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Radiometric dating on research drill core Urach III: a contribution to its geothermal history

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Abstract. The Urach III borehole (3,334 m depth) is located in the center of the Urach geothermal anomaly (35 km SE Stuttgart, Southern Germany). Radiometric age determinations were carried out on samples from the Rotliegend and from the crystalline basement. The biotites yield Rb/Sr ages of 325 ± 6 Ma. The age values are independent of borehole depth, present borehole temperatures and grain size. These ages are interpreted as cooling ages at which the rocks cooled to 330 ± 20 °C. Assuming a thermal gradient of 40 °C/km and an uplift rate of 0.14 mm/a, a crust 8 km thick has been eroded after the Hercynian orogeny. From mixtures of leached biotites and chlorites a maximum age value of about 200 Ma is inferred for the hydrothermal activity. A maximum possible temperature of only about 195 °C during the Mesozoic burial is estimated for a reheating of 100 Ma duration.

Downhole apatite fission track ages decrease from 49.5 Ma to 0.6 Ma due to the lower thermal stability of fission tracks in apatite. The corrected fission track age of 81.2 Ma (1,021 m depth) implies a complete track erasure during Mesozoic burial. Consequently, a temperature of at least 130 °C requiring a thermal gradient of 55–60 °C/km for the Cretaceous must be assumed. From apatite fission track ages vs. borehole temperatures, a closure temperature of 106 °C for apatites from 1,021 m depth is established and a cooling rate of 0.8 °C/Ma during the Cainozoic era can be estimated.

Cooling due to slow uplift beginning 80 Ma ago is suggested. A possible thermal overprint in connection with the Miocene volcanism has not exceeded the rock temperatures by more than 20 °C above the present temperatures. This points to an old, deep-seated, decaying heat source as a cause of the Urach geothermal anomaly.

Key words: Biotite Rb/Sr ages – Apatite fission-track ages – Closure temperatures – Geothermal history

Introduction

In recent years, many investigations on the Urach III borehole have been carried out on the present geological, mineralogical and geophysical status of the Urach geothermal anomaly (Haenel, 1982). The purpose of our contribution is the evaluation of the geothermal history of this anomaly using radiometric age determination techniques. Radioactive systems such as K/Ar, Rb/Sr, and uranium spontaneous fission do not only enable the dating of geological events, they also may be used as indicators of temperatures. Different radioactive systems close and open at different temperatures, e.g. the biotite K/Ar and Rb/Sr systems around 300 °C (Purdy and Jäger, 1976) and the apatite fission track system around 120 °C (Wagner and Reimer, 1972).

The combined application of various dating methods gives age vs. temperature data from which the thermal history of rocks can be reconstructed. As rocks cool, these inherent radioactive systems pass successively through three temperature zones of complete, of partial, and of negligible loss of daughter products. On reheating this sequence is reversed. The processes involved are diffusion of daughter nuclides and annealing of fission tracks. One uses the concept of closure temperature, although the closure process is not sharply defined in terms of temperature, because, among other parameters, the closure temperature depends upon cooling rate. According to Dodson (1979) the closure temperature is the temperature of the system at the time given by its apparent age. Its value can be calculated from diffusion and annealing experiments or directly measured in deep drill holes. In the latter case the drill core rocks are used in order to investigate the loss of the radiogenic daughter products under natural conditions. For this reason, geochronological studies on drill holes are of special interest.

The research borehole Urach III is situated in the center of a geothermal anomaly around Urach, 35 km SE of Stuttgart (Southern Germany). The region of the geothermal anomaly is more or less identical with the area where 350 volcanic pipes perforated the Schwäbische Alb during the Miocene (Weiskirchner, 1980). The borehole penetrated through about 900 m of Mesozoic sediments before reaching about 700 m of Permian and possibly Carboniferous sediments (Leiber and Münzing, 1979). The underlying section of crystalline rocks has a length of 1,732 m.

Recently published K/Ar biotite ages on the crystalline basement rocks from the Urach III borehole gave 325.2 ± 6.2 Ma (2σ-error) (Hammerschmidt and Wagner, 1983). On the base of argon diffusion experiments with biotite (KAW 1993) a closure temperature of 330 ± 20 °C was derived for an assumed cooling rate of 1 °C/Ma. More-

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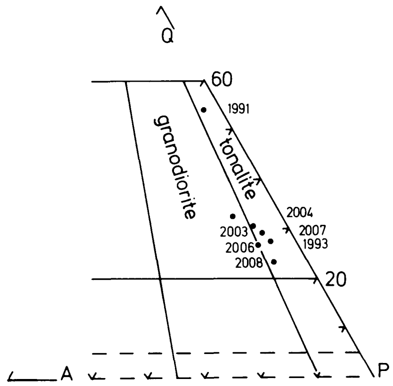

Fig. 1. Modal composition of the metablastic plagioclase-biotite hornblende-gneisses and the diatexites

over, from this experiment an upper temperature limit of 240 °C was estimated for a possible reheating period of 100 Ma (or 260 °C for 10 Ma, resp.) during the post-Hercynian history.

In this work Rb/Sr data on biotite and fission track data on apatites from the Urach III drill core are presented. The samples were taken from Rotliegend sediments (depth 1,021 m) and various crystalline basement rocks (depth 1,660 m to 3,300 m).

Sample description

The Rotliegend is composed of volcanoclastic sediments, arkoses, siltstones, and fanglomerates (Dietrich, 1982). Apatites (Ro 1021) were separated from a fanglomeratic arkose at 1,021 m depth. The apatites occur as well-rounded to slightly prismatic crystals, with hematite-coloured surfaces.

According to Stenger (1982), the first unit (from top to bottom) of the crystalline part of the bore-hole consists of coarse-grained metablastic plagioclase-biotite-(hornblende)-gneisses from 1,602 to 1,950 m depth (KAW 1991, 1993). These gneisses have magmatic textures. The modal composition of these rocks indicates granodiorite to tonalite. The second unit consists of mainly medium- to coarse-grained metablastic or metatectic plagioclase-biotite-(cordierite)-gneisses (1,950–3,000 m) of sedimentary origin. The third unit (3,000–3,334 m depth), is composed of fine- (KAW 2003, 2004) to medium-grained (KAW 2006–2008) diatectic rocks which display magmatic textures. Figure 1 illustrates the modal composition of rocks of the first and third unit in terms of the Streckeisen (1976) diagram. The composition of these rocks points to a granodiorite/tonalite predecessor (Fig. 1).

In all crystalline samples, the plagioclase has been partly altered to sericite and/or calcite. Along faults and fissures, biotite is changed into chlorite, ore and calcite. In particular, samples KAW 1996, 1997, 2000, 2001, and 2002 are extremely decomposed. They originate from two zones of strong hydrothermal alteration at depths of 2,050 to 2,200 m and 2,500 to 3,000 m. Plagioclase and biotite are decomposed into small (~2 μm) aggregates of chlorite, bleached biotites, sericite and calcite. Therefore, only bleached biotite intergrown with chlorite could be separated (KAW 1997).

Apatites from samples KAW 2001 and 2002 are well-rounded with corroded surfaces. The crystallographic habit of the apatites seems to be related to the rock type. In metablastic gneisses, many crystals could be separated in the 100–180 μm fraction (KAW 1991, 1993). Isometric, rounded and short prismatic figures are predominant. Metatectic and metablastic cordierite gneisses contain apatites of similiar size, but mostly with broken crystals. They all carry common fluids and mineral inclusions. By contrast, diatectic rocks contain long prismatic or needle-like apatites in the 40–100 μm fraction.

Rb/Sr dating

Experimental

Samples of the crystalline rocks, 3 kg per sample, from the Urach III borehole were ground and aliquots prepared for mass-spectrometric analyses by ion exchange and isotope dilution methods. The error of the ^{87}Rb/^{86}Sr ratios is typically 1% and that of the ^{87}Sr/^{86}Sr ratio is given in Table 1 as the 1σ-error. The ^{87}Sr/^{86}Sr ratio of the NBS 987 was measured as 0.709705 ± 75, normalized to a ^{86}Sr/^{88}Sr value of 0.1194. For age calculations, the recommended IUGS constants (Steiger and Jäger, 1977) were used. The handpicked biotite fractions of the crystalline rocks were also analysed. The mineral fractions, especially those from the hydrothermally altered rocks, are mixtures of biotites, leached biotites and chlorites. A previous study (Hammerschmidt, 1981) has shown that the analyses of different grain-size fractions of the same mineral species from the same rock sample allow checking of age resetting. In the biotite samples considered here, the grain size varies by a factor of about 25.

Whole rock Rb/Sr results

The Rb/Sr data are given in Table 1. The age values reported in column 9 have been calculated using the initial ^{87}Sr/^{86}Sr value of the corresponding whole rock. In column 8, mineral isochrons and their initial values are given. The whole rock data shown in Fig. 2 fall into two separate fields. The anatectic and diatectic plutonic rocks have ^{87}Rb/^{86}Sr values of between 0.79 and 1.10 and ^{87}Sr/^{86}Sr values of between 0.7119 and 0.7159, whereas the paragneisses have higher values in both ratios. The distribution of Rb and Sr is governed by the melting process (anatexis). The Rb content, both in the paragneisses and in the plutonic rocks, varies from 100 ppm to 170 ppm, but in the plutonic rocks, the Sr content is enriched by a factor of 4 to about 400 ppm relative to the Sr content of the paragneisses. After melting of paragneisses the first crystallizing plagioclase incorporates Sr and therefore, Sr will be enriched in the granodiorite to tonalite. Because of the small spread in the Rb/Sr ratio, a well-defined isochron with a small error was not expected. Given the different rock types and different states of hydrothermal alteration, an isochron is unlikely anyway.

Biotite Rb/Sr ages

The biotites of the unaltered samples have age values of 321 ± 14 Ma over the whole crystalline section of the borehole. In order to determine whether any age resetting of biotites from these rocks has occurred due to a thermal event, it is sufficient to examine fresh samples from the top and bottom of the crystalline section. Age resetting may be studied using different grain size fractions of biotite from the same rock sample. Therefore, biotites of the sam-

Table 1. Rb/Sr data

KAW-nr.	Sample	Size (µm)	^{87}Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	"mineral isochron"		age* (Ma)
1991 *T*	tonalite		37.3	346.8	1.10	0.715920±80			
/2	biotite	500–420	105.5	9.3	122.0	1.27410 ±20			324.4±1.5
/6	biotite	150-75	98.7	6.5	167.7	1.48835 ±20	325.5±1.4		325.8±1.5
/8	biotite	40-23	73.2	55.9	13.5	0.774100±80	*i*: 0.71111±36		330.4±1.5
1993 *T*	tonalite		27.8	361.0	0.79	0.715130±80			
1995 *T*	plag-bio-gn		51.1	133.0	3.94	0.73105 ±10			
	biotite	180-150	123.6	6.4	215.0	1.70000 ±10			322.5±1.5
1996 *T*	Kf-plag-gn		43.0	37.1	11.9	0.743670±80			
1997 *T*	Kf-plag-gn		34.4	72.1	4.9	0.72945 ±25			
/*A*		110-75	51.3	38.9	13.5	0.75780 ±15		206.8±2.0	231.7±4.0
/*B*		110-75	53.2	27.8	19.7	0.77852 ±10	227.3±2.2	*i*: 0.7204±5	233.1±4.0
/*C*		110-75	51.7	21.1	25.2	0.79465 ±10	*i*: 0.71374±50		225.8±4.0
/*D*		110-75	46.6	22.3	21.5	0.783310±80			228.1±4.5
1999 *T*	paragn		46.8	139.4	2.5	0.722910±80			
2000 *T*	paragn		37.1	120.5	3.2	0.753145±80			
	biotite	180-150	60.0	17.0	36.7	0.855160±90			214.0±2.0
2003 *T*	tonalite		32.8	388.6	0.86	0.71195 ±20			
	biotite	180-150	99.7	21.0	49.5	0.93299 ±15			319.2±1.6
2004 *T*	granodiorite		43.9	420.4	1.07	0.713470±80			
2006 *T*	tonalite		42.1	396.9	1.08	0.713060±75			
	biotite	180-150	129.7	50.6	26.5	0.824255±40			307.2±2.4
2007 *T*	tonalite		35.8	365.0	1.0	0.712590±70			
2008 *T*	tonalite		48.2	503.8	0.98	0.713560±90	322.6±1.2		
/2	biotite	420-250	135.2	30.8	45.7	0.916850±90	0.708392±15		319.5±1.4
/5	biotite	150-75	138.5	16.4	89.9	1.12205 ±10			322.7±1.4

$\lambda = 1.42 \times 10^{-11} y^{-1}$ * Corrected with the whole rock

T = total rock, *A–D* decreasing magnetic susceptibility of biotite, leached biotite and chlorite
Kf = K-feldspar, plag = plagioclase, bio = biotite, paragn = paragneiss

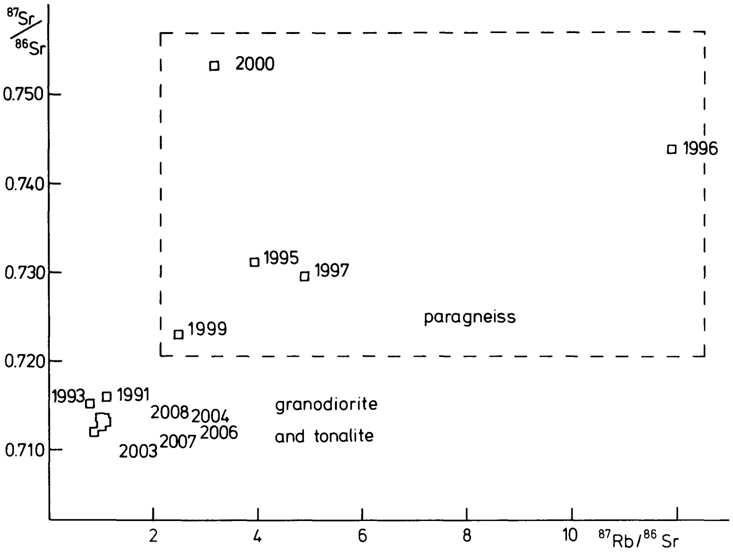

Fig. 2. Whole rock Rb/Sr data in the Sr-evolution diagram

ple KAW 1991 (1,661–1,664 m depth) varying in grain size from 0.8 to 0.02 mm were analysed. This gave a "mineral isochron" age of 325.5±1.4 Ma. In the case of sample KAW 2008, the whole rock together with two biotite fractions (grain size 0.42–0.25 and 0.15–0.1 mm), yields an age value of 322.6±1.8 Ma. These Rb/Sr ages agree closely with the K/Ar ages of biotites of 325.2±6.2 Ma (Hammerschmidt and Wagner, 1983). There is no significant difference between the two ages. The Rb/Sr ages of the biotites are independent of the rock type; for example, biotite from the paragneiss (KAW 1995) also gives the same age value within the stated error limits.

Biotites from different rock types (e.g. KAW 1991 and KAW 1995) give the same Rb/Sr age values of 325.5 Ma

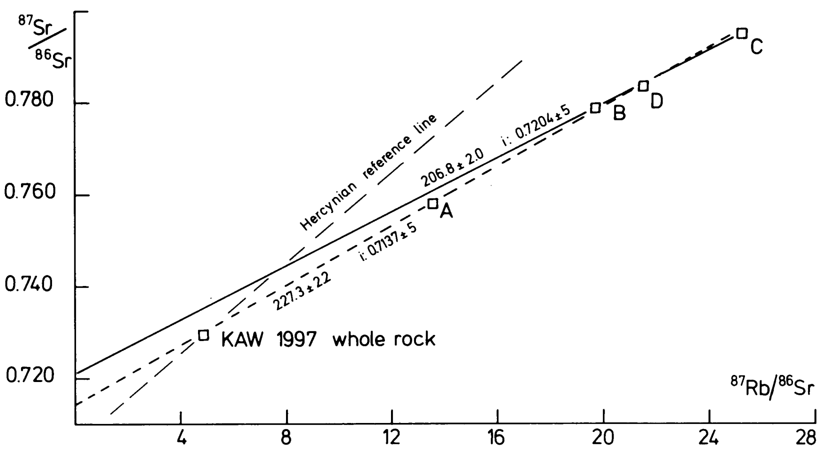

Fig. 3. Rb/Sr data of sample KAW 1997

and 322.5 Ma, respectively. Hence, they cooled together after the Hercynian orogeny, since the age values are cooling ages. These ages are comparable with biotite age values of the Schwarzwald. The geochronology of the Schwarzwald has recently been critically discussed by Hofmann (1979).

Purdy and Jäger (1976) have estimated the closure temperature of both, the K/Ar and Rb/Sr biotite system to be 300±50 °C, as deduced from petrological evidence. Recently, based on a diffusion experiment, the closure temperature for the K/Ar system in biotite KAW 1991 was determined as 330±20 °C, assuming a cooling rate of 1°/Ma (Hammerschmidt and Wagner, 1983), supporting the estimation by Purdy and Jäger (1976).

The Rb/Sr biotite ages are also independent of borehole depth within the error limits (2σ-error corresponds to 12 Ma). The 1,700 m thickness of crystalline rocks with its 12 Ma-cooling age interval enables the uplift rate to be estimated as more than 0.14 mm/a. Assuming a geothermal gradient of 40°/km and this minimum uplift rate of 0.14 mm/a an 8 km thick section of crust is eroded in 56 Ma. This model is supported by the Permo-?Carboniferous age of the sediments which lie discordantly upon the basement.

The biotites from the slightly altered samples KAW 1997 and 2000 have lower age values, in the range of 210 to 235 Ma. Mineral fractions *A* to *D* of sample KAW 1997 are of the same grain size (0.10–0.07 mm) but of different magnetic susceptibility. The mineral fractions fit a reference line corresponding to an age of 227 Ma. However, this line has no geological age meaning; the straight line simply reflects the variation of ^{86}Sr content and therefore the ^{87}Rb/^{86}Sr ratio. And indeed the Rb content (with the exception of fraction *D*) differ by about 4% only. From a mineralogical viewpoint, the reference line represents the mixing of two components, and the mineral fractions of this sample are indeed a mixture of bleached biotite overgrown with different amounts of chlorites. However, if the chloritisation of the biotites is an effect of the Hercynian metamorphism, the minerals, and also the mixtures of different minerals, have to fit a line whose slope corresponds to an Hercynian age. Considering the fractions with the most chlorite (*B, C, D*) in the Sr-evolution diagram (Fig. 3), the intercept gives a ^{87}Sr/^{86}Sr ratio of 0.7204 – i.e. enriched in ^{87}Sr in comparison with an Hercynian mineral isochron. This demonstrates that the hydrothermal alteration of these rocks occurred after the Hercynian orogeny, and that the age value of 220 Ma represents the maximum age of the alteration.

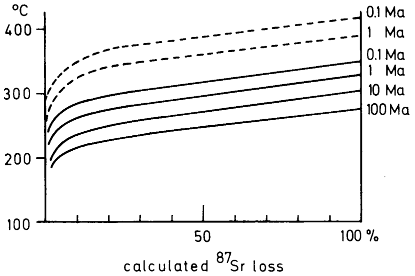

Fig. 4. Calculated radiogenic Sr loss vs. temperatures *straight lines* = grain size 0.04 mm, *dotted lines* = grain size 0.25 mm; the fraction of loss was calculated with a radial diffusion model in an infinite cylinder (Hammerschmidt and Wagner, 1983)

Based on following assumptions one can estimate from the Rb/Sr data an upper temperature limit for any posthercynian thermal event: (1) Thermally induced age reduction is controlled by diffusion. (2) The activation energy of ^{87}Sr for diffusion is the same as for ^{40}Ar. Hart (1964) and Hanson and Gast (1967) have shown that for biotite the activation energies of radiogenic ^{40}Ar and ^{87}Sr are of the same order. (3) Experimental diffusion observed in the laboratory is activated by the same mechanism as in nature. (4) The time span in the laboratory and in nature differs by eight orders of magnitude. This does not affect the diffusion process seriously.

In Fig. 4, the calculated ^{87}Sr loss of a biotite (KAW 1991/2, 0.5–0.4 mm) is shown for different temperatures over different time periods. Using the Ar diffusion results the activation energy is 275 kJ/mol, with a frequency factor $D_0/a^2 = 7.4 \times 10^7\ \mathrm{s}^{-1}$. For example, if a temperature of 350 °C has affected a biotite over a period of 1 Ma, a radiogenic ^{87}Sr loss of 30% will take place (dashed line).

The loss depends also, among other parameters, upon the grain size. For the grain size of KAW 1991/8 ranging between 0.02–0.04 mm no age reduction can be observed. The radiogenic isotope loss (^{87}Sr) of such a grain size (sample KAW 1991) is plotted vs. temperature (Fig. 4); for example, 30% of radiogenic ^{87}Sr is lost already at 280° C during a period of 1 Ma. Since no age reduction was observed for the fine-grained biotite KAW 1991/8, the upper temperature for a possible reheating can be estimated as 190 °C (for 100 Ma), 210 °C (for 10 Ma), or 240 °C (for 1 Ma).

Fission track dating

Experimental

For fission track dating apatite concentrates of 40–200 μm grain size were separated from 50–100 g rock sample. The apatites were dated with the population technique (Wagner, 1968). Aliquots of about 10 mg were taken for thermal neutron irradiation. Prior to irradiation, these aliquots were heated (430 °C, 4 h) in order to remove all spontaneous fission tracks. The irradiations were carried out in the thermal columns of the FR2 at KFZ Karlsruhe ($5.05 \times 10^{14} n_{th}/cm^2$) and the HMI reactor at Berlin ($4.97 \times 10^{14} n_{th}/cm^2$). The dose values were determined with the dosimeter glasses "Trebic" 1 and 2 (moldavite, MPI, Heidelberg, Co-calibration, Wagner, 1969, Au-calibration) and "NBS SRM 962" (Au calibration, Carpenter and Reimer, 1974). The irradiated and unirradiated aliquots were etched together for each sample (5% nitric acid, 35–42 s, 20° C). The track counting data, their statistical errors and the resulting ages are presented in Table 2. On apatite Ro 1021, lengths of spontaneous and induced tracks were also measured. Such measurements indicate the degree of thermal track annealing and allow the correction of thermally lowered fission track ages (Storzer and Wagner, 1969). The measurements were carried out on the projected track length. More than 500 spontaneous and induced tracks were measured (2 tracks per grain). The average length of spontaneous tracks is reduced to 82% relative to induced tracks. Using the correction curve of apatite T11 (Wagner, 1973; Wagner et al., 1977), a density reduction to 61% was deduced, resulting in a corrected age value of 81.2 Ma for Ro 1021. The objections raised by some authors (Gleadow and Duddy, 1981, Laslett et al., 1982) against such correction procedure do not apply in this case since both the correction curve and the length measurements were derived under strictly the same experimental conditions, such as unoriented crystal population, polished internal faces, etching, microscope manification and projected length. Obviously, such measurements do not reflect the true length distribution of fission tracks. However, the validity of this correction technique for apatite had first been empirically demonstrated by Wagner and Storzer, 1970.

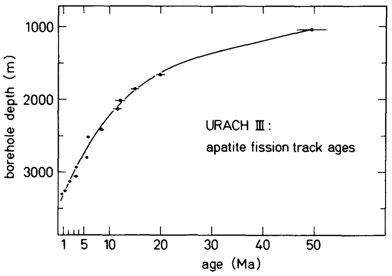

Fig. 5. Apatite fission track ages vs. borehole depth

Apatite age results and methodical interpretation

The ages determined range between 0.6 and 49.5 Ma. They decrease steadily with increasing drilling depth (Fig. 5), and lie in the transitional temperature range (Dodson, 1976) where partial track stability occurs. Since these ages are much younger than the K/Ar, the Rb/Sr and expected geological ages, they obviously are not related to the Hercynian orogeny of the crystalline basement rocks. In order to understand their geological meaning, one has to consider the sensitive annealing behaviour of fission tracks in apatite at elevated temperatures, as has been established in several experiments. As illustrated by Fig. 6, the track density is gradually reduced with increasing temperature and duration of annealing. By extrapolating the experimental data to long-term geological conditions, one concludes that temperatures between 50 and 150 °C are sufficient for the annealing of fission tracks in apatite. This enables the use of the apatite fission track clock as a very sensitive geological thermometer. In this way, cooling ages of 100 °C and 125 °C for the Odenwald crystalline basement and the Central Alps, respectively, have been determined (Wagner, 1968; Wagner and Reimer, 1972). As regards the apatites from the Central Alps, it has been observed that the fission track ages increase steadily with the topographic elevation of the sampling site, indicating tectonic uplift and erosion as causes of the cooling. However, cooling due to uplift is not the only thermal event to be detected by apatite fission track studies. The age and intensity of the thermal overprints may also be revealed, as has been shown for

Table 2. Apatite fission track data

Sample no.	Depth (m)	Temperature (°C)	*Ps** tracks/cm² ($\times 10^5$)	*Pi** tracks/cm² ($\times 10^5$)	*Ps/Pi*	Neutron Dose ($\times 10^{14}$n/cm²)	Age** ($\pm 1\sigma$) (Ma)	*U**** ppm
Ro 1021	1,021.75	66	6.23 (3853)	3.10 (1943)	2.010	4.97	49.5 ± 3.0	46
KAW 1991	1,664	93	5.14 (2370)	6.46 (2979)	0.796	5.05	20.0 ± 1.0	95
KAW 1993	1,857	98	3.78 (1922)	6.34 (2867)	0.596	5.05	15.0 ± 0.8	93
KAW 1995	2,015	104	0.55 (357)	1.14 (810)	0.482	5.05	12.1 ± 1.0	17
KAW 1996	2,126	107	0.70 (585)	1.51 (1302)	0.463	5.05	11.6 ± 0.8	22
KAW 1999	2,420	116	0.88 (636)	2.57 (1776)	0.344	4.97	8.5 ± 0.5	38
KAW 2000	2,519	119	1.97 (1723)	8.33 (7124)	0.236	5.05	5.9 ± 0.3	12
KAW 2001	2,799	127	1.03 (921)	4.58 (4394)	0.225	4.97	5.6 ± 0.3	68
KAW 2002	2,937	132	0.57 (361)	3.88 (2319)	0.147	4.97	3.6 ± 0.2	58
KAW 2003	3,058	135	0.70 (83)	4.96 (465)	0.140	4.97	3.5 ± 0.5	74
KAW 2004	3,127	137	0.57 (75)	6.27 (571)	0.090	4.97	2.3 ± 0.3	93
KAW 2006	3,254	141	0.12 (15)	2.15 (216)	0.056	4.97	1.4 ± 0.4	31
KAW 2008	3,330	142	0.08 (12)	3.05 (480)	0.026	5.05	0.64 ± 0.2	44

* Numbers of counted tracks are given in parantheses

** Ages were calculated with $\lambda_f = 8.46 \times 10^{-17} a^{-1}$ (Galliker et al., 1970); Wagner et al., 1975; $J = 137.88$ and $\sigma_f = 580.2$ barn

*** Calculated with a factor given by Wagner (1968)

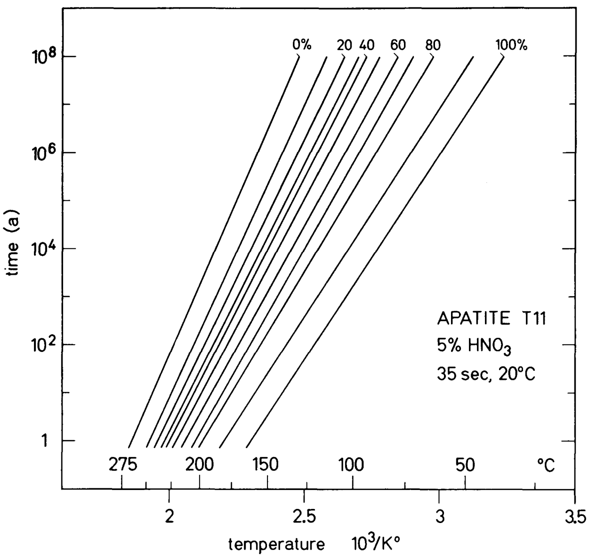

Fig. 6. Arrhenius diagram of fission track retentivity (0–100%) in apatite T11. Data are extrapolated from annealing experiments

the Nördlinger Ries impact crater (Miller and Wagner, 1979).

Downhole decreasing apatite fission track ages have also been observed for deep drill cores from North America and Australia (Naeser and Forbes, 1976; Naeser, 1979; Briggs, et al. 1981; Gleadow and Duddy, 1981), and in fact seem to be a general phenomenon which is hardly surprising, in view of the down-hole increasing temperature and the relatively low thermal stability of tracks in apatite.

Applied to the Urach III drill core, apatite fission track analysis can reveal the cooling by uplift following the Mesozoic burial, as well as a possible reheating in connection with the Miocene Urach volcanism. Different thermal histories cause characteristic age vs. down-hole temperature profiles. Figure 7 shows schematically the age vs. down-hole temperature profiles for a linear uplift model (curve *a*) and a static model (curve *b*), with an additional heat source such as a magma chamber underneath. In the uplift model, the tracks accumulate with increasing rate as the rocks cool through the zone of partial track stability, and with constant rate after full track stability is reached (Wagner, 1972; Dodson, 1979). On the other hand, when the pre-existing track density is annealed by a thermal overprint, the age vs. depth curve reflects the geothermal gradient in the partial stability zone and reaches constant age values in the full stability zone (Briggs et al. 1981). Obviously, under natural conditions more complex cases than these two models may occur. Such simplifying models are necessary for data interpretation since the age distribution depends on complex parameters such as temporarily and spatially changing geothermal gradients and the tectonic history.

Due to its corrected fission track age of 81.2 Ma, this sample must have been exposed to more than 130 °C, because all tracks had been erased by that time. In model *A*, the sample cools steadily to the present temperature (0.8 °C/Ma). In model *B*, the sample cools rather rapidly (10 °C/Ma) to 40 °C, and stays at this temperature until 15 Ma ago, when it is then re-heated for a short period (1 Ma), followed by cooling to the present temperature values. Model *C* is similar but the reheating 15 Ma ago reaches temperature values prevailing to recent times.

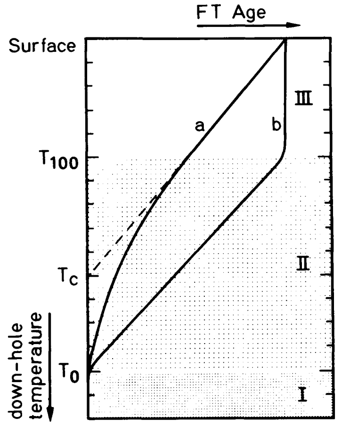

Fig. 7a and b. Model curves of fission track age vs. down-hole temperatures for **a** steady uplift and **b** thermal overprint. The temperature zones, I, II, III represent complete erasure, partial stability and full stability, respectively, of fission tracks

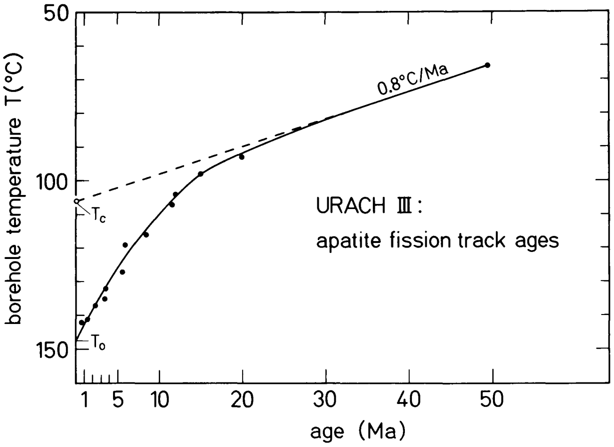

Fig. 8. Apatite fission track ages vs. borehole temperatures. The closure temperature $T_c = 106$ °C for fission tracks in apatite is extrapolated from the linear part of the curve

Table 3. Model cooling ages t_m to temperatures T_{1021} for the depth level 1021 (see text)

Sample	Depth (m)	T_a (°C)	T_c (°C)		t_m (Ma)	T_{1021} (°C)	
			0.8°/Ma	2.7°/Ma		0.8°/Ma	2.7°/Ma
Ro 1021	1,021	66	106	–	49.5	106	–
KAW 1991	1,662	93	109	–	20.0	82	–
KAW 1993	1,856	98	111	–	15.0	80	–
KAW 1995	2,015	104	114	136	12.1	76	98
KAW 1996	2,128	107	116	138	11.6	73	97
KAW 1999	2,416	116	123	139	8.5	75	89
KAW 2000	2,518	119	124	140	5.9	71	82
KAW 2001	2,798	127	131	142	5.6	70	81
KAW 2002	2,934	132	135	142	3.6	69	76
KAW 2003	3,056	135	138	143	3.5	69	75
KAW 2004	3,128	137	139	144	2.3	68	72
KAW 2006	3,254	141	142	144	1.4	67	70
KAW 2008	3,300	142	143	145	0.64	67	68

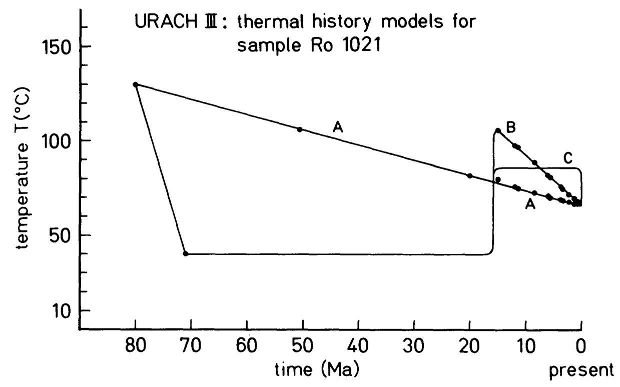

Fig. 9. Thermal history for sample Ro 1021 based on fission track data (see text)

For the steady-cooling model *A*, the apparent fission track ages t_m are cooling ages to the effective closure temperature T_c of the apatite fission track system. No unique value can be given for T_c because the samples had not yet reached the zone of full track stability. Clearly, for samples from the partial stability zone, the closure temperature increases with the actual temperature. For sample Ro 1021, one finds $T_c = 106$ °C by extrapolating the linear part of the curve to zero age (dashed line in Fig. 8). The slope of this line corresponds to 0.8 °C/Ma. By applying the same cooling rate for the remaining samples, the respective closure temperature T_c can be calculated (Table 3). For better comparison, these temperature data for various depth levels are reduced to 1021 m by using the actual temperature differences. The reduced values T_{1021} are the temperatures to which the sample Ro 1021 cooled successivley at time t_m. As shown in Fig. 9, these data are compatible with model *A*. Therefore, steady cooling since 80 Ma ago due to slow uplift, assuming the present temperature gradient (Haenel and Zoth, 1982) prevailing over this period, is in accordance with the fission track data. An additional heat source can be ruled out.

For model *B*, with a thermal pulse 15 Ma ago, one has to interpret the older apatite ages – i.e. for samples Ro 1021 and KAW 1991 – as mixed age values, which are composed of a thermally reduced pre-event and an unaffected post-event component. By using the annealing data of Fig. 6, one can calculate the intensity of the event from the degree of the reduction: if the duration of the thermal pulse is assumed as 1 Ma, one derives about 100 °C for 1,000 m and about 150 °C for 2,000 m depth, – i.e. about 40 °C above the present temperatures. The post-event ages are cooling ages analogous to those discussed for model *A* with an average cooling rate of 2.7 °C/Ma. The resulting closure temperatures and reduced cooling temperatures to a depth level of 1021 m are given in Table 3.

In model *C*, a 15-Ma-old, elevated but constant geothermal gradient reduces the original fission track ages of about 70–80 Ma to their apparent values. The temperatures required to satisfy the analytical data are about 85 °C for 1,020 m, 110 °C for 1,660 m, 120 °C for 1,860 m, 130 °C for 2,520 m and 145 °C for 3,300 m depth. These temperatures are somewhat higher than the actual observed ones.

Geological interpretation and conclusion

Geothermal history

The combined application of different radiometric dating methods, as well as diffusion experiments on Ar, gives a time-temperature relationship for the post-Hercynian geothermal history of the Urach crystalline basement (Fig. 10).

From Ar diffusion experiments K/Ar closure temperature of the biotite from the Urach borehole sample was determined as 330 ± 20 °C. The K/Ar and Rb/Sr biotite ages from different rock types of 325 ± 6 Ma indicate that the crystalline basement cooled down to 330 °C at that time. The age values are independent of borehole depth; therefore, the whole section of crystalline rocks (1,700 m) was uplifted more than 0.14 mm/a. Assuming a geothermal gradient of 40 °C/km, the cooling rate can be estimated as more than 5.6 °C/Ma. With this rapid cooling, a surface position should have been obtained not later than 270 Ma ago. This age corresponds with that of Permo-?Carboniferous sediment cover which discordantly overlies the basement rocks.

From diffusion experiments of Ar from biotite, upper temperature limits can also be calculated for the post-Her-

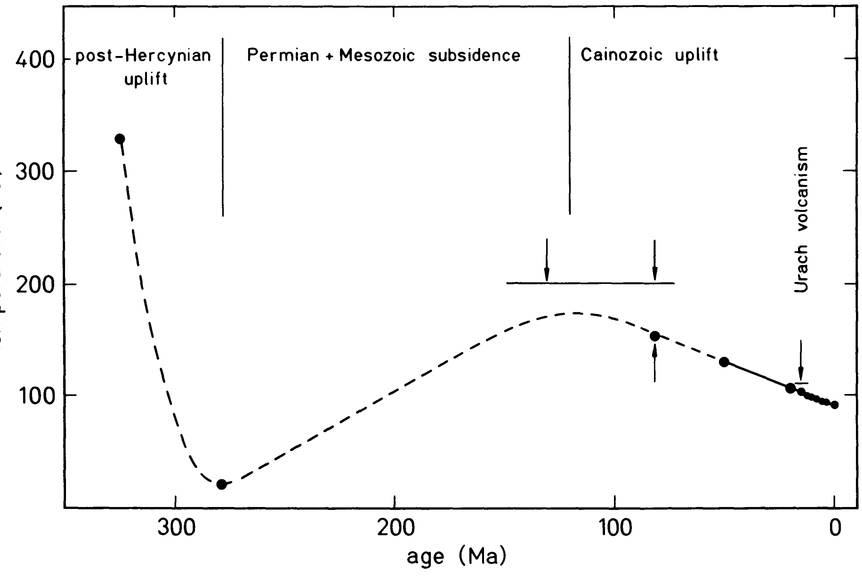

Fig. 10. Thermal history of top level of crystalline basement below Urach (see text)

cynian period. The detection limit of argon loss from biotite is conservatively estimated as 3%. Such an effect was not found, neither as a function of biotite grain size nor as a function of borehole depth. The diffusion coefficients of the relevant temperatures (200 to 400 °C) have been extrapolated from a diffusion experiment. The diffusion coefficients are related to Ar loss, temperature and time. If there is a thermal event of an assumed duration of 10 Ma, the temperature should not be greater than 260 °C, or, for a duration of 100 Ma, not greater than 240 °C. This calculation was done for a grain size of 0.4–0.5 mm. But biotite of grain size 0.02–0.04 mm also does not display a loss of radiogenic products within the error limits. Diffusion coefficients were therefore also calculated for this grain size. Assuming the same duration of the thermal events, the upper temperatures are calculated as 210 and 195 °C, respectively.

K/Ar and Rb/Sr dating on leached biotites from hydrothermally bleached zones give an upper age limit of 200 Ma for this hydrothermal event.

The corrected fission track age of 81.2 Ma for the "Rotliegend" sample from 1,021 m depth implies complete track erasure during Mesozoic burial. A burial duration in the order of 100 Ma requires a temperature of at least 130 °C for full track erasure. Based on the 2 km burial depth of this sample, a palaeo-gradient of 55 °C/km to 60 °C/km is estimated for the Cretaceous period.

According to the fission track data, the basement cooled slowly at an average rate of about 0.8 °C/Ma during the Cainozoic era. There is no indication of any significant re-heating. At the present stage of study, the fission track ages do not yet allow a detailed uplift history to be inferred from temperature depth distribution.

Origin of the geothermal anomaly

Miocene volcanism has been proposed as the most obvious possible sources for the geothermal anomaly, since both anomaly and volcanism occur in the same area (Carlé, 1958). As mechanism, residual heat from a cooling magma chamber, the ascent of deeply circulating water and post-volcanic gas exhalation have been considered. Exothermic reactions of hydrocarbons in Jurassic sediments have also been speculated (Schädel, 1982). These various possibilities have recently been summarised and evaluated critically by Werner (1982) and Berktold et al. (1982).

A crucial parameter in explaining the anomaly is the age. Buntebarth and Teichmüller (1982) concluded from coalification of organic matter in the borehole sediments that a high geothermal gradient of 43 °C/km was already active before the onset of the Tertiary uplift. A similar conclusion is derived from the apatite fission track data of the present work, although the palaeo-gradient of 55 to 60 °C/km down to 2 km depth during the Upper Cretaceous is somewhat higher. This rather early age of the elevated geothermal gradient certainly points against the Miocene volcanism as a source.

Furthermore, the thermal history models *B* and *C*, both of which take into account re-heating 15 Ma ago, set strict upper temperature limits for such an event. For a thermal overprint of 1 Ma duration, the maximal possible temperatures reached at a depth of 1 to 2 km are only 40 to 50 °C above present temperatures. Over a longer duration, these temperatures are even lower. It must be stressed that both models are geologically unrealistic since they assume rapid uplift after the Mesozoic subsidence to their present depth level and subsequently static conditions with a 30 °C/km gradient until re-heating 15 Ma ago. On the other hand, if gradual uplift is taken into account, re-heating caused by the Miocene volcanism could not have exceeded the temperatures by more than few degrees compared to those given by model *A*, i.e., temperatures 15 Ma ago did not exceed the present temperatures by more than 20 degrees. Therefore, the apatite fission track data rule out the possibility of any significantly higher palaeo-gradient during and after the Miocene volcanism compared with the present geothermal gradients.

The average cooling rate for the last 80 Ma is at least 0.8 °C/Ma, as calculated from the corrected age of sample Ro 1021. The same cooling rate is inferred independently from the age vs. depth profile (Fig. 5) for the period of 50 to 20 Ma ago. This cooling cannot be attributed to uplift only. Assuming a geothermal gradient of 40 °C/km, the average uplift would be 0.02 mm/a and the total uplift would amount to 1.6 km. This is not reconcilable with the geological data of ca. 1 km total uplift since Mesozoic subsidence. Also, the assumed cooling revealed by the fission track data is contradicted by the Obere Meeres Molasse cliff line 700–800 m altitude south of Urach, which attributes the uplift essentially to the last 18 Ma. Consequently, in addition to cooling due to uplift, the geothermal gradient (in the upper 2 km crust) must also have decreased from about 55 to 60 °C/km to the present values during the last 80 Ma. This points to an old, deep-seated, decaying heat source as the cause of the Urach geothermal anomaly.

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