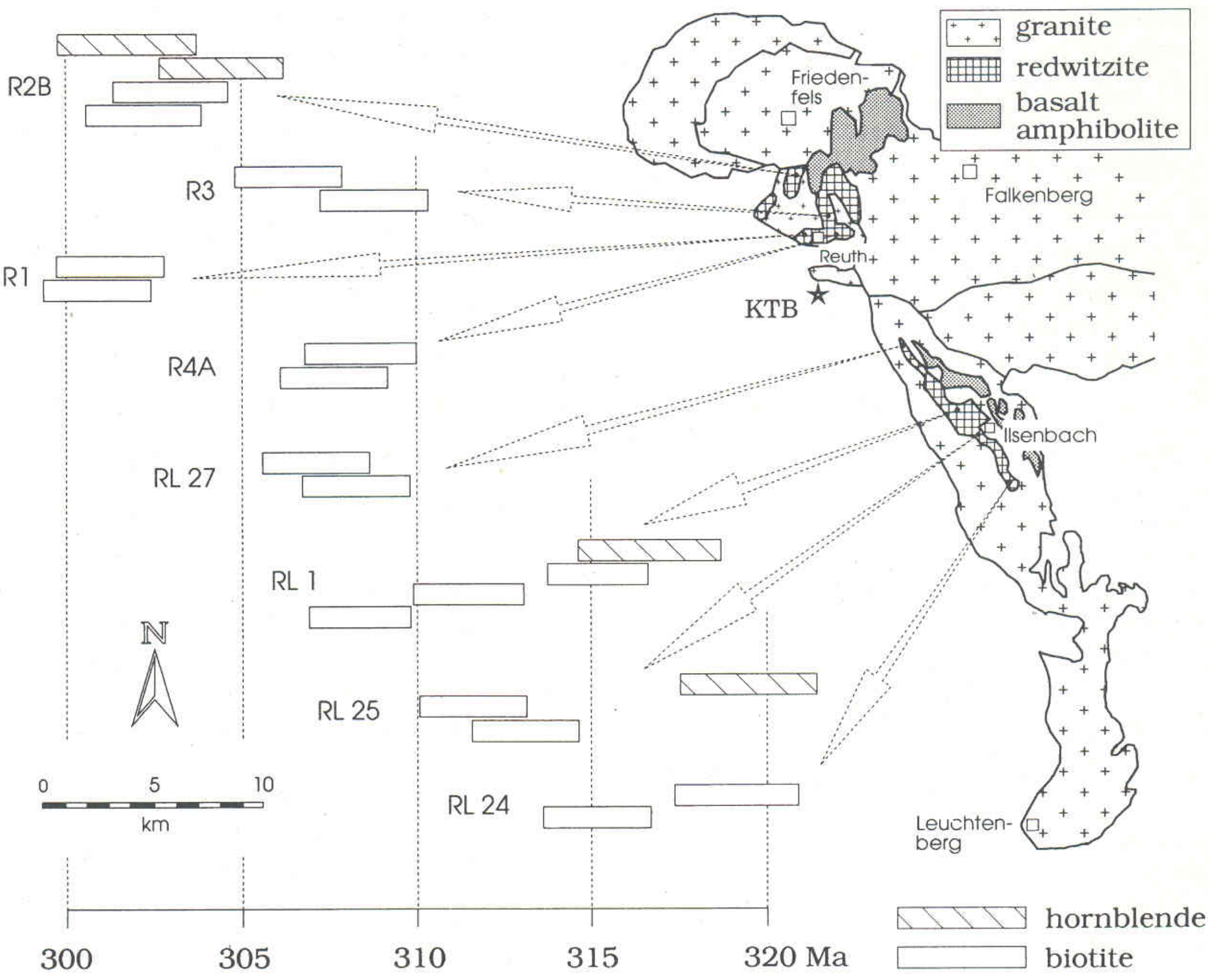

Fig. 3: Map showing the distribution of the apparent K-Ar ages of biotites and hornblendes in the redwitzite intrusions. RL samples: Wurz-Ilsenbach, R samples: Reuth-Erbendorf. For most samples, two distinct grain-size fractions of each mineral sample were available. The width of the boxes encompasses the 1σ confidence interval.

K-Ar data

The progressive decrease in K-Ar age towards the NW may be explained in terms of two end-member models (*comp.* Siebel 1995): Firstly, the age profile could suggest that the magmas were delivered to different emplacement levels that became deeper towards the NW, and subsequently experienced different rates of exhumation by differential rotation, tilting, or faulting. The Wurz-Ilsenbach redwitzites would therefore have been the first to be uplifted, followed by the Reuth-Erbendorf redwitzites.

Alternatively, the intrusion of the younger granites could have led to the development of a high thermal gradient in the aureoles of these intrusions. This requires a voluminous magmatic heat source in close proximity to the redwitzites. The nearby massive granites of Falkenberg, Friedenfels, and Steinwald intruded contemporaneously around 310 Ma (Wendt et al. 1986, 1988, 1992). The close similarity between the K-Ar amphibole the biotite dates of the redwitzites would imply contact-metamorphic reheating up to minimum temperatures of about 500°C. Furthermore, this age concordancy suggests that the biotites have closed not far below the amphibole closure range. However, complications arise from some of the Zainhammer muscovites, which retain K-Ar and Rb-Sr ages as high as 315 Ma and 314 Ma, respectively (Wendt et al. 1988), indicating that these samples were not affected to the same degree by later thermal events than the associated Reuth-Erbendorf redwitzites. Evidence for disrupted isotopic systematics within the Zainhammer granite comes from ^{40}Ar-^{39}Ar plateau ages for micas, ranging from 317 Ma to 305 Ma (Wendt et al. 1992). The discordant ages, in particular the inconsistency between the Reuth-Erbendorf amphibole dates and the Zainhammer muscovites dates point to different argon retention within the minerals during subsequent rejuvenation.

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