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Superposition of burial and hydrothermal events: post-Variscan thermal evolution of the Erzgebirge, Germany

Reinhard Wolff,[1] István Dunkl,[1] Jan-Michael Lange,[2] Christian Tonk,[2] Thomas Voigt[3] and Hilmar von Eynatten[1]

[1]*Geoscience Center, University of Goettingen, Goldschmidtstr. 3, Goettingen 37077, Germany;* [2]*Senckenberg Natural History Collections of Dresden, Section Petrography, Museum for Mineralogy and Geology, Koenigsbruecker Landstr. 159, Dresden 01109, Germany;* [3]*Friedrich Schiller University of Jena, Institute of Geosciences, Burgweg 11, Jena 07749, Germany*

ABSTRACT

The post-Variscan thermal history of the Erzgebirge (Germany) is the result of periods of sedimentary burial, exhumation and superimposed hydrothermal activity. The timing and degree of thermal overprint have been analysed by zircon and apatite (U–Th)/He and apatite fission track thermochronology. The present-day surface of the Erzgebirge was exhumed to a near-surface position after the Variscan orogeny. Thermal modelling reveals Permo-Mesozoic burial to temperatures of up to 80–100 °C, although the sedimentary cover thins out towards the north resulting in maximum burial temperatures of less than 40 °C. This thermal pattern was locally modified by Cretaceous hydrothermal activity that reset the zircon (U–Th)/He thermochronometer along ore veins. The thermal models show no significant regional exhumation during Cenozoic times, indicating that the peneplain-like morphology of the basement is a Late Cretaceous feature.

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Introduction

The Erzgebirge (Saxonian Ore Mountains) forms part of the Saxo-Thuringian unit of the Variscan mountain belt, located at the northern margin of the Bohemian Massif (Fig. 1A). It exposes mainly metamorphic rocks intruded by Carboniferous and Permian felsic igneous rocks (e.g. Kossmat, 1925; Romer *et al*., 2010a). Numerous studies deal with the Variscan evolution of the Erzgebirge (e.g. Kempe *et al*., 1999; Förster *et al*., 2007; Seifert, 2008; Linnemann and Romer, 2010; Romer *et al*., 2010a); however, its thermal history during Mesozoic and Cenozoic times is still insufficiently understood, as the post-Variscan sedimentary record is incomplete or missing. Locally, the thermal history was influenced by ore-generating hydrothermal fluids. Thus, the thickness of the eroded cover suggested by available apatite fission track (AFT) data is a matter of debate (Schröder and Peterek, 2001; Ventura and Lisker, 2003; Lange *et al*., 2008). In this study, we present the results of zircon and apatite (U–Th)/He (ZHe and AHe, respectively) and AFT thermochronology obtained on basement rocks and Permian strata of the Erzgebirge. The applied methods yield detailed information on the thermal history of the Variscan basement below 200 °C (e. g. Flowers *et al*., 2009; Gautheron *et al*., 2009; Guenthner *et al*., 2013) at a regional scale (Erzgebirge). This case study serves as an example for basement blocks in which the regional thermal structure is perturbed by local hydrothermal anomalies.

Correspondence: Reinhard Wolff, University of Goettingen, Geoscience Center, Goldschmidtstr. 3, Goettingen 37077, Germany. Tel.: +00491795022260; e-mail: rwolff@gwdg.de

Geological setting

The structure of the Erzgebirge is dominated by an antiform, exposing high- to medium-grade metamorphic rocks in the core surrounded by low-grade metamorphic units mainly composed of micaschists and phyllites. This Variscan metamorphic assemblage was intruded by late- and post-Variscan granitoids and partly covered by rhyolites (Romer *et al*., 2007; see Fig. 1B). The post-Variscan sedimentary cover of the region starts with Late Carboniferous to Early Permian continental deposits (Fig. 2A); later in Triassic times the area formed the margin of the Central European Basin (Ziegler, 1990) and experienced subsidence (Voigt, 1995). West, north and east of the Erzgebirge thin Permian to Triassic sequences are preserved (Fig. 1A), but the thickness of the former cover on the currently exposed Erzgebirge is still a topic of debate (Schröder, 1976; Brause, 1988; Götze, 1998; Voigt, 2009). Schröder (1987) estimated a cover thickness of 1.5 km, while Dudek *et al*. (1991) postulated post-Variscan denudation of at least 2.5 km.

The Erzgebirge is dissected by the Gera-Jáchymov and Flöha faults (Fig. 1B). These northwest–southeast striking major fault zones were active in Mesozoic time (Kley, 2013). Further northeast, across the Lausitz Thrust, sedimentological data and cooling ages from the Lausitz Massif reveal significant exhumation during Late Cretaceous basin inversion (Voigt, 2009; Danišík *et al*., 2010).

In the north-eastern part of the Erzgebirge, Cenomanian to Coniacian sediments transgressively overlie the Variscan basement (e.g. Pietzsch, 1913; Kossmat, 1925; Wolf *et al*., 1992; Voigt, 1995). A palaeo-river delivered these sediments into the northern part of the Bohemian Cretaceous Basin during the Middle Cenomanian (Voigt, 1998, 2009; Schröder and Peterek, 2001). Gravel composition reveals that by this time the Triassic sedimentary cover had already been removed. During Turonian and Coniacian time, the area of

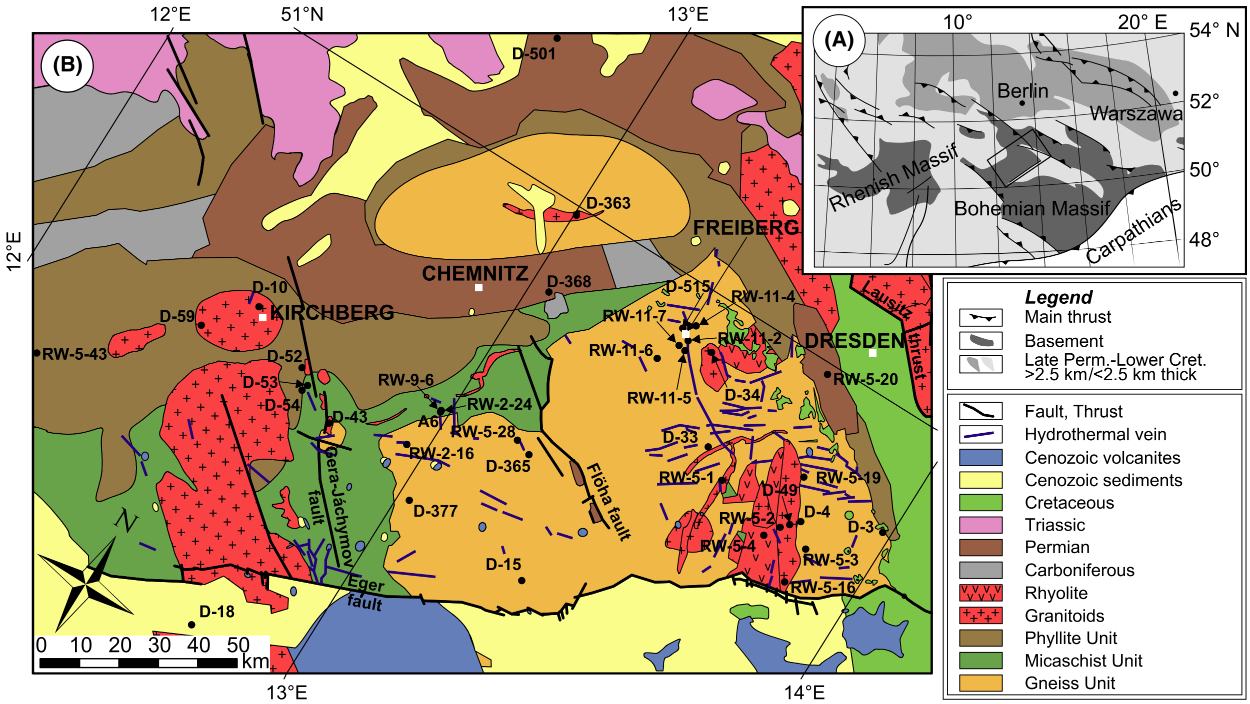

Fig. 1 (A) Position of the Erzgebirge within the European Variscides and surrounding Permo-Mesozoic basins. Rectangle represents the position of the study area magnified in (B) (modified after Kley, 2013). (B) Geological map of the Erzgebirge (simplified after Wolf *et al.*, 1992) with sample localities.

the later eastern Erzgebirge was buried, as indicated by the occurrences of marl and limestone layers preserved at the Eger Graben (Voigt, 2009).

Today, the Erzgebirge has relatively flat relief, slightly tilted towards the northwest. Palaeo-soil occurrences and kaolinite deposits indicate deep tropical weathering associated with the development of a peneplain in the Erzgebirge. According to Migoń and Lidmar-Bergström (2001) this preserved peneplain formed after approximately 80–70 Ma (i.e. Campanian time). Final exhumation of the Erzgebirge in late Cenozoic times was associated with the European Cenozoic Rift System (Ziegler and Dèzes, 2007) and led to the almost complete removal of the Upper Cretaceous sedimentary cover (Fig. 2A). In the southern Erzgebirge the basement is partly covered by Eocene to Oligocene fluvial deposits (Knobloch and Konzalová, 1998; Mai and Walther, 2000) and locally by Oligocene and Early Miocene mafic lava sheets (Suhr, 2003). The lava flows filled palaeo-valleys, but form elongated hills today. The relief inversion allows the post-Oligocene erosion to be estimated at less than 200 m.

Hydrothermal activity

The Erzgebirge is famous for numerous ore deposits. Two major periods of hydrothermal activity have been recognised. First, the late Variscan emplacement of granitoids and rhyolites was accompanied by increased hydrothermal activity, generating mainly Sn-W and Mo-rich greisen and skarn deposits at around 280 Ma (e.g. Stemprok and Sulcek, 1969; Baumann *et al.*, 2000). Second, long-lasting Mesozoic hydrothermal activity (*c.* 180–65 Ma) has generated ore veins at many sites in the basement (Fig. 1B and 2b; e.g. Romer *et al.*, 2010b). The Mesozoic mineralisation consists of predominantly barite–fluorite–sulphide and hematite–barite veins penetrating the metamorphic basement (e.g. Trinkler *et al.*, 2005; Seifert, 2008; Romer *et al.*, 2010b).

Thermochronology

Ventura and Lisker (2003) presented AFT data and modelled the thermal history from a borehole penetrating the basement in the south-western part of the Erzgebirge. Short track lengths (10.5–11.5 μm) combined with relatively old apparent AFT ages (151 to 89 Ma) imply a long residence in the apatite partial annealing zone (between *c.* 120 and 60 °C, e.g. Gleadow *et al.*, 1986) before final cooling. Ventura and Lisker (2003) suggested two episodes in which a thick cover layer was removed: (1) from Late Jurassic to Late Cretaceous (1.5–5.9 km) and (2) in the late Cenozoic (2.1–5.6 km). The two episodes were related to the breakup of Pangaea and to the tectonic activity of the Eger Graben, starting in the Oligocene respectively (Ventura and Lisker, 2003). However, the thickness of the eroded cover was questioned in later studies. Lange *et al.* (2008) presented AFT data covering the entire Erzgebirge and suggested a more complex exhumation pattern with less than 1 km of late Cenozoic erosion. Their AFT apparent ages range from 130 to 60 Ma, but in the central block of the Erzgebirge old ages up to 210 Ma are preserved, indicating limited post-Variscan burial and erosion.

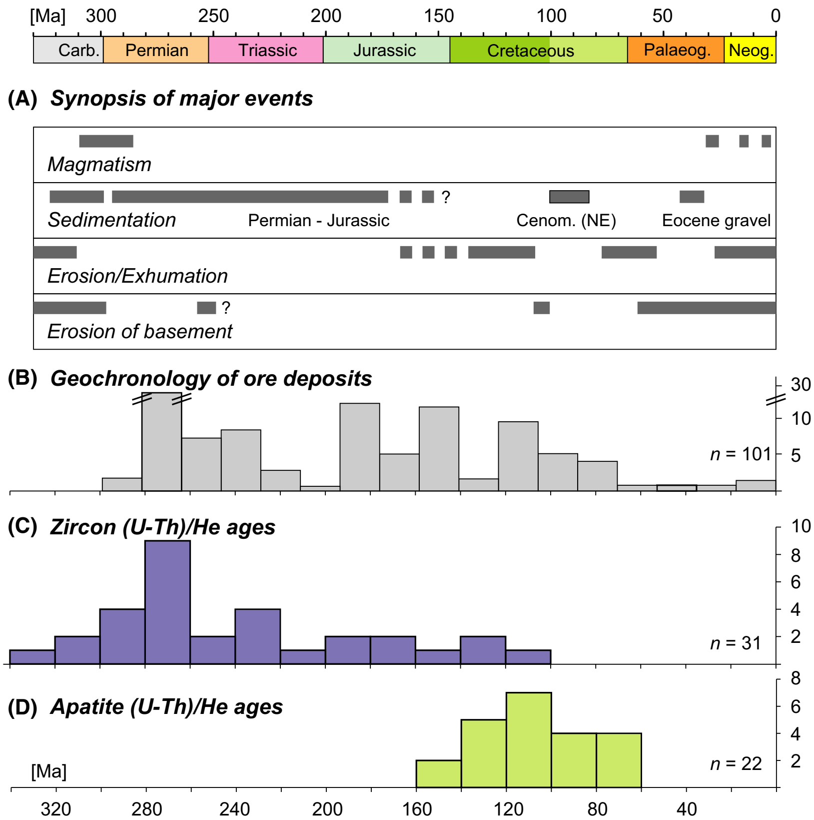

Fig. 2 (A) Synopsis of major events in the post-Variscan evolution of the Erzgebirge (for discussion and references, see chapter on Geological setting). (B) Compilation of geochronological data related to hydrothermal activity in the Erzgebirge (from Romer *et al.*, 2010b). (C and D) New low-temperature thermochronological data presented herein. For geological time-scale, see e.g. Gradstein and Ogg (2004).

Samples, results and thermal modelling

Apatite and zircon (U–Th)/He thermochronology (AHe and ZHe, respectively) was performed on the samples collected by Lange *et al.* (2008), on sample A6 of Kempe and Götze (2002) and on 17 new samples from the basement and the Permian (Fig. 1B). Details of the laboratory techniques are described in Wolff *et al.* (2012). The apatite (N = 60) and zircon (N = 99) (U–Th)/He single grain data are summarised as unweighted average ages in Table 1 and displayed on a simplified geological map, together with the contour map of the AFT ages from Lange *et al.* (2008) and the uppermost borehole sample of Ventura and Lisker (2003) (Fig. 3). The previously published AFT data from the Erzgebirge were complemented by three new ages and track length measurements determined on apatite crystals of uniform uranium content (Fig. 3 and Table 2, see details in Appendix S1–S3).

AFT thermochronometry of sample A6 from the central tectonic block between the Gera-Jáchimov and Flöha faults yields an age of 108 Ma and a mean track length of 13.6 µm. It is older than D-4 and D-53 from the other two blocks (98 and 85 Ma, showing track lengths of 13.4 and 13.2 µm, respectively). Together, they fit well into the existing AFT dataset. The apparent AHe ages range from 158 to 64 Ma (Fig. 2D). In the north-eastern Erzgebirge, the AHe ages range between 109 and 64 Ma, while in the central and western Erzgebirge they are typically older than 100 Ma (Fig. 3B). The apparent ZHe ages range from 323 to 112 Ma, with a prominent Permian age population and a broad Mesozoic age distribution (Fig. 2C). Permian ages dominate in the north-eastern and central part of the Erzgebirge, while Jurassic to Cretaceous ages dominate in the south-western part (Fig. 3B). However, two localities do not fit this pattern: sample D-34 yields 124 Ma, while six neighbouring samples at Freiberg (RW-11-X, D-515) give ZHe ages from 323 to 268 Ma. Similarly, we obtained ZHe ages of 112 and 232 Ma for two samples close to each other in the Kirchberg granite (D-10 and D-59). The ZHe ages show a negative correlation with the actinide concentration, mirroring an overall long stay in the helium partial retention zone (Fig. 4; e.g. Wolf *et al.*, 1996). The alpha dose controlled partial reset is responsible for at least part of the observed wide intrasample age scatter.

Five characteristic samples, representing the three different tectonic blocks and a pair from the Freiberg ore district with highly different ZHe ages, were selected for thermal modelling. The HeFTy software of Ketcham (2005) was applied considering the RDAAM algorithm, which includes the damage and annealing impact on helium diffusion (Flowers *et al.*, 2009; Gautheron *et al.*, 2009; Guenthner *et al.*, 2013). Modelling is based on the new AHe, ZHe and AFT ages and the AFT track length and Dpar measurements, on the dimensions of the dated crystals and on their actinide concentrations. The starting points of the time-temperature path for the basement samples were set after cooling from Variscan metamorphic conditions (*c*. 300 Ma, 200 °C). For all samples, good agreement between modelled time-temperature paths and measured data was obtained. The results of the thermal modelling are displayed in Figure 5 (for details, see Appendix S3).

Discussion

According to the areal distribution of the apatite low-T thermochronological data, three blocks having different thermal histories can be identified (Figure 3). The central block, between the Gera-Jáchymov fault and the Flöha fault, has considerably older AFT and AHe ages than the neighbouring blocks. This block had already been exhumed in the Early Cretaceous and has remained in a near-surface position since. Southwest of the Gera-Jáchimov

Table 1 Zircon and apatite (U–Th)/He ages and sample locations in the Erzgebirge, Germany. For analytical details, see Appendix S1–S3. Numbers in italics represent apatite samples where only one crystal yielded usable age information. D-samples are from the collection of the Dresden Fission Track Laboratory (DDSP-samples), A6 is from Kempe and Götze (2002). SE = 1σ standard error.

Sample No.	Latitude North	Longitude East	Elevation [m a.s.l.]	Lithology	ZHe [Ma] unweighted aver.	SE	AHe [Ma] unweighted aver.	S.E.
A6	50.64394	12.98133	365	Granite			140.1	5.6
D-3	50.83378	13.98092	400	Granite	276.5	6.5		
D-4	50.78441	13.80945	500	Granitoid	307.0	16.6		
D-10	50.63186	12.50243	380	Granite	232.2	24.8	*124.8*	*18.6*
D-15	50.49707	13.34174	500	Gneiss	276.1	8.9		
D-18	50.18681	12.75712	600	Granite	168.3	11.4	122.3	6.2
D-33	50.80493	13.54003	600	Rhyolite	302.1	5.9	88.1	4.0
D-34	50.92311	13.43227	370	Granite	124.2	6.0	91.2	4.8
D-43	50.54140	12.77551	500	Granite	143.1	21.3		
D-49	50.77181	13.79174	550	Rhyolite	226.4	17.4	73.5	3.1
D-52	50.59003	12.65937	570	Granite	134.2	25.2		
D-53	50.57223	12.69173	410	Granite	188.0	14.7	114.3	1.0
D-54	50.56218	12.68657	470	Granite	186.2	19.1		
D-59	50.56464	12.41329	430	Granite	111.9	3.5	103.9	4.7
D-363	50.98751	13.00509	250	Granite	208.7	20.7		
D-365	50.65754	13.20331	540	Gneiss			157.5	6.8
D-368	50.87239	13.04493	300	Gneiss			103.8	32.7
D-377	50.51185	13.03078	720	Gneiss			100.3	12.7
D-501	51.20099	12.74058	150	Rhyolite	270.5	11.3		
D-515	50.93058	13.34703	380	Gneiss	288.7	16.4	89.8	11.8
RW-2-16	50.57613	12.95476	569	Gneiss	275.1	9.2	92.3	11.0
RW-2-24	50.64394	12.98133	623	Granite			*134.9*	*6.5*
RW-5-1	50.77468	13.60706	690	Rhyolite	285.8	8.0	79.2	8.2
RW-5-2	50.76155	13.77623	688	Granite	268.7	8.2	64.4	5.6
RW-5-3	50.75443	13.85205	586	Granite	251.4	2.1		
RW-5-4	50.73906	13.75453	817	Rhyolite	276.1	20.5	79.6	7.8
RW-5-16	50.69792	13.85120	590	Gneiss	226.9	13.7	*102.9*	*9.1*
RW-5-19	50.84130	13.76144	333	Gneiss	234.5	22.7		
RW-5-20	50.98494	13.68278	203	Rhyolite	270.2	5.8	108.5	2.4
RW-5-28	50.66650	13.16324	623	Gneiss	252.2	7.6	129.1	26.8
RW-5-43	50.39903	12.11844	478	Sandstone	161.4	7.9		
RW-9-6	50.64394	12.98133	623	Granite			136.9	15.1
RW-11-2	50.91869	13.37285	340	Gneiss	267.9	5.6		
RW-11-4	50.94369	13.37018	340	Gneiss	281.2	15.8	101.0	5.0
RW-11-5	50.90474	13.37862	340	Gneiss	322.7	7.6		
RW-11-6	50.87397	13.33489	340	Gneiss	279.2	5.0		
RW-11-7	50.90680	13.36069	340	Gneiss	289.4	43.5		

fault the ZHe ages are significantly younger than in the central and NE blocks. However, the increased actinide concentration of these zircons indicates their less He-retentive character (Nasdala *et al*., 2004). Therefore, the apparent ZHe ages have to be evaluated carefully, and thermal modelling is required to reveal the thermal histories of the different blocks.

The detected differences between the low-T ages of the three major blocks cannot be related to a difference in the rather flat topography of the study area; thus, young vertical movements can be ruled out as the reason for the obtained age pattern. We postulate that the pre-Late Cretaceous differential development of the Erzgebirge is responsible for the detected age pattern. The boundaries between these blocks coincide with the major northwest-southeast striking brittle structures of the region. The Gera-Jáchymov fault and Flöha fault are the prime candidates owing to their prominent character and documented Mesozoic activity (Kley, 2013). The Flöha fault separates different units of high-grade and ultra-high-grade metamorphic formations of the Erzgebirge. Along this fault two Late Carboniferous to Early Permian intramontane basins were preserved, indicating the significance of the vertical offset (Fig. 1B).

Thermal history modelling

The locally preserved onlapping Upper Carboniferous to Lower Permian sequences prove that the Erzgebirge basement cooled to near-surface temperatures shortly after the Variscan orogeny. The modelling results of samples D-53 and D-4 indicate that their Permo-Mesozoic minimum burial temperature reached 80–100 °C, leading to a total reset of the AHe thermochronometer

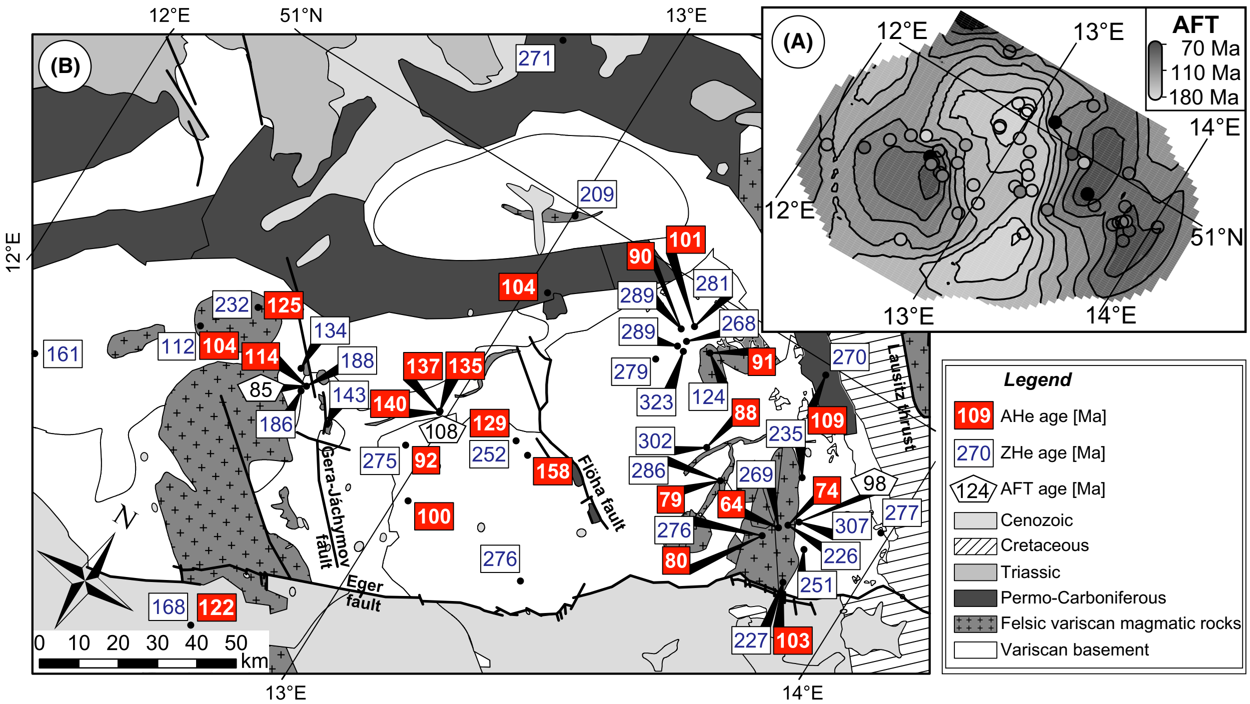

Fig. 3 (A) Apatite fission track isochron map generated by Kriging (Cressie, 1993) from the apparent AFT ages of Lange *et al.* (2008), the uppermost borehole sample of Ventura and Lisker (2003) and the AFT ages presented herein. (B) New (U–Th)/He and AFT ages plotted on the simplified geological map of the Erzgebirge.

Table 2 Details of the apatite fission track analysis. Cryst.: number of dated apatite crystals. Track densities (Rho) for spontaneous (S), induced (I) and dosimeter (D) tracks are as measured ($\times 10^5$ tr cm^{-2}); number of tracks counted (N) shown in brackets. P (χ^2): probability obtaining chi-squared value for n degrees of freedom (where n = no. crystals-1).

Sample	Cryst.	RhoS	Ns	RhoI	Ni	RhoD	Nd	Chi-sq. P (%)	Disp.	Central age [Ma]	Track length [μm, ± 1SD]	Dpar [μm]
A6	20	33.5	(1321)	40.1	(1580)	7.00	(2654)	80	0.00	108 ± 5.3	13.6 ± 1.4 (76)	1.9
D-4	20	7.24	(1098)	9.52	(1450)	7.04	(2654)	67	0.00	98.2 ± 4.1	13.4 ± 1.3 (73)	2.1
D-53	25	10.8	(988)	16.4	(1503)	7.02	(2654)	73	0.00	85.3 ± 3.7	13.2 ± 1.3 (110)	2.1

Disp.: Dispersion and Central age are calculated according to Galbraith and Laslett (1993). Numbers of measured horizontal confined tracks are indicated in brackets.

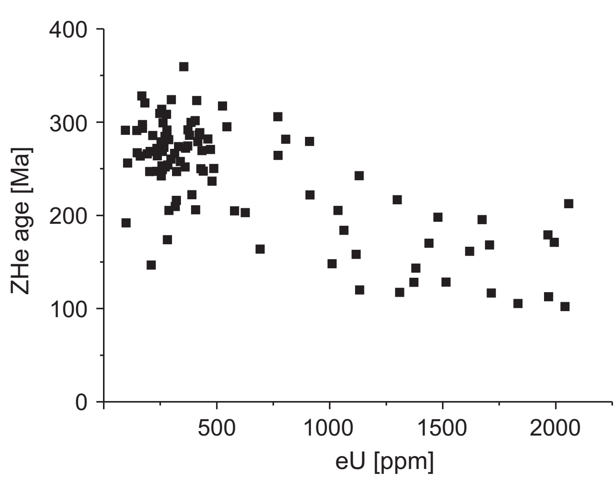

Fig. 4 Correlation of effective uranium concentration ([U]+0.235*[Th]) and (U–Th)/He age of all dated zircon single crystals.

(Fig. 5). The Permian to Cretaceous thermal history is only loosely constrained for samples A6 and D-34 owing to the relatively high temperatures they reached in the Early Cretaceous and therefore their relatively young apparent AHe ages. Only in the case of sample D-515 from the northernmost part of the study area did the pre-Cretaceous burial temperature remain below 80 °C (Fig. 5). As the incomplete relics of the Permo-Mesozoic sedimentary cover do not allow thickness estimates, these data provide the first evidence for limited Permo-Mesozoic burial in the northern part of the Erzgebirge. The relatively close sample D-34 does not show this effect for the reasons given below.

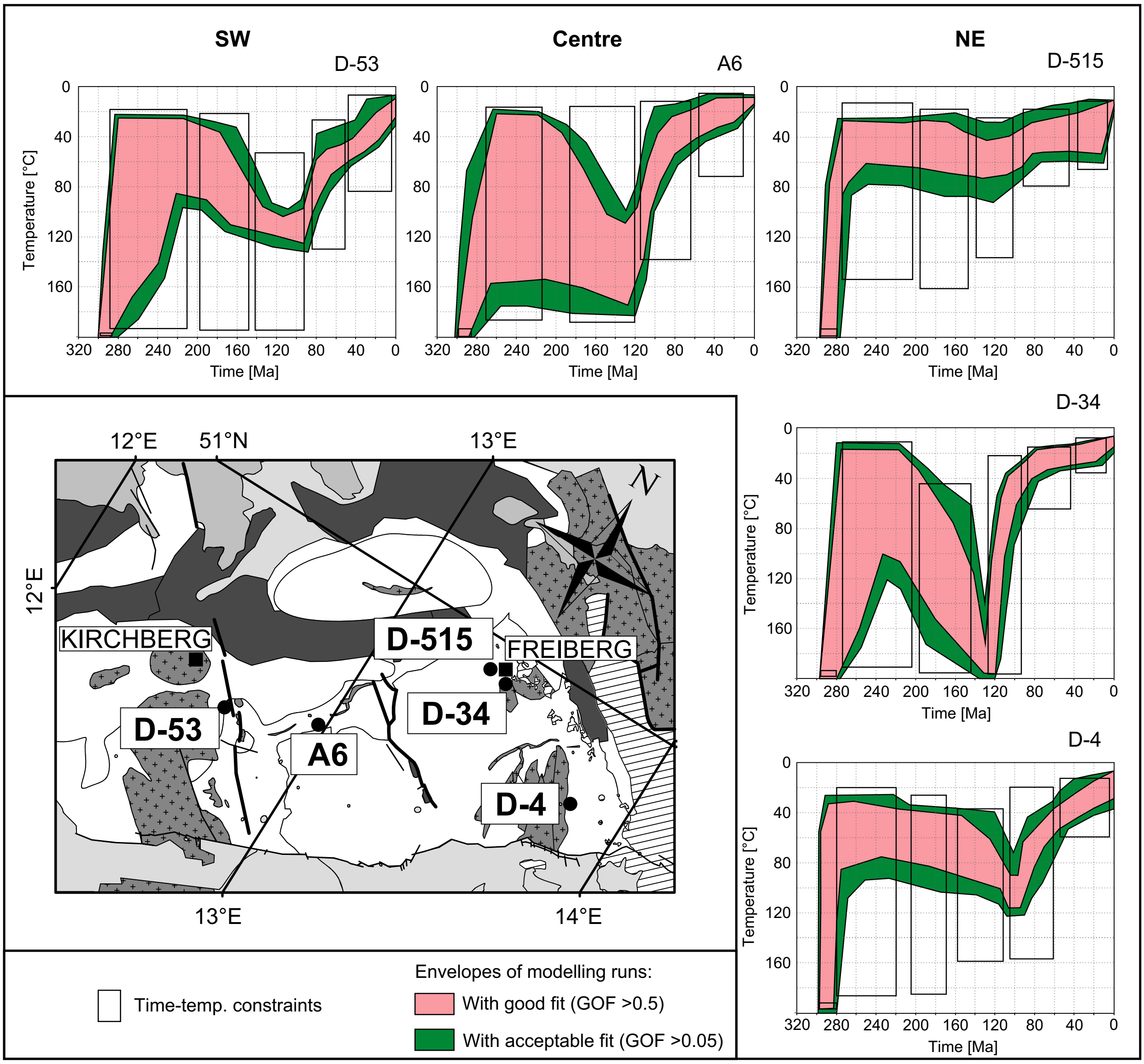

Fig. 5 Time-temperature paths obtained for selected localities in the Erzgebirge based on thermal modelling using HeFTy software (Ketcham, 2005). The top panels show the thermal histories from the three major tectonic blocks of the Erzgebirge (SW–NE). The right panels present the modelled thermal histories of neighbouring samples from the Freiberg ore district that experienced very different Cretaceous thermal overprints.

The characteristic feature of all modelled thermal histories is the pronounced Cretaceous thermal climax (*c.* 120 to 110 Ma) and the abrupt onset of cooling afterwards. We assume that rapid cooling was triggered by the cessation of the hydrothermal activity rather than by exhumation. The thickness of the removed Permo-Mesozoic sedimentary cover and basement cannot be determined exactly, but the composition of Cenomanian sediments indicates that the mid-Cretaceous erosion incised into the basement (Voigt, 1998).

Local reset of ZHe thermochronometer triggered by hydrothermal activity

Modelled t-T paths for the neighbouring samples D-515 and D-34 close to Freiberg are compared in Figure 5 (top right). Given the local geological situation, the contrast between the obtained thermal histories within a relatively short distance cannot be explained by faulting. Instead, the local abundance of Mesozoic hydrothermal veins suggests that the thermal event was triggered by the temperature of ore-forming fluids, which is inferred from fluid inclusion studies to have been *c.* 250 °C (e.g. Trinkler *et al.*, 2005). This temperature is sufficient to reset the ZHe thermochronometer even if the duration of the increased temperature is as short as 1 Ma (calculated by *Closure* software; Ehlers *et al.*, 2005). The temperature climax at *c*. 120 Ma in the thermal model is in good agreement with the Early Cretaceous ages recorded by other independent geochronometers (Fig. 2B) of Komínek *et al*. (1994), Förster (1996) and Romer *et al*. (2010b).

In contrast to Freiberg, the mineral veins in the Kirchberg granite have been considered to be late Variscan (Kempe, 2003), but the Cretaceous ZHe age (D-59) indicates a Mesozoic hydrothermal event affecting this ore district too. For samples D-34 and D-59 the AHe ages are roughly similar (91 and 104 Ma, respectively) indicating that the increased heat flow terminated in mid-Cretaceous time and was followed by rapid cooling below the helium partial retention temperature in apatite (Fig. 5, D-34).

Preservation of pre-Cenozoic landforms

The modelled thermal histories do not indicate significant re-heating or cooling during Cenozoic times, in contrast to the significant young denudation of the Erzgebirge proposed by Ventura and Lisker (2003). According to the here-presented multi-method thermochronological dataset covering a large area, the characteristic peneplain-like morphology of the Erzgebirge and the weathering-related deposits have been preserved since the Late Cretaceous.

Conclusions

1 According to thermal modelling of ZHe, AHe and AFT data, the Erzgebirge is dissected by two roughly NE–SW aligned fault zones, forming three structural blocks that experienced different post-Variscan thermal histories.
2 Basement rocks experienced cooling to near-surface temperature shortly after the Variscan orogeny and were then buried by Permian to Jurassic sediments. Thermal modelling of the northernmost sample suggests that the pre-Cretaceous burial was deeper in the southern to central parts of the Erzgebirge than in its northern part.
3 Local thermal anomalies resetting all investigated thermochronometers were generated by Cretaceous hydrothermal ore-forming fluids at Freiberg and in the Kirchberg granite. For the latter, this is the first indication of hydrothermal activity in Early Cretaceous times.
4 AHe data show no detectable regional exhumation or hydrothermal re-heating since the Late Cretaceous.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Details of the apatite and zircon (U–Th)/He results obtained on basement and Permian sedimentary samples from the Erzgebirge.

Appendix S2. Distribution of horizontal confined track lengths of the new apatite samples.

Appendix S3. Goodness of fit (GOF) values of the thermal modelling performed by HeFTy software (Ketcham, 2005). '–' indicates that the corresponding thermochronometer was not available.

