Abstract
Mainly acidic Stephanian to early Permian volcanic rocks and intercalated sediments accumulated in the Thuringian Forest Basin (TFB) in central Germany to a total thickness of ca. 2000 m. This basin offers a wide range of biostratigraphic information. New high-precision U–Pb CA–ID–TIMS (chemical abrasion–isotope dilution–thermal ionization mass spectrometry) zircon data are obtained from volcanic rocks for the first time in the TFB. Pre-treatment of the zircons by chemical abrasion was important to get rid of severe Pb loss. The zircon ages of the investigated formations indicate that the total duration of the volcanic activity in the TFB was considerably shorter [ca. 4 Myr: from 300 Ma for the oldest formation (Möhrenbach) until ca. 296 Ma for the youngest volcanic-rock-bearing formation (Rotterode)] than suggested in previous studies (ca. 20 Myr; 295 Ma to 275 Ma). Consequently, the well-documented gap of the sedimentary record from the early Permian volcanic rocks up to the Illawarra geomagnetic reversal has to be extended to ca. 25 Myr from the previously proposed 5 Myr. The zircon ages of the investigated volcanic rocks allow the constraining of some intercalated fossiliferous horizons crucial for biostratigraphic correlation of latest Carboniferous–early Permian (Rotliegend) sections. The high-precision age data require a new interpretation of the evolution of the TFB but also offer the chance to obtain a more reliable comparison of the timing of the main magmatic activity across intramontane basins as well as to obtain links to the Standard Global Stratigraphic Scale.

Keywords Geochronology · Zircon · Stratigraphy · ID–TIMS · Variscides · Thuringian forest

Introduction
From the late Carboniferous to the early Permian, the transition from the final stage of the Variscan orogeny to the stable continental regime of Pangea in Central Europe led to a change from compressive regimes to extensional/transtensional ones (Ziegler 1990; van Wees et al. 2000; McCann et al. 2006; Timmerman 2008; Kroner et al. 2016, 2020). Paleogeographically, large marine areas of high sea level turned into shallow marine marginal seas, merging in fringes of extensive swamp forests which fossilized to coal measures of Namurian to Westphalian age. In the latest Carboniferous (Stephanian), the humid environments became drier and fluviolacustrine sedimentation took place (e.g., Roscher and Schneider 2006; Paul 2012). Similar sedimentary sequences developed in elongated troughs inside the orogenic belt as in the Saar–Nahe Basin (e.g., Boy et al. 2012) or in the Thuringian Forest Basin (TFB) (Lützner et al. 2012). During the early Permian, these intramontane basins continued to form and fill up due to exhumation and erosion of the Variscan orogen, increasingly under the control of fault tectonics and magmatism.

The TFB is situated in a central and important geographic position in the Variscan orogenic belt in the Mid-German Crystalline Rise and Saxothuringian Zone between the Saar–Nahe and Kraichgau Basins in the SW and the Saale Basin in the NE (Lützner and Kowalczyk 2012; Andreas 2014). These basins were thoroughly studied during the last > 70 years for their geological structure, volcano-sedimentary successions (e.g., Lützner et al. 2012), magnetostratigraphy (e.g., Menning and Bachtadse 2012), and biostratigraphy (e.g., Martens 2012; Schneider and...
N Bohemia, NW part of the Polish Basin, SW Poland, NE
mian Basin/N Germany, W and central Germany, Saxony,
(Fig. 1a, e.g., Oslo Rift, Scotland, England, Southern Per-
thick volcanic successions across Europe and NW Africa
At the end of the Variscan orogeny, an extensive phase of
Carboniferous–Permian volcanism in Central Europe

Geological setting

Carboniferous–Permian volcanism in Central Europe

At the end of the Variscan orogeny, an extensive phase of
Carboniferous–Permian magmatism led to the extrusion of
thick volcanic successions across Europe and NW Africa
(Fig. 1a, e.g., Oslo Rift, Scotland, England, Southern Per-
mian Basin/N Germany, W and central Germany, Saxony,
N Bohemia, NW part of the Polish Basin, SW Poland, NE
Czech Republic, N Spain, Morocco, France, N Italy), with a
maximum volume in the late Carboniferous (Stephanian) to
early Permian. The eruption of volcanic rocks was accom-
panied by massive synextensional granitic intrusions and
hydrothermal mineralisation (Lorenz and Nicholls 1976,
1984; Hoth et al. 1993; Marx 1995; Marx et al. 1995; Benek
et al. 1996; Doblas et al. 1998; Breitkreuz and Kennedy
1999; Lorenz and Haneke 2004; Timmerman 2004, 2008;
McCann et al. 2006; Breitkreuz et al. 2007, 2009; Geißler
et al. 2008; von Sckendorff 2012; Hoffmann et al. 2013;
Willcock et al. 2013; Schmiedel et al. 2015).

In Europe, Stephanian to Permian volcanism resulted in
thermal destabilization of the lithosphere, intense fractur-
ing of the crust, disruption and erosion of its sedimentary
cover, and regional uplift in the area of the future Southern
Permian Basin (van Wees et al. 2000; Kroner et al. 2016).
Transtension led to the formation of more than 70 rift basins
across Europe. In the North German Basin (as part of the
Southern Permian Basin), volcanism between ca. 300 and
290 Ma is closely related in time and space to an episode of
major tectonic activity (right-lateral WNW- to W-trending
transtensional strike-slip movements; Plein 1993; Gast and
Gundlach 2006; McCann et al. 2006). The extensional tec-
tonics were important for supplying pathways for intrusive
and extrusive magmas.

The origin of the extensive and voluminous Carbonifer-
ous–Permian magmatism in Central Europe has been hotly
debated for more than 30 years with diverse theories arising
(see, e.g., Doblas et al. 1998; Timmerman 2004; McCann
et al. 2006; Geißler et al. 2008). This is partly due to the
large geochemical and mineralogical variety of the plutonic
and volcanic rocks, but likely also due to the structural and
lithospheric complexity of this part of Variscan Europe
(Lorenz and Nicholls 1976, 1984; Breitkreuz and Kennedy
1999; Breitkreuz and Mock 2004; von Sckendorff 2004,
2012; McCann et al. 2006; Breitkreuz et al. 2007, 2009).
A superplume has been invoked by Doblas et al. (1998) as a
background mechanism of this magmatic episode. Rifting,
thinning of highly asymmetric lithosphere, local decompre-
sion, and lithospheric mantle as the major source of the mid-
dle European Carboniferous–Permian volcanic rocks were
defined by Neumann et al. (2004). Mantle sources meta-
somatized by subduction-related material were inferred by
Timmerman (2004) to explain the geochemical character of
the volcanic rocks in NE Germany that does not agree with
an intra-plate setting.

The widespread Stephanian–early Permian (305–285 Ma,
Kasimovian–late Artinskian) alkaline to calc-alkaline intru-
sive and extrusive magmatism of the central European Vari-
scan area and its northern foreland (e.g., the North German
Volcanic Complex) is, based on trace element ratios, mantle-
derived and shows evidence of moderate crustal contamina-
tion (e.g., Marx et al. 1995; Benek et al. 1996; Breitkreuz

1. Define the age range of volcanic activity in the TFB
and compare it to the existing biostratigraphic data,
2. Constrain the gap between the end of major volcanic
activity with associated intramontane sediments and the
voluminous post-Illawarra paleomagnetic Reversal sedi-
tment accumulation of the late Permian stage, and,
3. To compare the timing of the main volcanic activity
across Permian basins in Central Europe.

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and Kennedy 1999; McCann et al. 2006). In the internal Variscides (South of the Variscan front, VF in Fig. 1a), mafic rocks are rare with felsic-intermediate compositions being dominant; whereas in the external areas, calc-alkaline SiO₂-rich volcanic rocks are more common (e.g., Timmerman 2008).

The late Stephanian to earliest Permian sequence (volcano-sedimentary and volcanic rocks as well as clastic fill)
reached its maximum thickness in the TFB (ca. 2000 m, a value comparable to maxima in N Germany.) The igneous rocks are lavas and pyroclastic rocks of mainly trachyandesitic to rhyolitic composition (Andreas et al. 1974; Obst et al. 1999; Obst and Katzung 2000; Lützner et al. 2007, 2012).

**Thuringian forest basin (TFB)**

**Geological overview**

The TFB is of exceptional value for the age determination of late Variscan Carboniferous–Permian basins because it is well investigated concerning lithostratigraphy (Lützner et al. 2012) and biostratigraphy (e.g., Schneider and Werneburg 2012; Schneider et al. 2020). The TFB also shows recurrent strong intra-basinal volcanism that produced piles of lava flows and tuffs hundreds of meters thick. Precise and accurate age dating of the TFB formations is, therefore, critical for the correct correlation and stratigraphic categorisation of a variety of other European late Carboniferous/early Permian basins.

Tectonically, the Thuringian Forest represents an uplifted block bordered by mainly NW–SE-striking faults and flexures that predominantly coincide with the morphological slopes of the range. The maximum altitudes are reached in the middle part (Großer Beerberg, 982 m) and in the northwest (Großer Inselsberg, 916 m), with decreasing altitudes (ca. 700 m) between both peaks and further to the southeast. The forelands are made up of Triassic sedimentary formations that predominantly coincide with the morphological block bordered by mainly NW–SE-striking faults and flexures; whereas, within the elevated range, Stephanian and early Permian successions and their Variscan base ment flexures; whereas, within the elevated range, Stephanian and early Permian successions and their Variscan basement are revealed (Fig. 1b).

The Stephanian–Rotliegend (late Carboniferous–early Permian) filling of the TFB disconformably overlies the Variscan basement. On the southeastern margin, the basement consists of Proterozoic and Paleozoic up to lower Carboniferous sedimentary units of the Saxothuringian Zone which were folded and underwent a low-grade Variscan metamorphism (Bankwitz and Bankwitz 2003; Meinel 2003).

To the northwest, the basin filling covers the “Thüringer Hauptgranit”, an early post-kinematic granite pluton of early Carboniferous age (330.3 ± 3.4 Ma to 337 ± 4 Ma from zircon Pb–Pb evaporation and dark mica Ar–Ar, and K–Ar dating; Zeh and Brätz 2000; Zeh et al. 2000; Goll and Lippold 2001) with a contact belt against the early Paleozoic in the Southeast (Fig. 1b; Bankwitz and Kaemmel 1957). The composition of the “Thüringer Hauptgranit” is heterogeneous and varies between quartzdioritic, granodioritic, and leucogranitic (Meinel 2003). These plutonic rocks had been eroded and deeply weathered before the development of the TFB (Lützner et al. 2012). The extension of the TFB spreads beyond the recent tectonic borders of the Thuringian Forest at least 12 km to the Northeast (borehole Gotha 1), and at least 20 km to the Southwest (boreholes Metzels, Thüringen Süd, Rannungen, not shown in Fig. 1). The extension to the NW is bordered by the Ruhla Crystalline Complex (RCC, Fig. 1b). Paleocurrent patterns indicate that the RCC was one of the source areas for the TFB sedimentary formations.

**Lithostratigraphy**

Figure 2 illustrates the lithostratigraphic subdivisions of the TFB. The lowermost formations (Georgenthal Formation in the NW and Möhrenbach Formation in the SE, thought to be coeval) reflect a first culmination of magmatic activity and are both dominated by intermediate volcanic rocks with additional rhyolites present in the Möhrenbach Formation. Thin sedimentary intercalations were used for internal correlations (Lützner et al. 2012: p. 430; Andreas 2014: p. 96). The overlying Ilmenau Formation displays local sedimentary beds alternating with volcanic and pyroclastic rocks of bimodal basaltic and rhyolitic composition (Lützner et al. 2012).

Extrusive volcanic rocks are extremely scarce in the two subsequent formations, i.e., in the coal-bearing Manebach Formation and in the fluvial–lacustrine Goldlauter Formation. Volcanic events are restricted to several tuff layers, which are used as tephrostratigraphic marker horizons (Andreas and Haubold 1975).

In the TFB, a second culmination of Rotliegend volcanism occurred during the following Oberhof Formation where volcanic rocks alternate with volcaniclastics and subordinately with alluvial red beds and lacustrine gray beds. The basal group of volcanic rocks within the Oberhof Formation consists of an association of basic, intermediate, and acidic volcanic rocks that is intercalated within the lower sedimentary beds of fluvial and lacustrine origin. The middle and upper parts of the Oberhof Formation are dominated by rhyolites and associated volcaniclastics. So-called Older Rhyolites prevail in the middle part. They are characterized by medium to large feldspar phenocrysts. Finally, the so-called Younger Rhyolites constitute the upper part of the Oberhof Formation. These rocks have typically small qtz–fsp phenocrysts of about 1 mm size. However, a few rhyolite domes intruding the Younger Rhyolite level also have large qtz–fsp phenocrysts. The Rotterode Formation consists of red sandstones with conglomeratic intercalations that surround several rhyolitic bodies and tuff layers. This formation was deposited on the Oberhof Formation with a low-angle unconformity separating the two formations. The angular unconformity was likely related to the tectonically induced uplift of the Ruhla crystalline complex, which caused rejuvenation of the relief and...
Fig. 2 Lithostratigraphic subdivision of the Carboniferous–Permian sediments of the Thuringian Forest Basin, presented as a schematic NW–SE cross-section. Circled letters label biostratigraphically important fossiliferous horizons: A—Öhrenkammer horizon (Georgenthal Fm.), B—Ilmtal horizon (Möhrenbach Fm.), C—Lindenberg horizon (base of Ilmenau Fm.), D—Sembachtal horizon (top of Ilmenau Fm.), E—Manebach fossiliferous horizons (Manebach Fm.), F—Sperbersbach horizon (lower Goldlauter Fm.), G—Gottlob horizon (upper Goldlauter Fm.), H—Lochbrunnen horizon (lower Oberhof Fm.), I—Wintersbrunn horizon (upper Oberhof Fm.), J—Bromacker horizon (Tambach Fm.). Numbers in yellow boxes represent new sample locations for zircon U–Pb CA–ID–TIMS dating.
resulted in deposition of granite-derived sands and gravels (Thomson and Zeh 2000; Andreas and Lützner, 2009).

The Tambach Formation starts with coarse conglomerates that cover an eroded surface. The conglomerates grade upwards into red sandstones and mudstones that contain the youngest fossil beds of stratigraphic significance in the TFB. The fossil-bearing red beds at the Bromacker locality are famous for tetrapod footprints and skeletal remains of terrestrial amphibians and reptiles. Paleontological projects were performed by T. Martens in cooperation with experts from the USA (Martens 2001; Eberth et al. 2000 and others). The state of biostratigraphic correlation was summarized by Schneider et al. (2020). They consider for the Bromacker Horizon an Artinskian age, which is not proven by radioisotopic studies. Volcanic rocks are missing in the Tambach Formation; volcaniclastic rocks are also presently unknown.

The Eisenach Formation only occurs on the western flank of the Ruhla Crystalline Complex and the adjacent Werra basin. Along the basin fringes, marginal alluvial fans are interfingered with sandy mudstones.

The Neuenhof Formation is the uppermost Permian formation of continental red beds. It consists of a 5–10 m thin-bedded alternate with fine gravels, sandstones, and siltstones of a mainly fluvial environment. Locally intercalated cross-bedded sandstones are probably of aeolian origin. At the top, the red-colored sandstones gradually pass over into gray sediments that were reworked by the invading Zechstein Sea. A scarce settling with brachiopods has been proven in places. The Kupferschiefer black shale follows with a sharp boundary.

Magnetostratigraphically, all formations of the TFB, including the Eisenach Formation, belong to the Kiaman Reversed Superchron. Only the red beds of the Neuenhof Formation proved to be part of the Permian–Triassic Mixed Superchron (Isozaki 2009; Menning et al. 1988). Thus, the Illawarra Reversal (266.66 ± 0.76 Ma, Hounslow and Balaban 2018) took place during a long hiatus (break of sedimentation, gap due to onlapping cover on morphology, and/or erosion). Nevertheless, the Neuenhof Formation has the appearance of the Rotliegend facies (Lützner et al. 2012), which is directly covered by the basal conglomerate and black shale (Kupferschiefer) of the Zechstein sea.

**Samples and methods**

**Samples**

We aimed to sample the whole Stephanian and early Permian sequence of the TFB by sampling various rhyolitic and rhyodacitic volcanic rocks (Figs. 1b, 2). From each formation, one or two samples were collected (Table 1). We preferred to sample acidic rocks with medium- to large-sized phenocrysts of quartz and feldspar because these rocks generally yielded sufficient zircon crystals. We briefly comment on the sample sites in the lithostratigraphic order (Fig. 2).

In the lowest section, rhyolites from the Möhrenbach and the Ilmenau Formations of the Southeastern TFB region were sampled. Samples were taken from two rhyolite outcrops within the Möhrenbach Formation: (i) from road cuts near Stützerbach (sample 7) and (ii) from the quarry at the Hundskopf hillside (sample 6). According to several authors (Andreas et al. 1974; Michael 1972; Lützner et al. 2012), the Stützerbach Rhyolite is situated in the middle section of the Möhrenbach Formation and thus has a somewhat lower position than the Hundskopf Rhyolite. The latter is considered to be a part of the Kienberg Rhyolite that occurs as a dissipated system of dykes, sill-like bodies, vent fillings and lava sheets. Both samples are good representatives of the Möhrenbach Formation.

The Ilmenau Formation (occurring above the Möhrenbach Formation) contains the Kickelhahn Rhyolite that typically has plenty of medium-sized quartz and feldspar phenocrysts and is well exposed at the type locality “High Hill Kickelhahn” near Ilmenau where sample 5 was taken. This formation is associated with thick pyroclastics.

The predominantly sedimentary Manebach and Goldlauter Formations were not sampled because these units lack extrusive volcanic rocks.

Extensive magmatic activity (rhyolites, rhyodacites, felsic intrusions, and various pyroclastic deposits) occurred in the Oberhof Formation. Two localities in the uppermost lava flow of the “Older Rhyolite Series” were selected near Lusenthal to sample a representative rhyolite in the middle section of the Oberhof Formation (based on the revised Geological Map; Enderlein and Ziegenthaler 1975; scale of 1: 25,000). Sample 2 was taken from the Klotzgrund valley and sample 3 from outcrops at the mouth of the Lehmgund valley. Both samples represent different parts of a uniform rhyolite body.

The Rotterode Formation comprises two fault-bound rhyolite bodies that did not contain zircon. In addition, several rhyolite dykes penetrate the red beds of the Rotterode Formation. They have been mapped in detail by Patzelt (1966) and were adopted in a revised map of the Rotterode Formation by Andreas and Lützner (2009). We sampled one of the rhyolite dykes in an outcrop in the village Struth-Helmershof (sample 1). It should indicate the median or minimum age of the Rotterode Formation.

The red beds overlying the Rotterode Formation, i.e., the Tambach and Eisenach Formations, do not contain volcanic rocks. Only the Elgersburg Formation, which is considered as an equivalent of the Tambach Formation, contains two rhyolite bodies and a basaltic layer in the lower part (Schwalbenstein Conglomerate Member). The Elgersburg Rhyolite represents the uppermost volcanic rock in the
| Sample no. | Location | GK25 | Easting [m] | Northing [m] | Longitude [°E] | Latitude [°N] | Formation | Rock type |
|-----------|----------|------|-------------|--------------|----------------|---------------|------------|-----------|
| 1         | Struth-Helmershof, outcrops „Kronstein“ near cemetery | Blatt 5229 Tambach-Dietzharz | 4,394,900 | 5,624,700 | 50.74828 | 10.50931 | Rotterode Formation | Komberg Rhyolite, dyke, intruded into sediments of the Rotterode Formation |
| 2         | Southeast of Luisenthal, Siegelgrund, right side of valley, at mouth of Klotzgrund valley | Blatt 5230 Oberhof | 4,410,800 | 5,626,150 | 50.76397 | 10.73419 | Oberhof Formation | „Zone der Älteren Porphyre, 6. Erguss“ (zone of older porphyries, 6th extrusion), according to mapping of Enderlein and Ziegenhardt (1975) a rhyolite sheet |
| 3         | Luisenthal, at the end of Lehmggrund, outcrop below Gothaer Hütte (Gotha Cabin) | Blatt 5230 Oberhof | 4,409,950 | 5,628,600 | 50.78586 | 10.72155 | Oberhof Formation | „Zone der Älteren Porphyre, 6. Erguss“ (zone of older porphyries, 6th extrusion), according to mapping of Enderlein and Ziegenhardt (1975) a rhyolite sheet |
| 4         | Kohltal, footpath to Wolfstein summit, lowest part of trail | Blatt 5331 Ilmenau | 4,419,070 | 5,618,430 | 50.69580 | 10.85308 | Supposed to be Elgersburg Formation | Rhyolite with large pale pink feldspars |
| 5         | Forest track at western flank of the Kleiner Herrmannstein | Blatt 5331 Ilmenau | 4,419,800 | 5,616,020 | 50.67424 | 10.86393 | Ilmenau Formation | Kickelhahn-Porphyry, light grey porphyric rhyolite |
| 6         | Quarry at Großer Hunds kopf, at the road from Alzunah to the Dreiherrstein and to Neustadt a. R | Blatt 5331 Ilmenau | 4,420,280 | 5,608,600 | 50.60762 | 10.87232 | Möhrenbach Formation | Upper section, part of Öhrenstock-Schichten Kienberg Rhyolite (quartz poor to quartz free); Michael (1972) mapped this as a subvolcanic intrusion, time equivalent to the widely exposed Kienberg Rhyolite |
| 7         | Quarry at the road from Gasthof Auerhahn (inn) to Ilmenau, between Hinter Erbskopf and Hohe Tanne | Blatt 5331 Ilmenau | 4,420,830 | 5,612,500 | 50.64274 | 10.87925 | Möhrenbach Formation, lower to middle section | Stützerbach Rhyolite, quartz poor to quartz free |

Coordinates are given as Gauss–Krueger (Zone 4) for maximum precision and decimal degrees (WGS84) for international comparability. GK is the 1: 25,000 Geological Map of Thuringia.
TFB. Unfortunately, separated zircons from this rhyolite had xenomorphic forms; idiomorphic grains were lacking. Therefore, we excluded this sample from dating and instead used the Wolfstein Rhyolite, which appears near the base of Elgersburg conglomerates (No. 4). It was first described as “Preußenshöhe Porphyry” by Zimmermann (in Lorentz et al. 1908, p. 122) and Deubel (1960, p. 429). The Wolfstein Rhyolite is characterized by medium to large phenocrysts of quartz and feldspar and contains idiomorphic zircon crystals suitable for high-precision dating.

**Methods**

Recent development in ID-TIMS dating substantially reduced the analytical error of zircon dating, especially through the application of chemical abrasion (CA) on single zircon grains prior to their analysis. It was demonstrated in several studies that this pre-treatment considerably reduces Pb loss that—if not detected—would result in exceedingly young ages (Mattinson 2005; Schaltegger et al. 2015; Tichomirowa et al. 2019). In addition, due to efforts of the EARTHTIME initiative (http://www.earthtimetestsite.com/), the inter-laboratory bias of zircon ages has been reduced to 0.1% through the use of precisely and accurately calibrated tracers (Condon et al. 2015) and the standardization of raw data correction by the development and supply of open source programs (McLean et al. 2015). As a result, the accuracy and external reproducibility of zircon ages from participating laboratories can be ≤ 0.1% and can be proved by their reported international zircon standard ages. Consequently, the CA–ID–TIMS method has the ability to produce the most precise and accurate ages (Schaltegger et al. 2015).

U–Pb CA–ID–TIMS dating was performed in the TIMS lab at the TU Bergakademie Freiberg (Germany). Selected zircon grains with the most idiomorphic forms (ca. 15–30 per sample) were annealed for 72–96 h at 850 °C and subsequently chemically abraded for 12–15 h at 180 °C with concentrated HF and HNO3. This procedure dissolves crystal domains with the most intense radiation damage, which are suspected to have experienced post-crystallization lead loss (Mattinson 2005). After this chemical leaching procedure, single idiomorphic grains are transformed into fragments that represent those zircon parts with the lowest uranium content (Mattinson 2005). Afterwards, the acid, together with dissolved zircon material, was completely pipetted out. 3.5 N HNO3 was added to the remaining zircon fragments, and the mixture was left for 30 min at 50 °C to remove surface lead. Several cleaning cycles with water, combined with repeated ultrasonic treatment were conducted before single zircon fragments were selected for further processing.

Single zircon fragments were washed with 3 N HNO3 and transferred into cleaned microcapsules with a small drop of this fluid and 3 drops of concentrated HF. Samples were spiked with 6–10 mg of a 205Pb/233U–235U tracer solution (ET535 at TU Bergakademie Freiberg; Condon et al. 2015). For final dissolution, the microcapsules were placed in Parr vessels and heated to 200 °C for 48 h followed by drying at 130 °C and then re-dissolution in 6 N HCl for 24 h at 200 °C to transfer them into chlorides. After repeated drying, the samples were dissolved in 10 drops (ca. 50–60 mg) of 3.1 N HNO3 and transferred into 50 µl micro-columns for column chemistry. U and Pb were separated from the rest of the sample by anion exchange chromatography (AG 1-X8, 200–400 mesh) using HCl and H2O. The U- and Pb-containing fraction was loaded on degassed rhenium filaments with a drop of silica gel and measured with a Finnigan Mass Spectrometer MAT 262 using a secondary electron multiplier (SEM). The common Pb was corrected using the model of Stacey and Kramers (1975) instead of applying a specific lab blank value because this correction resulted in the most concordant values for reference materials (two international standards—see below).

Ages of two international zircon standards (Temora 2, 91500) were acquired contemporaneously with those of the Thuringian Forest volcanic rocks to ensure their accuracy. Similar to the samples, both standards were pre-treated with chemical abrasion (CA) to get comparable results. Data are given as 206Pb/238U age-ranked plots in Fig. 3. The Temora 2 standard has an accepted age of 416.8 ± 0.3 Ma (Black et al. 2003). The majority of our single grain ages have a spread of < ±0.3% with a few slightly older ages (Table 2, Fig. 3). We obtained a weighted mean age of 417.34 ± 0.28/0.33/0.56 Ma for this standard. The standard 91500 was dated at 1062.4 ± 0.4 Ma (Wiedenbeck et al. 1995) and 1063.6 ± 0.3 Ma (Schoene et al. 2006). In our data, a few ages are slightly (<1%) younger than the main age cluster, indicating the presence of small lead loss despite CA pre-treatment (Table 2). The remaining data used for the weighted mean age calculation have a spread of <0.3% and yielded a weighted mean age of 1064.6 ± 0.55/0.60/1.30 Ma (Fig. 3). Altogether, our results are within 0.1% of the accepted values, assuring the accuracy of our CA–ID–TIMS ages at the 0.1% level.

**Results**

The U–Pb isotopic results of seven samples are given in Table 2 and presented in Fig. 4 as 206Pb/238U age-ranked plots for each individual sample. Eight to fifteen grains were analyzed for each sample. Mean sample ages were calculated from age clusters that are interpreted as crystallization ages. The error of weighted mean ages is given as ±δx/δy/δz, where x is the internal 2σ measurement error, y is the internal 2σ error plus tracer calibration uncertainty, and z additionally
Nine zircons were dated from sample 1. The youngest age was discarded and interpreted as slight lead loss because of its offset from the remaining eight results. The other eight analyses yielded ages from $295.7 \pm 0.2$ Ma to $297.6 \pm 0.9$ Ma. The youngest three of these eight dates define a cluster of identical ages with a weighted mean age of $295.8 \pm 0.1/0.2/0.4$ Ma (MSWD = 0.1), which we interpret as the crystallization age. The five remaining dates show a slight increase from $296.3 \pm 1.5$ to $297.6 \pm 0.9$ Ma. These deviating ages are interpreted as zircons incorporated during intrusion from slightly older magma batches (antecrystic grains, Miller et al. 2007).

Ten single zircon grains were analyzed from sample 4. Three of them are more than 5 Ma older than the rest and are interpreted as inherited grains. Four of the remaining dates show a tendency towards younger ages, while the other three grains define an age cluster at $299.4 \pm 0.3/0.3/0.5$ Ma (MSWD = 1.3), interpreted as the crystallization age of this sample. If this interpretation is valid, severe lead loss has to be assumed for the remaining four grains (the youngest date results in $296.5 \pm 0.4$ Ma, which is 1% below the defined mean age). Therefore, lead loss is most pronounced in zircons from sample 4 but also present in zircons from samples 1, 2, 5, 6, and 7.

The analysis of 15 zircon grains from sample 5 yielded ages that range from $298.4 \pm 0.2$ Ma to $302.8 \pm 0.1$ Ma, with one inherited age at $319.3 \pm 0.2$ Ma. Three other grains are significantly older than the majority of ages and are interpreted as antecrystic zircons. The remaining eleven zircons reveal a much smaller scatter from $298.4 \pm 0.2$ Ma to $299.3 \pm 0.1$ Ma. We interpret the younger dates as affected by lead loss and calculated a weighted mean age of $299.3 \pm 0.1/0.1/0.3$ Ma (MSWD = 1.2) using the five oldest grains from this population.

Nine zircon grains were dated from sample 6. The statistically significant age cluster includes seven single grain ages and yields a weighted mean age of $300.0 \pm 0.3/0.3/0.5$ Ma (MSWD = 0.9). One age is significantly younger than this cluster and is interpreted as having been affected by lead loss; another age is significantly older and is interpreted as an antecrystic grain.

Ten zircon grains were analyzed from sample 7 and show ages from $298.0 \pm 0.6$ Ma to $299.9 \pm 0.7$ Ma. The youngest ages are not identical but show a tendency toward lower ages that is interpreted as having been affected by lead loss. A well-defined age cluster is formed by the four oldest grains of this sample at $299.7 \pm 0.3/0.3/0.4$ Ma (MSWD = 0.2).

Fig. 3 $^{206}$Pb/$^{238}$U ages of two international standards obtained by CA–ID–TIMS. Single ages are shown by bars representing 2σ errors (including analytical, tracer, and decay constant uncertainties); unfilled bars are considered outliers. All uncertainties associated with weighted mean $^{206}$Pb/$^{238}$U ages are reported at the 95% confidence level and given as ±x/y/z, with x as analytical uncertainty, y including tracer calibration uncertainty, and z including $^{238}$U decay constant uncertainty. The accepted mean ages, together with their 2σ uncertainties for these standards (see text for values) are given in green for comparison.
Table 2  U–Pb CA–ID–TIMS analyses of standard and sample zircons; data used for 206Pb/238U-weighted mean age calculations are given in bold

| Fraction and sample | Dates (Ma) | 206Pb/238U ± 2σ | 207Pb/235U ± 2σ | 207Pb/206Pb ± 2σ | Corr. Coef | % disc | Pb* | Pb**/Pbc | 206Pb/204Pb | 206Pb/238U ± 2σ | 207Pb/235U ± 2σ | 207Pb/206Pb ± 2σ |
|---------------------|------------|-----------------|-----------------|-----------------|------------|-------|------|---------|----------------|-----------------|-----------------|-----------------|
| 91500               |            |                 |                 |                 |            |       |      |         |                 |                 |                 |                 |
| 91500–1             | 1059.6     | 2.7             | 1065.5          | 19.1            | 1064       | 53    | 0.96 | 0.38   | 13.4           | 3.5             | 3.81            | 258             |
| 91500–2             | 1060.1     | 2.4             | 1054.3          | 16.1            | 1045       | 45    | 0.90 | 0.26   | 35.8           | 8.0             | 4.49            | 302             |
| 91500–3             | 1061.1     | 2.0             | 1056.3          | 4.0             | 1047       | 11    | 0.58 | 1.35   | 76.7           | 7.0             | 11.0            | 697             |
| 91500–4             | 1061.9     | 1.8             | 1062.4          | 11.8            | 1067       | 33    | 0.88 | 1.26   | 22.1           | 3.6             | 6.17            | 406             |
| 91500–5             | 1062.3     | 3.4             | 1060.6          | 23.6            | 1063       | 66    | 0.93 | 0.03   | 10.9           | 3.5             | 3.07            | 212             |
| 91500–6             | 1063.0     | 2.1             | 1055.6          | 9.2             | 1042       | 26    | 0.66 | 2.26   | 77.3           | 9.4             | 8.19            | 537             |
| 91500–7             | 1063.3     | 1.1             | 1063.8          | 6.9             | 1067       | 19    | 0.84 | 0.33   | 69.5           | 6.5             | 10.6            | 685             |
| 91500–8             | 1063.5     | 1.4             | 1059.9          | 3.2             | 1056       | 9     | 0.66 | 3.26   | 59.6           | 6.1             | 9.71            | 632             |
| 91500–9             | 1064.5     | 2.9             | 1059.2          | 3.5             | 1052       | 10    | 0.53 | 1.14   | 59.4           | 6.2             | 9.51            | 619             |
| 91500–10            | 1064.6     | 2.9             | 1064.6          | 3.6             | 1072       | 10    | 0.58 | 4.26   | 55.4           | 7.8             | 7.06            | 464             |
| Temora2             |            |                 |                 |                 |            |       |      |         |                 |                 |                 |                 |
| Tem-1               | 415.5      | 1.9             | 414.3           | 24.8            | 412        | 152   | 0.98 | 0.73   | 6.64           | 3.3             | 2.03            | 149             |
| Tem-2               | 416.5      | 1.9             | 416.7           | 3.1             | 419        | 17    | 0.55 | 0.64   | 185            | 9.9             | 18.6            | 1183            |
| Tem-3               | 416.8      | 0.9             | 418.3           | 11.0            | 429        | 67    | 0.93 | 2.86   | 15.6           | 3.4             | 4.55            | 302             |
| Tem-4               | 417.1      | 0.8             | 415.9           | 1.9             | 409        | 11    | 0.60 | 1.85   | 71.6           | 6.8             | 10.5            | 666             |
| Tem-5               | 417.2      | 0.6             | 417.9           | 5.9             | 423        | 36    | 0.86 | 1.48   | 32.8           | 3.8             | 8.66            | 562             |
| Tem-6               | 417.4      | 0.6             | 413.3           | 2.2             | 396        | 13    | 0.64 | 5.54   | 60.8           | 7.7             | 7.89            | 516             |
| Tem-7               | 417.8      | 0.7             | 414.3           | 2.1             | 401        | 13    | 0.65 | 4.09   | 62.6           | 11              | 5.96            | 400             |
| Tem-8               | 417.8      | 2.1             | 423.4           | 23.2            | 457        | 139   | 0.81 | 8.58   | 12.3           | 5.4             | 2.27            | 158             |
| Tem-9               | 418.2      | 0.9             | 418.6           | 6.3             | 423        | 38    | 0.76 | 1.03   | 31.3           | 5.9             | 5.32            | 350             |
| Tem-10              | 419.3      | 0.6             | 417.8           | 7.9             | 412        | 48    | 0.96 | 1.86   | 20.0           | 3.1             | 6.46            | 430             |
| Tem-11              | 419.7      | 1.9             | 417.5           | 18.8            | 409        | 115   | 0.83 | 2.65   | 12.6           | 4.6             | 2.76            | 192             |
| Fraction and sample | Dates (Ma) | Composition | Isotope ratios |
|---------------------|------------|-------------|----------------|
|                     | \( ^{206}\text{Pb}/^{238}\text{U} \pm 2\sigma \) | Pb\(^{a}\) [pg] | \( ^{207}\text{Pb}/^{206}\text{Pb} \pm 2\sigma \) |
| Tem-12              | 425.3 0.9  | 422.0 11.0  | 407 67 0.92  |
|                     | 422.0 11.0 | 407 67 0.92 | 3.4 4.67 8.40 3.7 2.24 10.8 |
|                     | 206.0/204.0 | 15.8 3.4 4.76 | 8.0 3.7 2.24 10.8 |
|                     | 206.0/204.0 | 207.0/235.0 | 206.0/238.0 |
| Tem-13              | 429.5 1.8  | 422.2 22.8  | 388 139 0.96 |
|                     | 422.2 22.8 | 388 139 0.96 | 15.8 3.4 4.76 | 8.0 3.7 2.24 10.8 |
|                     | 206.0/204.0 | 207.0/235.0 | 206.0/238.0 |

Sample 1

| Sample | Date (Ma) | Pb\(^{a}\) [pg] | \( ^{207}\text{Pb}/^{206}\text{Pb} \pm 2\sigma \) |
|--------|-----------|-----------------|-----------------|
| 1-1    | 295.0 0.1 | 296.0 0.5 304 5 | 0.25 2.88 94.0 1.0 94.7 |
| 1-2    | 297.6 0.9 | 297.7 1.3 299 8 | 0.69 0.43 81.3 1.2 66.4 |
| 1-3    | 296.9 0.3 | 297.2 1.8 299 16 | 0.15 0.83 53.1 1.9 28.0 |
| 1-4    | 296.4 0.4 | 297.3 0.6 304 3 | 0.88 2.57 208 1.3 162 |
| 1-5    | 295.7 0.2 | 296.2 1.1 300 10 | 0.19 1.34 38.6 0.9 44.2 |
| 1-6    | 295.8 0.2 | 297.3 0.5 309 4 | 0.40 4.42 85.3 0.7 120 |
| 1-7    | 296.5 0.2 | 297.4 1.3 305 11 | 0.17 2.83 28.9 0.7 38.7 |
| 1-8    | 296.3 1.5 | 300.4 4.4 333 36 | 0.31 11.1 84.8 7.3 11.6 |
| 1-9    | 297.3 1.4 | 308.3 7.5 392 63 | 0.16 24.2 37.3 6.0 6.23 |

Sample 2

| Sample | Date (Ma) | Pb\(^{a}\) [pg] | \( ^{207}\text{Pb}/^{206}\text{Pb} \pm 2\sigma \) |
|--------|-----------|-----------------|-----------------|
| 2-1    | 296.0 0.3 | 299.6 1.6 328 14 | 0.15 9.65 198 6.7 29.6 |
| 2-2    | 296.8 0.3 | 300.0 2.9 326 25 | 0.09 8.88 113 6.8 16.7 |
| 2-3    | 297.4 0.4 | 299.7 1.7 317 15 | 0.18 6.17 180 6.4 28.3 |
| 2-4    | 297.3 1.1 | 299.8 6.9 319 60 | 0.13 6.94 104 15 7.08 |
| 2-5    | 296.6 0.7 | 298.6 3.3 314 29 | 0.18 5.64 195 13 14.9 |
| 2-6    | 296.4 0.6 | 298.8 2.6 317 22 | 0.21 6.62 135 7.4 18.3 |
| 2-7    | 296.7 0.3 | 300.4 3.4 329 30 | 0.08 9.85 75.8 5.3 14.4 |
| 2-8    | 297.0 0.4 | 300.4 4.1 327 35 | 0.08 9.15 67.3 5.7 11.8 |
| 2-9    | 296.4 1.4 | 300.2 23.1 329 202 | 0.01 9.92 22.1 9.6 2.42 |

Sample 3

| Sample | Date (Ma) | Pb\(^{a}\) [pg] | \( ^{207}\text{Pb}/^{206}\text{Pb} \pm 2\sigma \) |
|--------|-----------|-----------------|-----------------|
| 3-1    | 298.1 0.2 | 299.3 1.5 308 13 | 0.17 3.31 11.5 3.5 33.0 |
| 3-2    | 299.3 0.3 | 299.9 2.1 305 19 | 0.12 1.73 57.1 2.3 24.9 |
| 3-3    | 297.6 0.2 | 298.1 1.7 302 15 | 0.10 1.51 47.2 1.5 30.8 |
| 3-4    | 297.1 0.3 | 298.1 0.4 306 3 | 0.59 3.05 307 1.9 165 |
| 3-5    | 297.5 0.3 | 298.6 0.8 307 7 | 0.30 3.14 111 1.8 63.3 |
| 3-6    | 296.9 0.1 | 298.1 0.4 307 4 | 0.34 3.32 97.5 0.8 116 |
| 3-8    | 297.6 2.4 | 297.0 4.1 292 32 | 0.50 1.86 114 9.4 12.2 |
| 3-9    | 301.2 1.2 | 301.8 8.3 306 72 | 0.11 1.72 73.5 13 5.82 |
Table 2 (continued)

| Fraction and sample | Dates (Ma) | Composition | Isotope ratios |
|---------------------|------------|-------------|----------------|
|                     | $^{206}\text{Pb}/^{238}\text{U}$ | $^{207}\text{Pb}/^{235}\text{U}$ | $^{206}\text{Pb}/^{208}\text{Pb}$ | Corr. Coeff | Pb% | Pb% | Pb% | Pb% | Pb% | Pb% | Pb% |
|                     | $\pm 2\sigma$ | $\pm 2\sigma$ | $\pm 2\sigma$ | $\pm 2\sigma$ | $\pm 2\sigma$ | $\pm 2\sigma$ | $\pm 2\sigma$ | $\pm 2\sigma$ | $\pm 2\sigma$ | $\pm 2\sigma$ | $\pm 2\sigma$ |
| Sample 4            |            |             |             |             |      |      |      |      |      |      |      |
| Sample 5            |            |             |             |             |      |      |      |      |      |      |      |
| Sample 6            |            |             |             |             |      |      |      |      |      |      |      |
Table 2 (continued)

| Fraction and sample | Dates (Ma) | Composition | Isotope ratios |
|---------------------|------------|-------------|----------------|
|                     | $^{206}\text{Pb}/^{238}\text{U} \pm 2\sigma$ | $^{207}\text{Pb}/^{235}\text{U} \pm 2\sigma$ | $^{207}\text{Pb}/^{206}\text{Pb} \pm 2\sigma$ | Corr. Coeff | $^{206}\text{Pb}^*$ Pb$^c$ [pg] | $^{206}\text{Pb}^*/^{204}\text{Pb}$ | $^{207}\text{Pb}^{206}\text{Pb} \pm 2\sigma$ | $^{207}\text{Pb}^{235}\text{U} \pm 2\sigma$ |
|                     | (abso- | (abso- | (abso- | b | c | d | e | f | g | h | i | j | k | l |
|                     | lute) | lute) | lute) | | | | | | | | | | |
| 6-5                 | 299.9   | 0.7    | 300.1  | 9.5 | 302  | 83  | 0.08 | 0.69 | 3.2 | 5.74 | 326 | 0.0476 | 0.24 | 0.3439 | 3.66 | 0.0524 | 3.65 |
| 6-6                 | 295.3   | 0.7    | 298.3  | 9.7 | 321  | 85  | 0.03 | 8.12 | 4.1 | 5.79 | 321 | 0.0469 | 0.23 | 0.3415 | 3.75 | 0.0528 | 3.75 |
| 6-7                 | 300.0   | 0.4    | 302.3  | 5.0 | 320  | 44  | 0.06 | 6.36 | 3.3 | 11.1 | 607 | 0.0476 | 0.15 | 0.3468 | 1.93 | 0.0528 | 1.92 |
| 6-8                 | 299.8   | 0.7    | 302.3  | 9.8 | 322  | 85  | 0.03 | 6.36 | 4.0 | 6.28 | 323 | 0.0476 | 0.22 | 0.3468 | 3.73 | 0.0528 | 3.73 |
| 6-9                 | 300.4   | 0.6    | 301.2  | 4.7 | 307  | 41  | 0.11 | 2.28 | 3.2 | 11.9 | 643 | 0.0477 | 0.19 | 0.3453 | 1.81 | 0.0525 | 1.80 |
| Sample 7            |          |        |        |    |      |    |      |    |      |    |      |    |      |    |      |    |
| 7-2                 | 298.0   | 0.6    | 301.0  | 7.0 | 324  | 61  | 0.05 | 8.03 | 5.9 | 7.92 | 441 | 0.0473 | 0.21 | 0.3450 | 2.68 | 0.0529 | 2.68 |
| 7-3                 | 298.9   | 0.6    | 301.7  | 8.6 | 323  | 75  | 0.04 | 7.44 | 3.6 | 6.81 | 362 | 0.0475 | 0.20 | 0.3460 | 3.30 | 0.0529 | 3.30 |
| 7-4                 | 298.9   | 0.4    | 301.2  | 4.1 | 319  | 36  | 0.08 | 6.44 | 3.4 | 14.5 | 741 | 0.0475 | 0.15 | 0.3453 | 1.57 | 0.0528 | 1.57 |
| 7-5                 | 299.7   | 0.6    | 302.6  | 8.7 | 325  | 75  | 0.03 | 7.86 | 3.4 | 7.18 | 357 | 0.0476 | 0.22 | 0.3472 | 3.31 | 0.0529 | 3.31 |
| 7-6                 | 299.9   | 0.7    | 301.5  | 6.0 | 314  | 52  | 0.09 | 4.88 | 3.5 | 9.69 | 516 | 0.0476 | 0.22 | 0.3457 | 2.29 | 0.0527 | 2.28 |
| 7-7                 | 299.6   | 0.5    | 301.6  | 4.8 | 317  | 42  | 0.11 | 5.53 | 3.5 | 11.2 | 629 | 0.0476 | 0.18 | 0.3458 | 1.84 | 0.0527 | 1.83 |
| 7-8                 | 299.5   | 0.4    | 301.8  | 4.6 | 320  | 40  | 0.08 | 6.45 | 3.2 | 12.0 | 656 | 0.0476 | 0.14 | 0.3462 | 1.76 | 0.0528 | 1.76 |
| 7-9                 | 299.3   | 0.5    | 301.5  | 6.0 | 319  | 52  | 0.03 | 6.14 | 3.1 | 9.57 | 512 | 0.0475 | 0.16 | 0.3458 | 2.29 | 0.0528 | 2.29 |
| 7-10                | 298.9   | 0.4    | 302.5  | 4.6 | 331  | 40  | 0.05 | 9.66 | 3.2 | 12.7 | 656 | 0.0475 | 0.12 | 0.3471 | 1.78 | 0.0530 | 1.77 |
| 7-11                | 299.7   | 0.5    | 302.3  | 6.9 | 322  | 60  | 0.03 | 6.96 | 3.3 | 7.96 | 451 | 0.0476 | 0.16 | 0.3468 | 2.63 | 0.0528 | 2.63 |

a—Isotopic dates calculated using $\lambda_{238} = 1.55125 \times 10^{-10}$ (Jaffey et al. 1971) and $\lambda_{235} = 9.8485 \times 10^{-10}$ (Jaffey et al. 1971)
b—$\%$ discordance = 100 – (100×($^{206}\text{Pb}/^{238}\text{U}$ date)/($^{207}\text{Pb}/^{206}\text{Pb}$ date))
c—Total mass of radiogenic Pb
d—Total mass of common Pb
e—Ratio of radiogenic Pb (including $^{208}\text{Pb}$) to common Pb
f—Measured ratio corrected for fractionation and spike contribution only
g—Measured ratios corrected for fractionation, tracer and blank
Discussion

New radiometric zircon ages

We discuss the results in stratigraphic order, first with regard to the lithostratigraphic subdivision of the TFB, then to the biostratigraphic aspects. In the following, we use the error expressed as $z$ that also includes the error in tracer calibration and that of the decay constant (see above). This allows us to compare our ages to those obtained with other tracers and other dating systems.

Samples 7 and 6 yielded identical (within errors) $^{206}\text{Pb}/^{238}\text{U}$ mean ages ($299.7 \pm 0.4 \text{ Ma vs. } 300.0 \pm 0.5 \text{ Ma}$) representing the age of the Möhrenbach Formation. Considering the uncertain lithostratigraphic relation between the two sample sites (compare with Section “Geological setting”), the results of samples 7 and 6 clearly indicate an age in the range between 300.5 Ma and 299.3 Ma for the middle to upper part of the Möhrenbach Formation. Consequently, the Möhrenbach Formation was deposited during the latest Carboniferous, i.e., the Gzhelian (Standard Global Chronostratigraphic Scale) or Stephanian (West European regional scale).

Our new age of the Ilmenau Formation (sample 3) is the first precise depositional age for this unit. The sample dates the Kickelhahn Rhyolite near Manebach to $299.3 \pm 0.3 \text{ Ma}$. This age overlaps with the recorded age of the Carboniferous–Permain boundary ($298.90 \pm 0.15 \text{ Ma}$; International Chronostratigraphic Chart 2019/05; the age was obtained by the same U–Pb CA–ID–TIMS method using the 535 spike; Ramezani et al. 2007). Thus, the age of the Kickelhahn Rhyolite provides important information for the stratigraphic position of the C–P boundary in the Thuringian Forest Basin, which has long been discussed as not exactly known.

After mapping the TFB on a scale of 1: 25,000, Beyenschlag (1895: p. 599) concluded that “late” Carboniferous deposits are missing in the Thuringian Forest and that the entire sequence belongs to the Rotliegend (synonym for “Lower” Permian). Later, Gothan (1928) described from the basal, coal-seam-bearing sediments at the Öhrenkammer near Ruhla (letter A in Fig. 2) a peat-forming flora with Stephanian characteristic forms, which (supposedly) no longer occur in the Rotliegend. The Stephanian age of the Öhrenkammer and Ilmtal horizons (letters A and B, Fig. 2)
was also confirmed by the fauna of insects and amphibians (Schneider 1996; Schneider and Werneburg 2006, 2012). From then on, the C–P boundary was assumed to be undefined in the overlying volcanic sequence. Barthel and Rößler (2010) described plant remains from a silicified tuff horizon at the base of the Ilmenau Formation on the Lindenberg hill near Ilmenau (letter C in Fig. 2) as a typical Rotliegend flora. According to this assessment, the C–P boundary was "tentatively" assumed at the base of the Ilmenau Formation (Lützner et al. 2012; Gebhardt et al. 2018; Schneider et al. 2020).

The Kickelhahn Rhyolite (near Manebach village) is only covered by 10–15 m of tuffaceous conglomerates, above which the Manebach Formation begins with grey fluviatile sandstones. In the northwestern part of the Thuringian Forest, above an approx. 100 m thick rhyolite, 30 m of grey to black, fossil-rich lake sediments with tuff layers and subeffusive mafic rocks follow (formerly called “Melaphyr”). These rocks are covered by gray sandstones of the Manebach Formation. Considering the low thickness of post-rhyolitic volcanoclastic sedimentation, we estimate that the C–P boundary should be positioned approximately

![Fig. 5](image-url)  
Compilation of age data from the Rotliegend section of the Thuringian Forest. Radiometric age data are from a Goll and Lippolt (2001), b Zeh and Brätz (2000), c Lützner et al. (2007). The blue bars show the tentative assessment of the Thuringian Forest formations to the International Stratigraphic Chart 2019 after d Schneider and Werneburg (2012), e Menning et al. (2016; explanatory notes in Gebhardt et al. 2018) and f Schneider et al. (2020). Our new CA–ID–TIMS ages are shown in red. Numbers in yellow boxes are sample numbers for new zircon U–Pb CA–ID–TIMS dating. Obviously, most of the previous age data and assessments are remarkably younger than the new zircon ages.
at the boundary between the Ilmenau and Manebach Formations (cp. Fig. 5).

The U–Pb zircon age of a silicified tuff layer from the middle part of the Manebach Formation was determined to be 297.8 ± 2.0 Ma by laser ICP–MS (Trümper et al. 2020). This finding fits well with the result of sample 5 (Fig. 6).

Our new data suggest an age difference of about 2.5 Myr between sample 5 and sample 3. During this time, the Manebach and Goldlauter Formations filled a pull-apart basin with paludal, lacustrine, fluvial, and alluvial sediments. The thickness of both formations is nearly 1000 m, i.e., the rate of subsidence (uncorrected) corresponds to about 400 m/Myr. Such subsidence rates are common in grabens/riift settings (e.g., Einsele 1992; Dogliioni et al. 1998) and can reach extreme values in pull-apart basins like in the Ridge Basin in California (e.g., Yeats 1978: 2000 m/Myr).

Samples 3 and 2 reflect the culmination of the second volcanic phase within the TFB, which occurred in the range between 296 and 297 Ma. In future studies, it will be possible to better constrain the age of the Oberhof Formation by dating the rhyolites at the base (Heuberg- and Inselsberg Rhyolite) and the coarse crystalline Greifenberg rhyolite in dome structures near the upper boundary at the site of Großer Buchenberg near Tambach-Dietharz.

The age of the Komberg Rhyolite intrusion is provided by sample 1 and dates the red beds of the Rotterode Formation. As this formation clearly overlies the Oberhof Formation, the youngest zircon age of this sample (295.8 ± 0.4 Ma) is in agreement with the stratigraphy.

Sample 4 was dated with the idea of determining a representative age for the Elgersburg Formation. However, the obtained age is much older than expected; similar to that of the Möhrenbach Formation. The Wolfstein Rhyolite is directly bordered by the Schöffenhaus fault that dislocates the Elgersburg Formation against members of the Ilmenau Formation and the Oberhof or (in question) Rotterode Formations. Thus, we suggest that the Wolfstein Rhyolite could be interpreted as a small, tectonically uplifted block. Similar small uplifted blocks are well known from faults along the southwestern margin of the Thuringian Forest. The rock type of the Wolfstein Rhyolite with especially large phenocrysts of quartz and feldspar occurs within the Möhrenbach Formation as a widely ramified rhyolite dyke system. It has been described as Meyersgrund Rhyolite by Zimmermann (in Loretz et al. 1908: p. 100, 126), named after a tributary valley of the Ilm river.

In most occurrences of this Meyersgrund Rhyolite, the large quartz and feldspar phenocrysts are very fresh. In

### Table: Basins in Germany, Czech/Polish Basins, and Basins in France

| Basins in Germany | CBz/Polish Basins | Basins in France |
|-------------------|-------------------|------------------|
| **Thuringian Forest Basin** | **SBN** | **HB** | **SB** | **DB** | **BF** | **ISB** | **RB** | **AB** |
| **Amphibolite Formation** | | | | | | | | |
| **Samples** | **CA-ID-TIMS** | **LA-ICP-MS** |
| **Sample** | **Age** | **Sample** | **Age** | **Sample** | **Age** | **Sample** | **Age** | **Sample** | **Age** |
| **Tambach-Fm** | **Elgersburg-Fm** | | | | | | | | |
| **J** | 296.8 ± 0.4 Ma | 297.8 ± 0.4 Ma | 296.9 ± 0.4 Ma | 297.8 ± 0.4 Ma | | | | | |
| **Rotterode-Fm** | | | | | | | | | |
| **I** | 296.8 ± 0.4 Ma | | | | | | | | |
| **Oberhof-Fm** | | | | | | | | | |
| **H** | 296.8 ± 0.4 Ma | | | | | | | | |
| **Goldlauter-Fm** | | | | | | | | | |
| **G** | 296.8 ± 0.4 Ma | 297.8 ± 0.4 Ma | | | 297.1 ± 0.3 Ma | | | |
| **Manebach-Fm** | | | | | | | | | |
| **E** | 296.8 ± 0.4 Ma | 297.8 ± 0.4 Ma | | | | | | | |
| **Ilmenau-Fm** | | | | | | | | | |
| **D** | 296.8 ± 0.4 Ma | 297.8 ± 0.4 Ma | | | | | | | |
| **Georgenthal-Fm** | | | | | | | | | |
| **A, B** | 300.0 ± 0.5 Ma | 299.7 ± 0.4 Ma | | | | | | | |
| **C** | | | | | | | | | |

**Basins:** SBN - Saar-Nahe Basin, HB - Hessian Basin, SB - Saale Basin, DB - Döhllin Basin, BF - Boskovicz Forell, ISB - Intrausudetic Basin, RB - Roudnice Basin, AB - Autobahn Basin.

**CA-ID-TIMS ages:** All errors are given as ± values including uncertainties for tracer calibration and for the decay constant. In the TFB, all samples represent rhyolites.

**References:** 1 - Wernberg in Schneider et al. (2020), 2 - Schneider et al. (2020), 3 - this study: 4 - Opdustil et al. (2016), 5 - Opdustil et al. (2017), 6 - Penlend et al. (2017), 7 - Trümper et al. (2020).

**Fig. 6 CA-ID-TIMS U–Pb zircon age data of the TFB and surrounding basins in relation to biostratigraphic zoning based on amphibians and insects.**
contrast, the Wolfstein Rhyolite is found in a highly altered state. In the small outcrop area, the rock is often so strongly weathered that the phenocrysts can only be recognized as hollow forms. It is possible that the fluid movements on the Schöffenhaus fault zone led to a particularly strong alteration. The result of sample 4 is also difficult to interpret due to the wide dispersion of the single grain ages and the low cluster density. For example, taking only the two youngest dates as clusters, the resulting age would be almost identical with sample 1, close to the expected age of the Elgersburg Formation.

The new zircon data for the profile of Carboniferous–Permian volcanic rocks in the TFB show older ages compared to the previously published age data (Fig. 5; data in summarized form in Lützner et al. 2012). This reflects the fact that the pre-treatment of the dated zircons by CA removed those components that suffered severe Pb loss. For most dated samples, the still-existing slight Pb loss resulted in few single ages that are 1–2 Ma younger than the calculated mean age (Fig. 4). Exceptions are sample 4 (which still has pronounced Pb loss; many single grain ages are up to 4 Ma younger) and one measurement of sample 6 (that is 5 Ma younger than the mean age). In general, the new zircon ages (single zircon ages as well as mean sample ages) show less age scatter than those of earlier publications. Consequently, the total duration of the volcanic activity in the TFB was considerably shorter. Whereas previously an age interval between 295 and 275 Ma was expected for the interval between the Möhrenbach Formation and the Elgersburg Formation (Lützner et al. 2007), our new data suggest a range between ca. 300 Ma for the Möhrenbach Formation and ca. 296 Ma for the Rotterode Formation. Even if the age of the youngest rhyolite (Elgersburg) has not yet been determined, the total duration of volcanic activity has to be reduced from ca. 20 Myr to ca. 4 Myr. The sedimentary gap up to the Illawarra Reversal (ca. 265 Ma after Isozaki 2009; 266.66 ± 0.76 Ma after Hounslow and Balabanov 2018; base of Upper Rotliegend II) therefore has to be extended to > 25 Myr. This result requires a new view on the early evolution of the Thuringian Forest Basin. The sedimentary hiatus, which can extend locally to 30 Myr in Northern Germany (e.g., between Permian volcanics and the Wustrow Member as the oldest Permian sediment), is at least partially caused by volcano-topographic features (morphology) besides intrabasinal tectonics according to Geißler et al. (2008). Further work is required to evaluate this hiatus in sedimentation for the TFB region as well.

Comparison to biostratigraphic data

The modern state of biostratigraphy in the continental basins of Pangea has been summarized by Schneider et al. (2020). The authors describe “biostratigraphic timelines” which are calibrated for Europe and North America by marine zone fossils and are dated for certain levels by radioisotopic zircon ages (including U–Pb CA–ID–TIMS zircon ages) from the Bashkirian (early Pennsylvanian: ca. 319 Ma) to the late Asselian (early Cisuralian: ca. 295 Ma). On this basis, stratigraphic correlations can be done at a local and regional scale. However, there are only a few continental basins at the Pangea margins that are well linked to the global marine standard biostratigraphy. Accordingly, more chronostratigraphic data from Pangea continental basins are urgently needed.

In the TFB, biostratigraphy is well investigated in the sedimentary record. Collecting biostratigraphic data (occurrences) and evaluating biostratigraphic events (first and last appearances) have been used to establish biostratigraphic zoning for insects, especially cockroach wings, for amphibians, vertebrate foot prints and conchostraca as well. However, the correlation with biostratigraphic data in continental Carboniferous and Permian basins is partially problematic (e.g., Schneider et al. 2020). Comparison of Fig. 2 of Schneider et al. (2020) with our new age data for the formations near the Carboniferous–Permian boundary (Möhrenbach Fm. plus Ilmenau Fm. = Gehren subgroup) indicates that both datasets are compatible. However, contradictory interpretations are obtained for the Rotterode Formation: According to our new ages, the Rotterode Formation corresponds to the Asselian Stage while Schneider et al. (2020) place the Rotterode Formation in the Artinskian Stage.

Schneider and Werneburg (2006, 2012) biostratigraphically correlated the Ilmtal fossiliferous horizon in the Möhrenbach Formation (letter B in Fig. 2 and Fig. 6) with the Breitenbach Formation (Saar–Nahe Basin) and the Wetting Subformation (Saale Basin) on the basis of index fossils of the Branchiopetona saalensis–Apatone intermedius assemblage zone (amphibians) and of the Sysciophlebia euglyptica–Syscioblatta dohnri assemblage zone (insect wings). Schneider et al. (2020) have inferred the late Stephanian (late Gzhelian) time from a zircon SHRIMP age of an intrusive rhyolite near Halle (Breitkreuz et al. 2009). The Stephanian age is also confirmed here by the age for the Kickelhahn Rhyolite (Ilmenau Formation).

The next amphibian biozone following upward, i.e., Apatone dracyensis–Melanerpeton sembachense assemblage zone comes from the Sembach fossiliferous horizon near the top of the Ilmenau Formation (letter D in Figs. 2 and 6) and is also reported from the Muse Formation near Dracy St. Loup (Autun basin, France). The upper part of the Muse oil shale is dated between 298.6 ± 0.4 Ma and 298.0 ± 0.4 Ma by the U–Pb CA–ID–TIMS zircon age method (Pellenard et al. 2017; Fig. 6). This fits well to the 299.3 ± 0.3 Ma age of the Kickelhahn Rhyolite when taking into account that the Sembach Horizon is situated at the top of the Ilmenau
Formation and that the Kickelhahn Rhyolite has a somewhat lower position.

Furthermore, the *Sysciophlebia balteata–Spiloblattina homigtalensis* a.z. (insect zone 7), known from the lower Goldlauter Formation in the TFB (letter F in Fig. 2 and Fig. 6), was also discovered in the Ričany Formation, Boskovec Furrow (Czech Republic) (Schneider and Werneburg 2012). There, at the top of the underlying formation, a tuff yielded a CA–ID–TIMS U–Pb zircon age of 298.9 ± 0.4 Ma (Opluštil et al. 2017; Fig. 6). This age stands approximately for the *Sysciophlebia balteata–Spiloblattina homigtalensis* assemblage zone, which had been established in the TFB section by Schneider and Werneburg (2012).

The Goldlauter Formation comprises amphibian zone 5, i.e., *Branchierpeton reinholdi–Apateon flagrifer flagrifer–Melanerpeton eisfeldi* assemblage zone of Werneburg in Schneider et al. (2020) (letters F and G in Figs. 2 and 6). There are no precise radiometric ages for this biostratigraphic zone (Fig. 6).

An important amphibian biozone occurs in the uppermost part of the Oberhof Formation (amphibian zone 7 in Schneider et al. 2020, formerly zone 8 in Schneider and Werneburg 2012, Fig. 8) termed the *Melanerpeton pusillum–Melanerpeton gracile* assemblage zone, found in the Wintersbrunn fossiliferous horizon [syn. Upper *Protriton* Horizon (letter I in Figs. 2 and 6)]. The evidence of this biozone is widespread. It is reported from the Niederhäslich Formation (Döhlen Basin, Saxony), the Schöneck Formation (Hessian Basins), the Humberg Horizon (top of Meisenheim Formation, Saar–Nahe Basin), from several French basins and from the Olevětín Member (Broumov Formation, Intrasudetic Basin) as well (Fig. 6). In the Intrasudetic Basin, this biozone is found in the Ruprechtice limestone horizon in the middle part of the Olevětín Member. Below, at the top of the Nowaruda Member, there occurs the Vraní hory Rhyolite, which is dated by the CA–ID–TIMS U–Pb method of a Stephanian to early Permian (lower Rotliegend) profile in the Thuringian Forest Basin. We draw the following conclusions.

1. First, the results fulfill the expectation that the ages change in the same order as the lithostratigraphic sequence. That is, formations following one another in the order given by lithological mapping yielded zircon ages from older to younger in the same order. Sample 4 is an exception that can be explained by the local tectonics of this sample site.

2. New geochronological results for the Ilmenau Formation (sample 5) and the Oberhof Formation (samples 2 and 3) indicate an age difference of 2.5 Myr between both formations, indicating a ca. 2.5 Myr quiescent magmatic period for the predominantly sedimentary Manebach and Goldlauter Formations. This is in accordance with different biostratigraphic zones. However, still-existing discrepancies between biostratigraphy and geochronology have to be resolved by further geochronological dating and additional paleobiological data.

3. The zircon ages of sample 5 (Kickelhahn Rhyolite, Ilmenau Formation) and the two rhyolite samples (samples 6 and 7, Möhrenbach Formation) are very close to the internationally valid chronostratigraphic Carboniferous–Permian boundary (International Chronostratigraphic Chart 2019) at 298.90 ± 0.15 Ma. Based on the new Kickelhahn Rhyolite zircon age, we assume that the position of the C–P boundary should be located at the base of the Manebach Formation. Consequently, the position of the C–P boundary in the TFB could be established more precisely compared to previous estimates.

4. Compared to earlier concepts, the new zircon ages indicate that the total duration of the volcanic activity in the TFB was considerably shorter. Whereas previously an age interval between 295 and 275 Ma was expected for the whole volcanic period in the TFB, now the range is reduced to a period from ca. 300 Ma (Möhrenbach Formation) to ca. 296 Ma (Rotterode Formation). Consequently, the total duration of volcanic activity is shortened from ca. 20 Myr to ca. 4 Myr. We consider the pre-treatment of the dated zircons by chemical abrasion an important procedure in removing zircon parts with strong Pb loss, e.g., due to late magmatic–hydrothermal activities, that resulted in exceedingly young ages in previous studies.

5. Consequently, the possible time span from the early Permian volcanic rocks (top Rotterode Formation) up to the Illawarra Reversal has to be extended to ca. 30 Myr. This
result requires a new view on the evolution of the TFB. This stratigraphic interval can cover 25–30 Myr in parts of the external Variscides.

6. Our newly obtained ages of the dated TFB formations that contain important biostratigraphic fossils can be used as time marks for certain biostratigraphic zones in other continental late Carboniferous–early Permian basins.

7. In the future, the chronostratigraphic sequence in the Thuringian Forest could be even more precisely defined by dating the Inselsberg and/or Heuberg Rhyolite as a mark for the base of the Oberhof Formation, and the Elgersburg Rhyolite as a mark for the youngest rhyolite. In addition, new age data from the other continental basins are urgently needed, in particular from the Saar–Nahe Basin, the Saale Basin near Halle and the Chemnitz Basin. Such new data will allow the definition of volcanic–subvolcanic–plutonic complexes as genetic systems and the assessment of their geochemical signatures, thermal history, and magmatic–hydrothermal evolution in an integrated way.

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