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ORIGINAL PAPER

Reworked Middle Jurassic sandstones as a marker for Upper Cretaceous basin inversion in Central Europe—a case study for the U–Pb detrital zircon record of the Upper Cretaceous Schmilka section and their implication for the sedimentary cover of the Lausitz Block (Saxony, Germany)

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Abstract The Saxonian–Bohemian Cretaceous Basin (Elbsandsteingebirge, E Germany and Czech Republic, Elbtal Group) comprises Upper Cretaceous sedimentary rocks from Upper Cenomanian to Santonian age. These sandstones were deposited in a narrow strait of the sea linking the northern Boreal shelf to the southern Tethyan areas. They were situated between the West Sudetic Island in the north and the Mid-European Island in the south. As known by former studies (e.g. Tröger, Geologie 6/7:717–730, 1964; Tröger, Geologie von Sachsen, Schweizerbart, 311–358, 2008; Voigt and Tröger, Proceedings of the 4th International Cretaceous Symposium, 275–290, 1996; Voigt, Dissertation, TU Bergakademie Freiberg, 1–130, 1995; Voigt, Zeitschrift der geologischen Wissenschaften 37(1-2): 15–39, 2009; Wilmsen et al., Freiberger Forschungshefte C540: 27–45, 2011) the main sedimentary input came from the north (Lausitz Block, southern West-Sudetic Island). A section of Turonian to Coniacian sandstones was sampled in the Elbsandsteingebirge near Schmilka (Elbtal Group, Saxony, Germany). The samples were analysed for their U–Pb age record of detrital zircon using LA-ICP-MS techniques. The results show main age clusters typical for the Bohemian Massif (local material) and are interpreted to reflect the erosion of uniform quartz-dominated sediments and basement rocks. Surprisingly, these rocks lack an expected Upper Proterozoic to Lower Palaeozoic age peak, which would be typical for the basement of the adjacent Lausitz Block (c. 540–c. 560 Ma). Therefore, the Lausitz Block basement must have been covered by younger sediments that acted as source rocks during deposition of the Elbtal Group. The sandstones of the Elbe valley (Elbtal Group, Schmilka section) represent the re-deposited sedimentary cover of the Lausitz Block in inverse order. This cover comprised Permian, Triassic, Jurassic and Lower Cretaceous deposits, which are eroded already today and cannot be investigated. Within the samples of the Elbtal Group (Schmilka section), the zircon age patterns change significantly towards the Lower Coniacian (topmost sample of the analysed section), where a major input of Meso- and Paleoproterozoic grains was obtained. Comparable ages are generally scarce in the working area. To have a reference for the detrital zircon age spectra of Triassic and Jurassic sediments of the area, two Upper Triassic und two Middle Jurassic clastic sediments of Germany were analysed. Surprisingly, the two Middle Jurassic (Dogger) sandstones from Bavaria and Lower Saxony showed similar detrital zircon age compositions as the Coniacian sediments on top of the Schmilka section (Elbe valley, Elbtal Group). In contrast, the two Upper Triassic sediments could be excluded as possible source rocks for the Upper Cretaceous sandstones of the Elbe valley (Schmilka section, Elbtal Group). The Meso- and Paleoproterozoic zircon age populations in the uppermost sandstone sample of the Schmilka section are

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assumed to originate from recycled Jurassic (Dogger) sandstones, resting on the Lausitz Block. These Middle Jurassic deposits were strongly influenced by a sedimentary input from the Scandinavian region (southern Baltica and North Sea Dome). The Turonian sandstones of the Schmilka section (samples below the topmost Coniacian sample) are interpreted to represent re-deposited Lower Cretaceous sediments resting on the Lausitz Block. A proposed synsedimentary uplift of about 5 km during the Upper Cretaceous along the Lausitz Fold (Lange et al., Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 159(1):123–132, 2008) would have caused erosion of the pre-existing sedimentary cover of the Lausitz Block followed by inverse accumulation of the detritus into the Cretaceous Basin (Elbe valley, Elbtal Group). The Permian and Triassic cover units of the Lausitz Block were not exposed during the Upper Cretaceous, but are assumed to have contributed to younger (post-Coniacian) sediments of the Elbtal Group, which were eroded during uppermost Cretaceous and lower Paleogene. Based on this study, the detrital zircon record of the Jurassic Dogger sandstones of Germany can be seen as “marker ages” for the European Cretaceous Basin inversion. This paper presents the first results of a case study with further investigations in other areas of Europe to follow.

Keywords Middle Jurassic · Upper Cretaceous · Schmilka · Lausitz Block · Zircon U–Pb geochronology · Provenance

Introduction

Provenance analysis has experienced a significant upturn due to geochronological analyses during the last years. Especially, age distribution of detrital zircon grains has become a powerful tool in provenance analysis (Fedo et al. 2003). Zircon has both, a very high weathering resistance and thermal stability and can therefore be used in sedimentary sequences of high textural maturity and in metamorphic sedimentary rocks. Zircon grains can survive several erosion–deposition cycles and might therefore not reflect a direct source area of the sediment that includes them. Besides, signals of discrete source rocks might be diluted. The analysis of slightly more than 100 single detrital grains (at least 117 analyses according to Vermeesch 2004) eliminates disturbances by chance and creates age spectra of statistical significance.

The Central European Basin represents a complex intracontinental upper Paleozoic to Mesozoic basin which underwent phases of extension and compression related to the Pangea break-up and convergence of the African and Eurasian plate (e.g. Ziegler 1990; Scheck and Bayer 1999). Different stages of evolution resulted either in uplift of the basin margins or intrabasinal highs or in deformation of the basin fill during contraction or formation of subbasins, graben shoulder uplift and resulting basin separation during extension.

Provenance of the filling of the Central European Basin was mainly reconstructed on the base of belt extension facies studies (e.g. Ziegler 1990; Geluk and Röhling 1999) or sedimentary structures like cross-bed orientation (e.g. Wurster 1964). It was possible to reconstruct potential source areas based on studies of heavy mineral compositions (e.g. Füchtbauer 1988). In addition, the increasing amount of isotopic analyses leads to new information, and in part, to different ideas and interpretations on the history of some rock samples or entire sample areas.

A very good way to study possible changes in the source area is the comparison of zircon age spectra through a stratigraphic succession. This is especially true, if a possible source area experienced strong uplift and might, therefore (1) exhume new source rocks for erosion and (2) increase the erosion and deposition rates due to higher relief. Studies done by Voigt (1995), Voigt and Tröger (1996), Lange et al. (2008) and others showed that both are true for the Saxonian–Bohemian Upper Cretaceous Basin (Elbe Zone, SE Saxony, E Germany, Fig. 1), which is a part of the Central European Mesozoic Basin. Here, Upper Cretaceous sandstones were deposited in a narrow strait of the sea that links the northern temperate Boreal shelf with the southern warm-water Tethyan areas (Voigt 2009; Wilmsen 2011). It was bordered to the south by the northern part of the Mid-European Island (Bohemian Massif) and to the north by the southern part of West Sudetic Island (Lausitz Block, Fig. 1). Lange et al. (2008) showed an Upper Cretaceous synsedimentary uplift of the Lausitz Block directly situated to the north of this basin. In this study, the change in age spectra of a quartz-dominated sandstone succession (Upper Cretaceous Schmilka section, Figs. 1, 2, 3) which was deposited during Upper Cretaceous basin inversion in Central Europe is presented.

The overall results will show the influence of a today no longer existing Mesozoic sedimentary source, which turns out to have extended over huge areas Mesozoic Germany (maybe even the entire Central Europe). This also has implications for the Cretaceous basin inversion in Germany (as part of Central Europe) and leads to a new interpretation for the source area of the studied rock samples. This paper presents the first results of a case study with further investigations in other areas of Europe to follow.

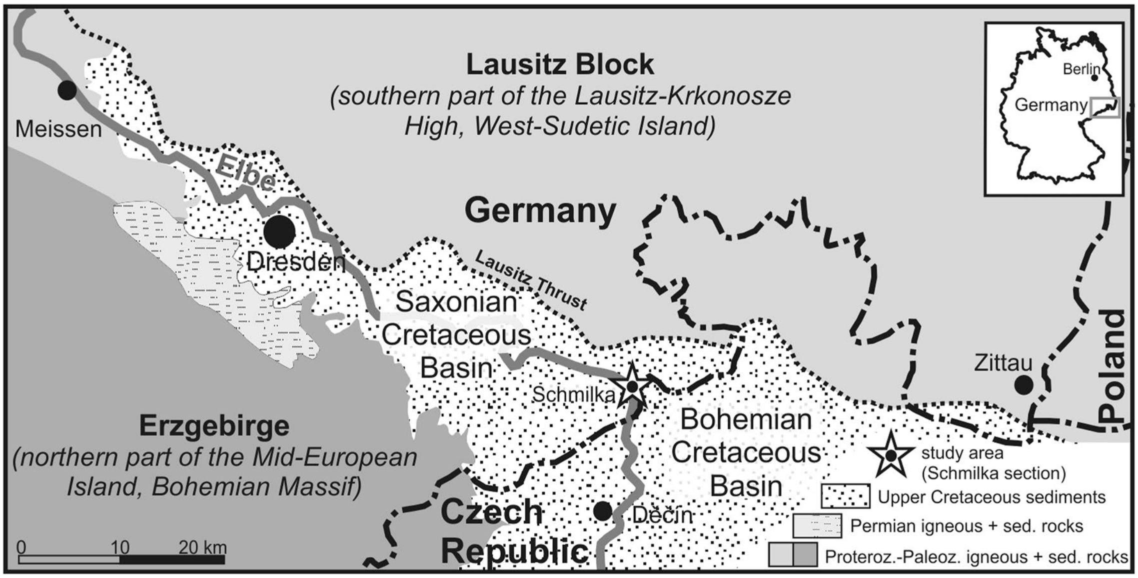


Fig. 1 Geological overview map showing the Saxonian–Bohemian Upper Cretaceous Basin in Saxony (eastern Germany) and in the north-western part of the Czech Republic. The locality of the Schmilka section is indicated by the asterisk. The Upper Cretaceous narrow sea strait was bordered to the north by the West Sudetic Island and to the south by the Bohemian Massif. Map based on Wilmsen et al. (2011)

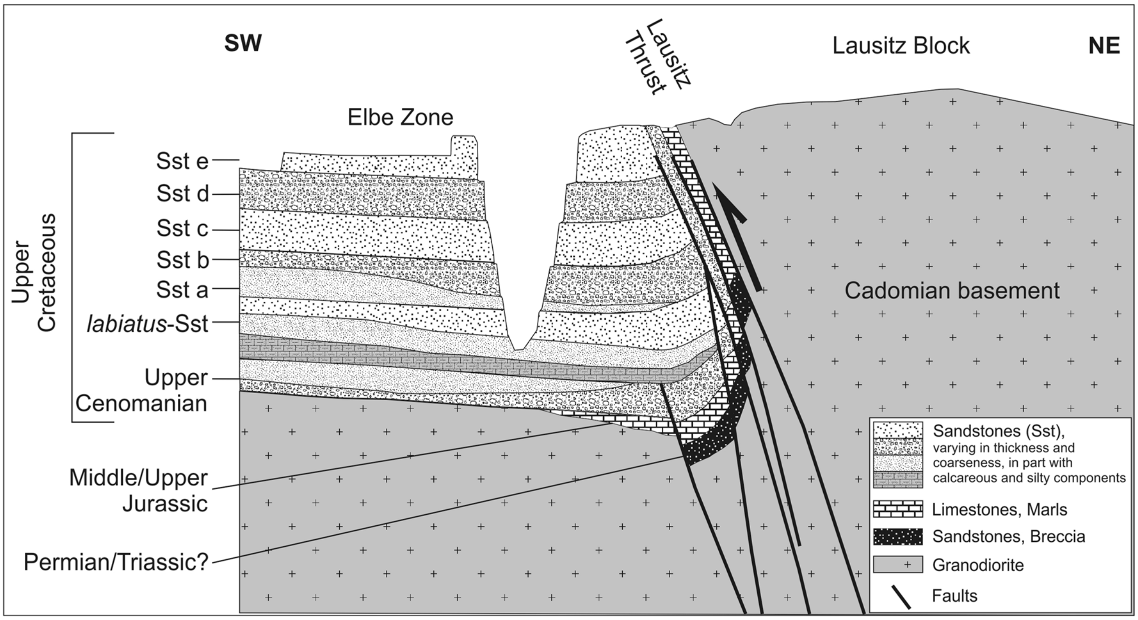


Fig. 2 Idealized cross-section of the Saxonian Cretaceous Basin showing the thrusting of the Lausitz Block on the Mesozoic deposits. Important is the appearance of Jurassic deposits along the fault, which are absent elsewhere in Saxony. Their occurrence below the Cretaceous sedimentary rocks allows the assumption of a widespread Jurassic cover of the Lausitz Block. Figure based on the section in the geological map of the national park Sächsische Schweiz (Lobst 1993)

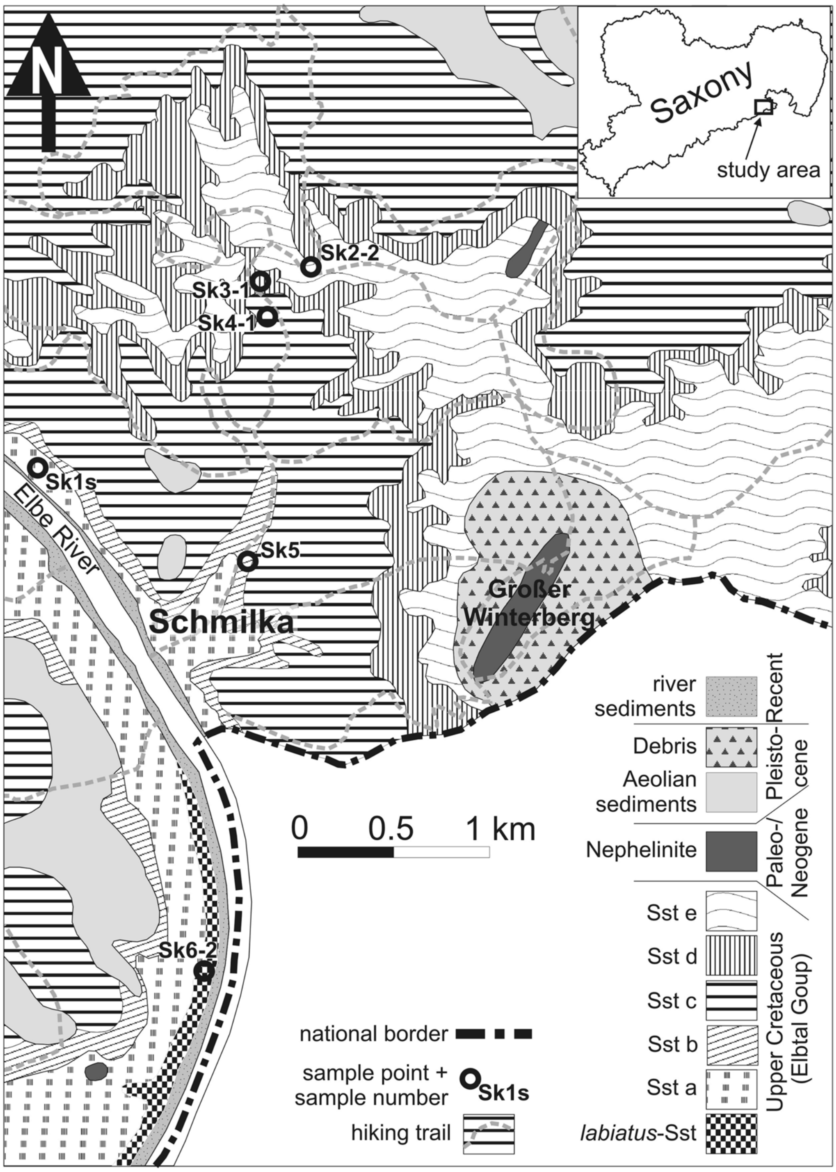


Fig. 3 Geological map of the study area based on the geological map of the national park Sächsische Schweiz (Lobst 1993) showing the upper Cretaceous sedimentary rocks from the lowermost labiatus sandstone (Sst) up to the sandstone e on the top (Schmilka, Postelwitz and Schrammsteine formations). Sample points are indicated

Geological setting

Evolution and sedimentary record of the Central European Basin

After initial rifting and intense volcanic activity during the Lower Permian, a large epicontinental sag basin was formed in Central Europe. It was filled in the initial stage with continental red beds (Upper Rotliegend), followed by thick marine evaporitic sequences (Zechstein Group). According to Ziegler (1990) and others, the clastic sedimentary rocks derived from some persistent source areas located at the basin margin. The biggest part of these sequences is already eroded today, but scattered occurrences show their former extend. As deduced from Fig. 2, few remnants of these once probably very thick successions are still assumed to occur on the base of the study area in the Saxonian Cretaceous Basin (Pietzsch 1963; Lobst 1993). In the north, the Scandinavian High contributed with clastic sediments to the northern Central European Basin margin, while to the south a group of isolated heights such as the Armorican Massif, the Bohemian Massif and possibly the Rhenish Massif, fed the southern basin (Ziegler 1990). This general situation did not change during the Lower and Middle Triassic. The first sedimentological re-organisation of the basin occurred during the early Upper Triassic (Lower Keuper, Erfurt Formation and Middle Keuper, Stuttgart Formation) when the basin was overfilled, opening the way for river sediments from the north and north-east (Wurster 1964; Paul et al. 2008). Paul et al. (2008) found Caledonian K/Ar ages (c. 555 to 665 Ma) within the Upper Triassic sandstones and explained them as the results of rapid uplift of the graben shoulders of the Viking graben and exhumation of the Caledonides of southern Norway.

These ages are also dominant in Middle Jurassic sandstones (Paul et al. 2008). However, in contrast to the situation during Upper Triassic and Lower Jurassic, these Middle Jurassic deposits extent far into the Central European Basin towards the south. Paul et al. (2008) interpreted this as a Cadomian source in the south-east, or alternatively, as a mixture of Fennoscandian and Caledonian ages. This period was followed by intense Upper Jurassic to Lower Cretaceous rifting in Central Europe, creating NW–SE and N–S striking graben structures like the Elbtal halfgraben of the Elbe Zone in Saxony (study area, Figs. 1, 2). After a period of decreasing rifting activity and the Cenomanian transgression (Upper Cretaceous), which led to marine deposition in almost the whole of Central Europe, a complete basin reorganisation started in the Turonian. The convergence of the African plate and Iberia caused compression of the central European crust and the inversion of the Central European Basin system. This can be studied very well in the Saxonian Cretaceous Basin (study area, Schmilka section). Large basement uplifts, inverted graben structures, the reverse activation of normal faults and formation of marginal troughs are the main features of this event. These processes were studied on sediments surrounding the Harz Mountains by von Eynatten et al. (2008). In this case study of an intrabasinal basement high, stepwise exhumation and redeposition of the Mesozoic succession in reverse order was shown. The same approach is the base for this recent study on the sandstones of the Schmilka section.

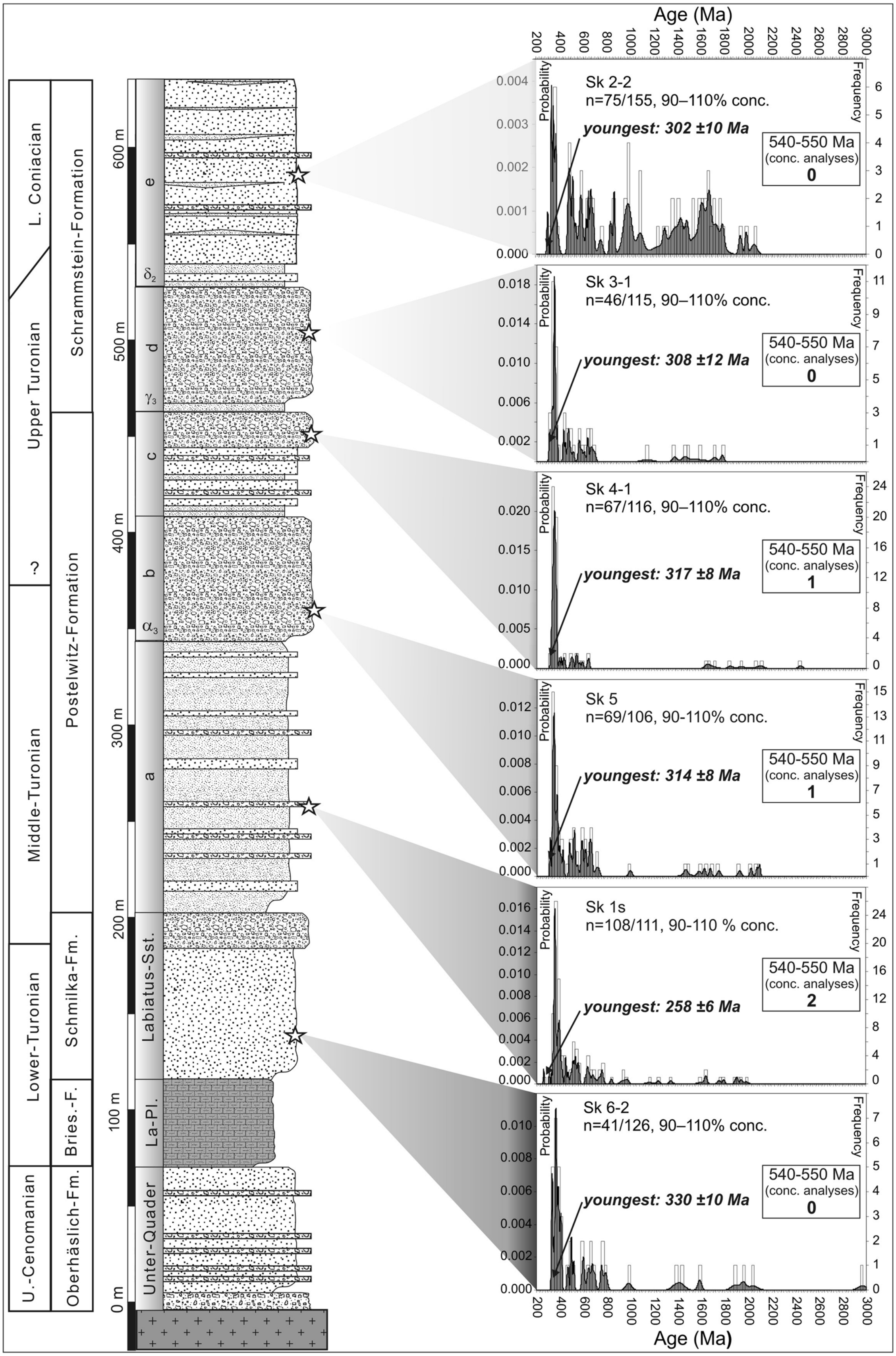
During the Upper Cretaceous, erosion was exceptionally intense at the southern margin of the Central European Basin and continued during the Paleogene (Voigt 2009; Danisik et al. 2010). Uplift resulted in a widespread exhumation of the basement (e.g. Cadomian ages of the Lausitz Block), accompanied by the complete erosion of a 4–10 km thick rock pile of unknown composition (Lange et al. 2008; Danisik et al. 2010). The provenance of the clastic basin fill in the Upper Cretaceous marginal troughs is therefore often enigmatic.

Mesozoic deposits and basin inversion along the Lausitz Thrust (northern border of the Bohemian Massif)

The Saxonian–Bohemian Cretaceous Basin (Fig. 1) represents an inversion-related basin which was established on deeply eroded metamorphic and magmatic units of the Bohemian Massif (Fig. 2). The time gap between erosion of the Variscan mountain system and renewed deposition during Upper Cretaceous spans about 200 Ma (e.g. Ziegler 1990; Voigt 2009). After the Variscan orogeny, the Bohemian Massif acted as a main sediment source area during Upper Permian and Triassic as it is indicated by grain size trends and composition of clastic rocks (Voigt 2009 and others). The geological history during Jurassic and Lower Cretaceous is unknown, because potential sedimentary units of this period were either never deposited (unlikely) or had been removed during later uplift and erosion. The composition of conglomerates and sandstones in the Saxonian–Bohemian Cretaceous Basin reflects erosion of sandstones, ironstones and limestones, while the Precambrian greywackes and granodiorites of the basement of the Bohemian Massif and the West-Sudetic Island did not seem to contribute to the basin fill (Voigt 2009). As mentioned before, the stratigraphy of the eroded sedimentary rocks once lying on top of the basement is unknown and can so far only be assumed on the base of the sparse occurrences of lower Mesozoic sedimentary rocks in Saxony. They are represented by a few limited remains of Lower Triassic sandstones situated north of the Bohemian Cretaceous Basin and some scattered occurrences of Middle Jurassic sandstones and Upper Jurassic limestones along the southern margin of the Lausitz Block, where they became involved in the Lausitz Thrust (Pietzsch 1963; Lobst 1993, Fig. 2).

Upper Cretaceous sedimentary rocks represent the majority of Mesozoic deposits in Saxony and Bohemia. They cover parts of the Bohemian Massif and reach their highest thickness along the Elbe Zone in Saxony, a NW–SE striking fracture zone which was formed in the Lower Carboniferous (late Variscan orogeny) and got re-activated several times during the Upper Paleozoic and Mesozoic (Linnemann 2008; Franke 2000). The Elbe Zone separates the Bohemian Massif (metamorphic rocks and intrusives of the Variscan orogeny) from Cadomian (Upper Proterozoic) greywackes and lower Cambrian granodiorites of the Lausitz Block (Fig. 1).

The Cretaceous sedimentary record of the Elbe Zone starts in the Cenomanian and continues at least to the Lower Coniacian (Figs. 3, 4). The youngest sedimentary rocks in the Saxonian–Bohemian Upper Cretaceous Basin are Santonian. Cenomanian to Santonian sedimentation within the Elbtal Group is characterized by a coarse clastic belt of sandstones passing into marls and claystone towards the west. The whole succession is up to 1000 m thick. It reflects a synsedimentary active source area in the north-east. This source area is the “West-Sudetic Island” (e.g. Tröger 1964; Voigt 2011), which represents the recent Lausitz-Krkonoše High (Fig. 1). Deposition within the Cretaceous Saxonian–Bohemian Cretaceous Basin starts in the Cenomanian with fluvial valley fills (Niederschöna Formation) that are followed by marine sedimentary rocks, spanning from the Upper Cenomanian to Lower Coniacian (Oberhäslich, Schmilka, Postelwitz and Schrammsteine formations), and where existing, Santonian. In the study area around Schmilka, the topmost sandstone units are of Coniacian age (Fig. 4). Santonian deposits can only be found further to the east.


U.-Cenomanian
Lower-Turonian
Middle-Turonian
?
Upper Turonian
L. Coniacian
Oberhäslich-Fm.
Bries.-F.
Schmilka-Fm.
Postelwitz-Formation
Schrammstein-Formation
0 m
100 m
200 m
300 m
400 m
500 m
600 m
Unter-Quader
La-Pl.
Labiatus-Sst.
a
α_3
b
c
γ_3
d
δ_2
e
Age (Ma)
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Probability
Frequency
Sk 2-2
n=75/155, 90–110% conc.
youngest: 302 ±10 Ma
540-550 Ma (conc. analyses) 0
Sk 3-1
n=46/115, 90–110% conc.
youngest: 308 ±12 Ma
540-550 Ma (conc. analyses) 0
Sk 4-1
n=67/116, 90–110% conc.
youngest: 317 ±8 Ma
540-550 Ma (conc. analyses) 1
Sk 5
n=69/106, 90-110% conc.
youngest: 314 ±8 Ma
540-550 Ma (conc. analyses) 1
Sk 1s
n=108/111, 90-110 % conc.
youngest: 258 ±6 Ma
540-550 Ma (conc. analyses) 2
Sk 6-2
n=41/126, 90–110% conc.
youngest: 330 ±10 Ma
540-550 Ma (conc. analyses) 0

◂**Fig. 4** Section for the Elbsandsteingebirge around Schmilka (Großer Winterberg region) based on Lamprecht (1928), Tröger (2008) and own field observations. One sample of each sandstone unit was analysed. Sample points are indicated. AgeDisplay diagrams of all samples are based on 1-sigma errors (Sircombe 2004). All measurements with a degree of concordance between 90 and 110% were regarded as concordant and used for the diagrams. $n=$number of concordant analyses (used for this diagram)/number of all analyses made for this sample. ^{206}Pb/^{238}U ratios were used for age calculation for all ages below 1000 Ma, whereas for older grains ^{207}Pb/^{206}Pb ratios were used. Youngest concordant single zircon age of each sample is given with 2-sigma error. In the box of each AgeDisplay the absolute number of analyses with ages between 540 and 550 Ma is given, representing the basement of the Lausitz Block. It is obvious that there is no significant input of these rocks. Remarkable is the increased input of Meso- and Paleoproterozoic ages in the uppermost sandstone sample, indicating the influence of a new source

The NW–SE directed, elongated subsidence maxima of the basin is also reflected in the thickness distribution of the Upper Cenomanian sedimentary rocks. In the Turonian, sedimentation was clearly influenced by the uplift of the Lausitz Block (Lausitz- Krkonoše High, Figs. 1, 2), as reflected by the presence of a clastic belt at the north-eastern basin margin and by thickness distribution typical of a marginal trough (Tröger 1964; Voigt 2009). The active basin margin was later transformed to a thrust (Lausitz Thrust, Fig. 2), which placed Upper Proterozoic greywackes and Lower Cambrian granodiorites of the Lausitz Block above the Upper Cretaceous units of the northern basin margin. Apatite fission track data show an uplift of at least 5 km of the Lausitz-Krkonoše High during the Upper Cretaceous (Lange et al. 2008); or even 10 km on the base of zircon fission tracks in the same time frame (Danisik and Migon 2010). The uplift was synsedimentary and led to bending of the Upper Cretaceous sediments along the Lausitz Thrust (Fig. 2, Pietzsch 1963; Lobst 1993).

Samples

Samples of the Upper Cretaceous Schmilka section (Saxony)

The area between Schöna and Bad Schandau in the southern Elbsandsteingebirge (Saxony, Germany) is the type locality of the lithostratigraphic subdivision of Cretaceous sandstones of the Elbtal Group (Prescher 1954, 1981). It exposes a complete succession of about 500 m of marine sandstones from the Upper Cenomanian Oberhäslich Formation to the Lower Coniacian Schrammsteine Formation (Figs. 1, 2, 3, 4). Only the Lower Turonian Briesnitz Formation in the subsurface is composed of silty marlstones. Together with bioturbated sandstones of the Postelwitz Formation, they are attributed to a lower shore face environment. Thin layers of coarse-grained sandstones with rippled top in those sandstones indicate a storm-controlled setting (Voigt 2011).

Figure 3 shows the geological map for the working area and Fig. 4 a generalised profile with the location of all sample points.

The main part of the succession (sandstone members b and c of the Postelwitz Formation, sandstone members d and e of the Schrammsteine Formation, Fig. 4) consists of massive, medium- to coarse-grained quartz sandstones, only sometimes interrupted by cross-bedded units and gravel bags. On the basis of sparse occurrences of marine bivalves and trace fossils, they are interpreted as marine, upper shoreface sands. Composition of all sandstones is characterized by an exceptionally high quartz content, which may represent nearly 100%. Feldspar and some sedimentary lithoclasts (ironstones, limonitic sandstones) occur in the Postelwitz Formation. The heavy mineral composition is dominated by tourmaline, zircon and rutile.

In the Upper Paleogene/Lower Neogene, these sandstone packages became intruded by various mafic volcanics (nephelinitic and basaltic dykes, Lobst 1993). Today, one of them forms the top of the highest mountain of the Schmilka area (Großer Winterberg, Fig. 3).

In total ten sandstone samples were analysed regarding their zircon U/Pb ages. Six of these samples represent exposed Upper Cretaceous sandstone units of the Schmilka, Postelwitz and Schrammsteine formations. The sample localities are marked in Figs. 3 and 4. Sample coordinates are given in Table ESM 1 (electronic supplementary material). The results of these six samples were surprising. Therefore, we included further samples to check and substantiate our assumptions.

Further samples: Triassic and Jurassic sandstones of Germany

To extend the data base of potential source rocks for the Upper Cretaceous sandstones of the Schmilka section, further samples were included into this study. Two sandstones representing the Middle Jurassic (Dogger) and two samples from the Upper Triassic (Keuper, Schilfsandstein) were sampled and also analysed for their detrital U–Pb zircon ages.

One of the Jurassic samples (sample Bayern-2) was sampled in southern Germany, at the Hesselberg section c. 1.5 km north of Gerolfingen in Bavaria. The second Jurassic sandstone (WOB 1) was sampled close to Wolfsburg (Lower Saxony, northern Germany). Both samples represent marine sandstones with a very high iron-content (probably due to weathering of the source area). These Dogger sandy layers are special for the Jurassic units, which otherwise contain mainly siltstones and marls. A change of provenance is expected for these samples, as this clastic sedimentary input is unique for the Jurassic sediments of Germany. The detection of an exotic provenance (exotic in terms of “different from the rocks under- and overlying them”) might be significant for the later interpretation of the detrital zircon input of the samples from the Schmilka section (Upper Cretaceous). The purpose of analysing two samples from sample sites, nearly 500 km apart, was to check if their detrital zircon input changes or if it stays the same. If the latter is true, then this assumed “exotic provenance” might be representative for the Middle Jurassic sandstones of Germany and maybe for Central Europe.

The two Triassic samples come from an old opencast mine close to Großmonra in Thuringia (sample Thuer 7), and from a cut bank of the Roter Mail river close to the Bodenmühle in Bavaria (sample Bayern 1–1). They belong to the so called “Schilfsandstein” within the Stuttgart Formation. According to Wurster (1964) and others, these Upper Triassic Keuper sandstones are remnants of a braided river system coming from north or north-east and would therefore be capable of providing an exotic provenance compared to over- and underlying strata. These two Upper Triassic samples were selected far apart from each other to check if the detrital zircon record of these Keuper sandstones shows such an exotic provenance. If so, this could be assumed to be the case for all Schilfsandstein horizons in Germany.

Sample coordinates are given in Table ESM 2 (electronic supplementary material, Triassic samples) and in Table ESM 3 (electronic supplementary material, Jurassic samples).

Methods

Zircon concentrates were separated from 1 to 2 kg sample material at the Senckenberg Naturhistorische Sammlungen Dresden (Germany). All samples represent one single sample point and are not based on a combination of several sample points. After crushing the rocks in a jaw crusher, the material was sieved for the fraction between 400 and 43 µm. The heavy mineral separation was performed using heavy liquid LST (sodium heteropolytungstates in water). In a second step, concentration of the diamagnetic heavy minerals was realised with a Frantz magnetic separator. Final selection of the zircon grains for U–Pb dating was achieved by hand-picking under a binocular microscope. Zircon grains of all grain sizes and morphological types were selected, mounted in resin blocks and polished to about half their thickness. The zircon grains where then examined regarding their cathodoluminescence signal using an EVO 50 Zeiss Scanning Electron Microscope (Senckenberg Naturhistorische Sammlungen Dresden, Germany) prior to U/Pb analyses. This helps to distinguish different growth and maybe metamorphic zones within the single grains. For U/Pb analyses the laser spots where placed in zones with monophase growth patterns that show no metamorphic overprint. In general, core zones of the zircon grains were selected for further analyses. Where rim areas were detectable in the CL-images, these areas were analysed, too, if they were suitable for a laser spot. Zircon grains were analyzed for U, Th, and Pb isotopes by LA-SF ICP-MS techniques at the Senckenberg Naturhistorische Sammlungen Dresden (Museum für Mineralogie und Geologie, Sektion Geochronologie, Germany*)*, using a Thermo-Scientific Element 2 XR sector field ICP-MS coupled to a New Wave UP-193 Excimer Laser System. A teardrop-shaped, low volume laser cell (modified version of the NERC Isotope Geosciences Laboratory in UK, see Bleiner and Günther 2001; Gerdes and Zeh 2006, 2009) constructed by Ben Jähne (Dresden) and Axel Gerdes (Frankfurt/M.) was used to enable sequential sampling of heterogeneous grains (e.g. growth zones) during time resolved data acquisition. Each analysis consisted of 15 s background acquisition followed by 20 s data acquisition, using laser spot-sizes of 20, 25 or 35 µm. A common-Pb correction was carried out if necessary, based on the interference- and background-corrected ^{204}Pb signal and on a model Pb composition (Stacey and Kramers 1975). The necessity of this correction was judged on whether the corrected ^{207}Pb/^{206}Pb lay outside the internal errors of the measured ratios. Discordant analyses were always interpreted with care. Raw data were corrected for background signal, common Pb, laser-induced elemental fractionation, instrumental mass discrimination, and time-dependant elemental fractionation of Pb/Th and Pb/U using an Excel® spreadsheet program developed by Axel Gerdes (Gerdes and Zeh 2006, 2009; Frei and Gerdes 2009). Reported uncertainties were propagated by quadratic addition of the external reproducibility obtained from the standard zircon GJ-1 (~0.6 and 0.5–1% for the ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U, respectively) during individual analytical sessions and the within-run precision of each analysis. Concordia diagrams (2σ error ellipses) were produced using Isoplot/Ex 2.49 (Ludwig 2001). For ages above 1.0 Ga, the ^{207}Pb/^{206}Pb ratio provides a more reliable age. Therefore, this ratio was used instead of the U/Pb ratio for the probability–frequency plots (AgeDisplays, Sircombe 2004). Concordant and discordant analyses were all recorded in the data tables ESM 1, ESM 2 and ESM 3 (electronic supplementary material). Only values with a concordance between 90 and 110% were regarded as “concordant” and used for all diagrams. Apart from the AgeDisplay plots, which are all based on a one sigma error level, all other diagrams, as well as mentioned ages with errors in the text, always refer to a two sigma error level. For further details on analytical protocol and data processing see Gerdes and Zeh (2006, 2009) and Frei and Gerdes (2009).

Statistical comparison of age distributions between different samples and external datasets was carried out using a Kolmogorov–Smirnov (K–S) test. This test matches *D* values (values of difference) to *P* values (probability values) for two samples (Shaw et al. 2014). For this study, any two samples that pass the test with *P* values exceeding 0.05 (95% confidence level) were seen as highly reliable that these populations are not statistically different. This means they might derive from the same source areas or from source areas with rocks containing the same parent zircon populations in the same relative proportions (Shaw et al. 2014). K–S test was performed using a macro-based Excel®-spreadsheet developed from the Arizona LaserChron Center (ALC) in the Department of Geosciences at the University of Arizona (Guynn and Gehrels 2010). To focus on the differences or similarities in the Proterozoic (Lower Neoproterozoic to Paleoproterozoic) age patterns for the samples of this study, only ages older than 900 Ma were used for all samples.

Results

Zircon grains of the Upper Cretaceous sandstones (Elbtal Group, Schmilka section, Saxony)

Zircon grain sizes, degree of roundness, and colour are very similar for all samples. The general grain sizes vary from 80 to 250 µm. Some grains are up to 300 µm in size, few even up to 350 µm. Most grains show rounded edges, whereas some are well rounded in general. Only very few grains show sharp edges without any signs of rounding. There are needle shaped and prismatic grains in all samples, nearly all of them with rounded edges at least. Zircon grains of the Schmilka section are generally colourless.

There is no obvious trend of special zircon grain types throughout the samples of the Schmilka section.

The results of the U–Pb analyses of the samples from the Schmilka section are summarized in Table ESM 1 (electronic supplementary material) and were used for Figs. 4, 5 and 6.

The U/Pb zircon ages show very similar spectra for the six samples (Sk 6-2, Sk 1 s, Sk 5, Sk 4-1, Sk 3-1 and Sk 2-2) which represent the sandstones of the Schmilka Formation (Labiatus Sandstone), the Postelwitz Formation (sandstones a, b and c) and the lower Schrammsteine Formation (sandstones d and e; Figs. 4, 5). The youngest concordant measurement for each sample is given in the AgeDisplay diagrams in Fig. 4. The amount of measured and of concordant analyses is also given in the AgeDisplay diagrams and in table ESM 1. The youngest single zircon grain was found in sample Sk 1 s, giving an age of 258 ± 6 Ma. Ages around 350 to 320 Ma are the most abundant ones for all samples of this section. They represent between 10 and 35 percent of the total concordant zircon ages. In general, there is a more or less continuous age spectrum between 300 and 800 Ma for all Schmilka samples. After this follows the scattered (for samples Sk 6-2, Sk 1 s, Sk 5, Sk 4-1, Sk 3-1) or many (sample Sk 2-2) Meso- and Paleoproterozoic zircon ages up to c. 2000–2100 Ma. For sample Sk 2-2 these ages represent 51.9% of all concordant analyses. An Archean age was only found at the base of the section in sample Sk 6-2 (Schmilka Formation) given by one zircon grain with an age of 2969 ± 76 Ma. There is only one more grain older than 2100 Ma found in sample Sk 4-1 (sandstone c) with an age of 2441 ± 34 Ma (Figs. 4, 5, Table ESM 1, electronic supplementary material).

In comparison to the lower five samples, the age spectrum changes significantly in the Upper Schrammsteine Formation (sample Sk 2–2, sandstone member e). In this sample, a relatively higher amount of Meso- and Paleoproterozoic ages is associated with a decrease in Paleozoic ages (Fig. 6, Table ESM 4, electronic supplementary material), although ages of 350–320 Ma are still dominantly present in the age record (about 9% of all concordant analyses).

Zircon grains of the Upper Triassic sandstones (Keuper, Schilfsandstein, Thuringia and Bavaria)

The general grain sizes vary from 70 to 250 µm. Most grains show rounded edges, whereas there are a few prismatic shapes ones with sharp edges. The analysed zircon grains from the Keuper sandstones are mainly colourless. Some show a slightly yellowing tinge.

The results of the U–Pb analyses of the Triassic samples (Thuer 7, Bayern 1–1) are summarized in Table ESM 2 (electronic supplementary material) and were used for Fig. 7.

The main age peak for both samples is represented by Mesozoic ages between c. 250 and 300 Ma. This means that the Triassic samples contain the youngest zircon grains of all samples analysed in this study: 231 ± 5 Ma (single grain) for sample Thuer 7 (Thuringia, central Germany) and 248 ± 7 Ma (single grain) for Bayern 1–1(Bavaria, southern Germany). Both samples show similar Paleozoic ages. They differ slightly in the Neoproterozoic age record: While sample Bayern 1–1 shows a more or less continuous age spectra from c. 250 to 750 Ma, sample Thuer 7 is represented by an age gap between c. 500 and 600 Ma. Most important for the further interpretation of this study is the small amount of Meso- and Paleoproterozoic ages in both samples. Although both samples show analyses with these ages, their absolute number is very low. The oldest concordant zircon grain for sample Thuer 7 gives an age of 2926 ± 46 Ma. The oldest concordant age for sample Bayern 1–1 is 2381 ± 23 Ma (single grain).

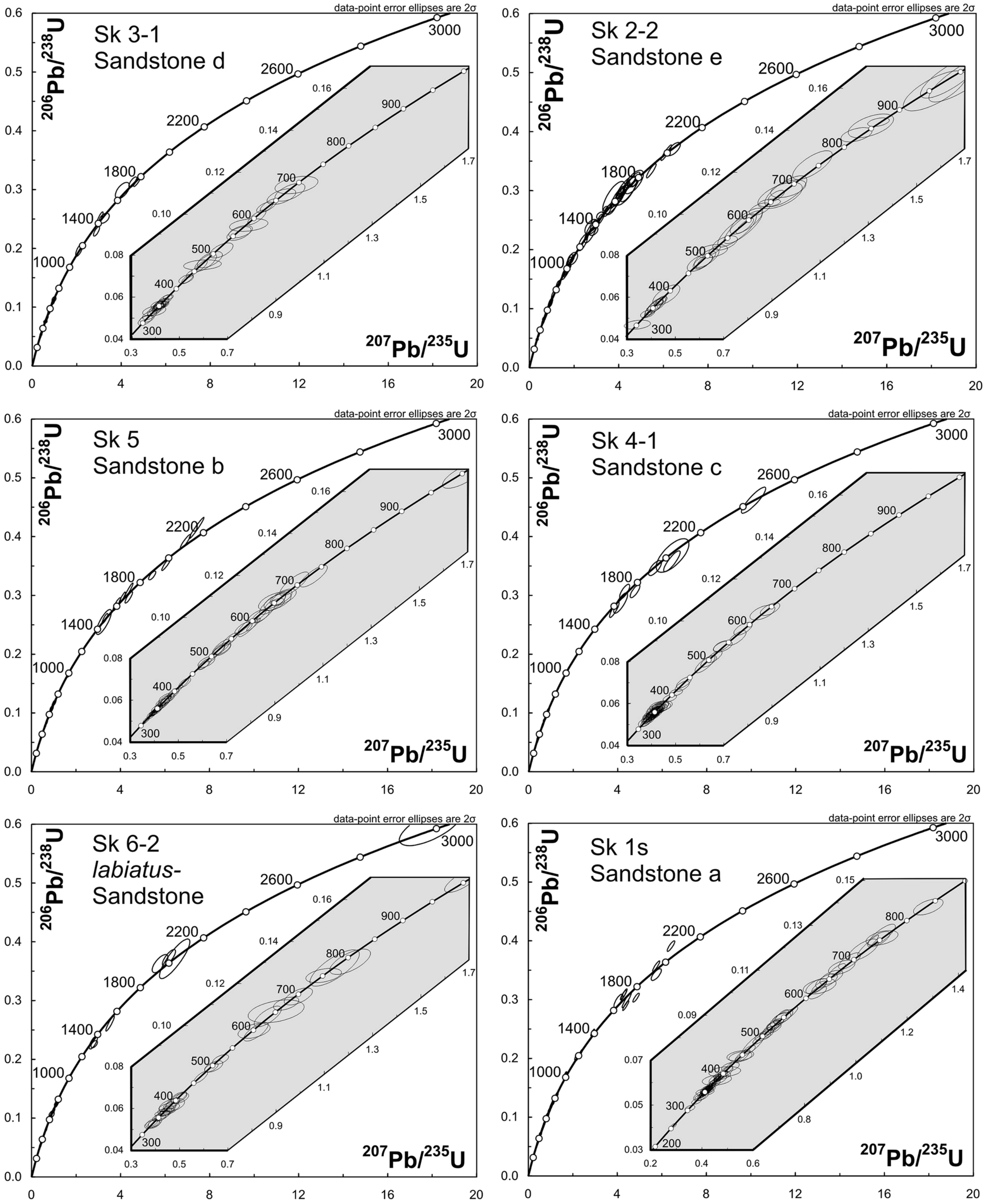


Fig. 5 Concordia diagrams of all six Upper Cretaceous sandstone samples of the Schmilka section (plotted with a two sigma error) showing all U/Pb zircon ages with a degree of concordance between 90 and 110%. Grey boxes show ages between 300 and 1000 Ma in enlarged view

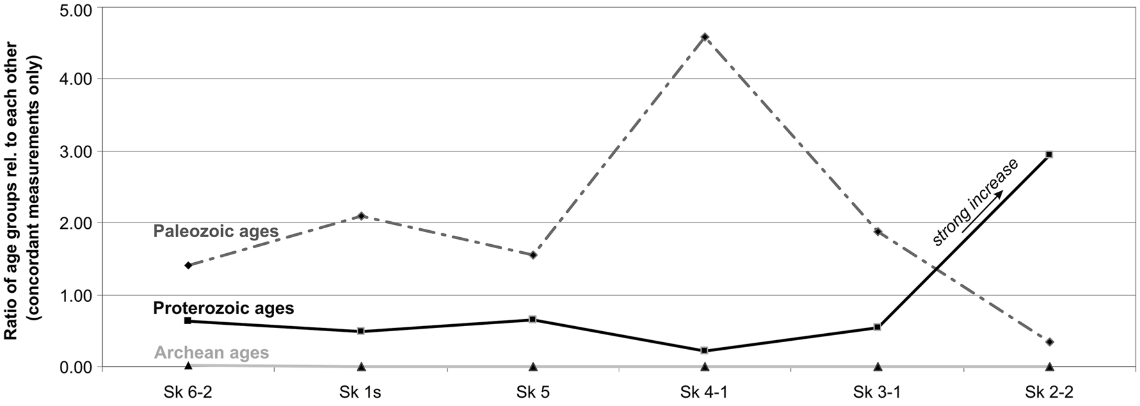


Fig. 6 Diagram showing the change in age classes (Archean, Proterozoic and Palaeozoic) for all analysed Upper Cretaceous sandstones of the Schmilka section. Note the sudden increase of Proterozoic ages in the uppermost sample (Sk 22, Sandstone e, Schrammsteine Formation) in comparison to the five samples below. The diagram is based on the values given in Table ESM 4

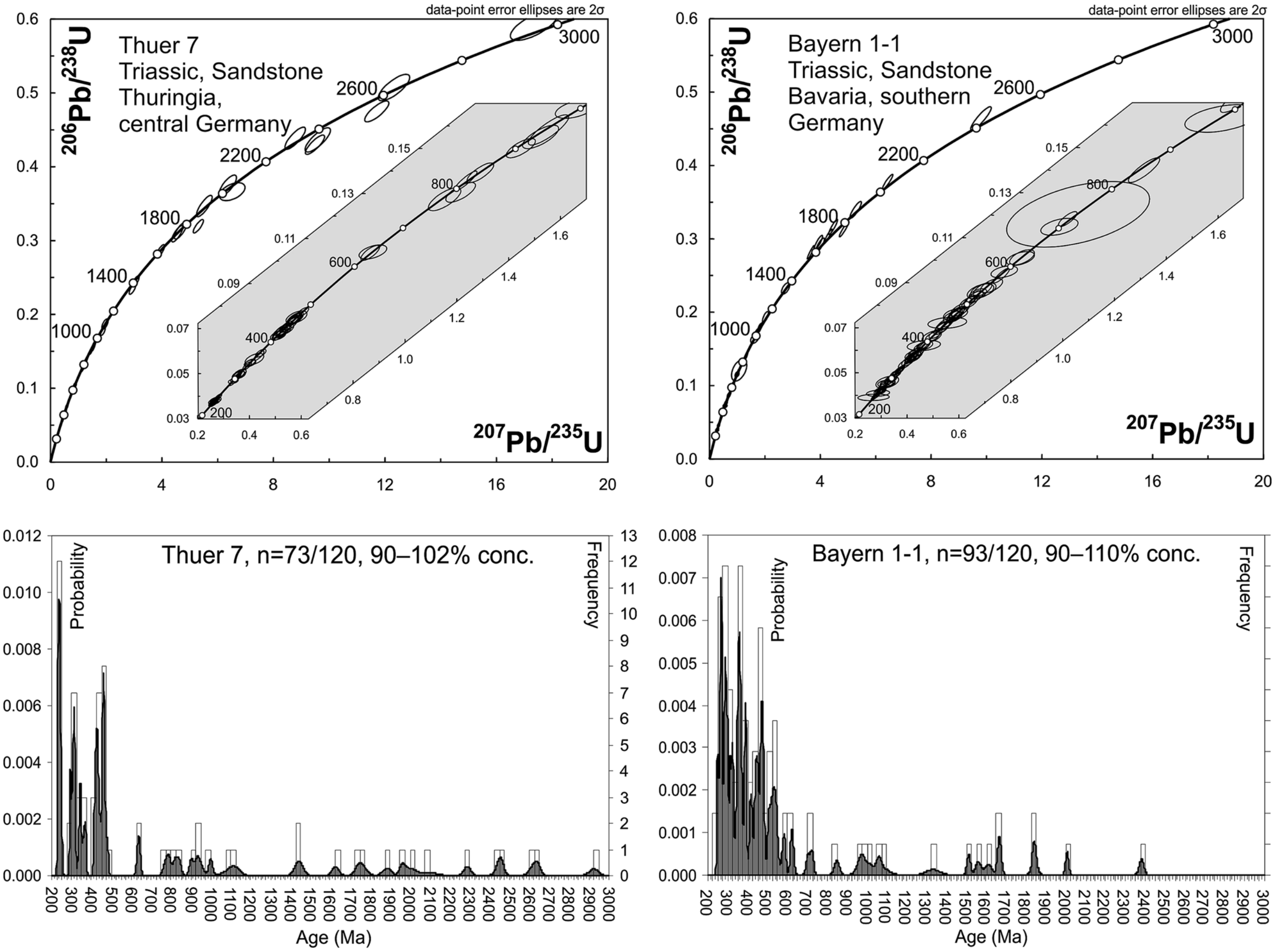


Fig. 7 Concordia diagrams and AgeDisplay plots of the two Upper Triassic samples (Keuper, Schilfsandstein) from Thuringia (Thuer 7) and from Bavaria (Bayern 1–1). Concordia diagrams are plotted on a two sigma error. The grey boxes show ages between 200 and 1000 Ma in enlarged view. AgeDisplay plots are based on a one sigma error. Note that, although these Schilfsandstein samples are interpreted to have a northern source area, typical Scandinavian ages (Meso- and Paleoproterozoic ages) are nearly missing

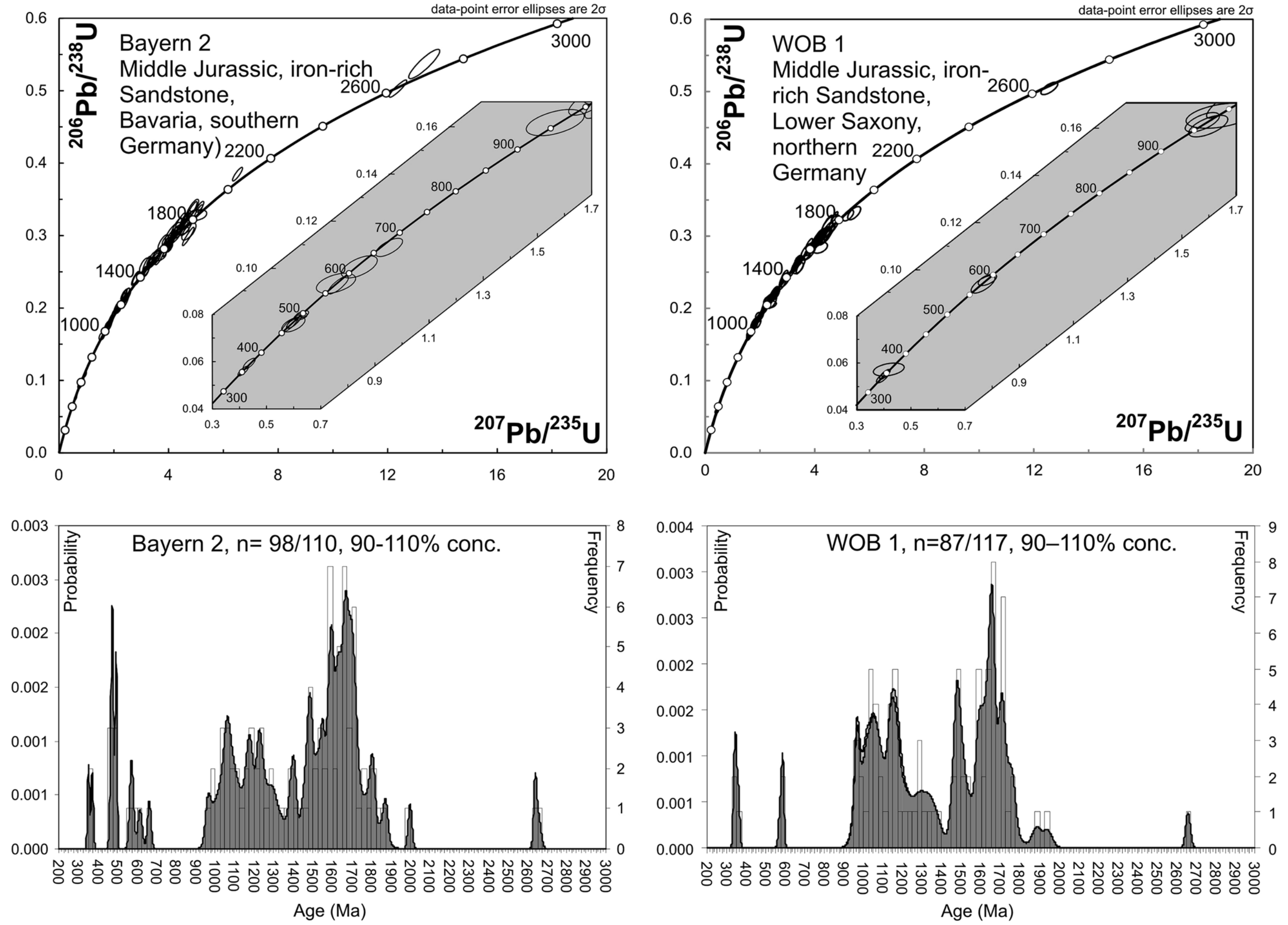


Fig. 8 Concordia diagrams and AgeDisplay plots of the two Middle Jurassic samples (Dogger) from Lower Saxony (WOB 1) and from Bavaria (Bayern 2). Concordia diagrams are plotted on a two sigma error. The grey boxes show ages between 300 and 1000 Ma in enlarged view. AgeDisplay plots are based on a one sigma error. Note that the highest amount of calculated ages lies in the Meso- and Paleoproterozoic, typical for a Scandinavian (Baltica) source

Zircon grains of the Middle Jurassic sandstones (Dogger, Lower Saxony and Bavaria)

Zircon grains of Proterozoic ages and older differ in grain size between approximately 60 to c. 250 µm and are generally well rounded. Some elongated grains reach a size of 300 µm. Most zircon grains are colourless. Only a few show a slightly yellow to brownish colour.

The results of the U–Pb analyses of the Jurassic samples (Bayern 2, WOB 1) are summarized in Table ESM 3 (electronic supplementary material) and were used for Fig. 8.

Although taken from sections which are about 500 km apart, the two Middle Jurassic samples show a very similar U–Pb zircon age pattern (Fig. 8, Table ESM 3, electronic supplementary material). Both include no Mesozoic detrital zircon ages. The youngest ages are at c. 352 Ma for sample Bayern 2 (Bavaria, southern Germany) and at c. 338 Ma for sample WOB 1 (Lower Saxony, northern Germany). The majority of the detrital zircon ages of these two samples fall within the Proterozoic age span between c. 900 and 2000 Ma. There were found only very few Archean ages. Upper Neoproterozoic and Paleozoic ages are only represented by distinct ages at c. 360, 480 Ma and 550–650 Ma for sample Bayern-2 and age clusters around 340–350 Ma and 570–580 Ma for sample WOB 1.

About 25–30% of the zircon grains found in sample Sk 2–2 (top of Schmilka section) were similar in age to those found in the two Jurassic samples.

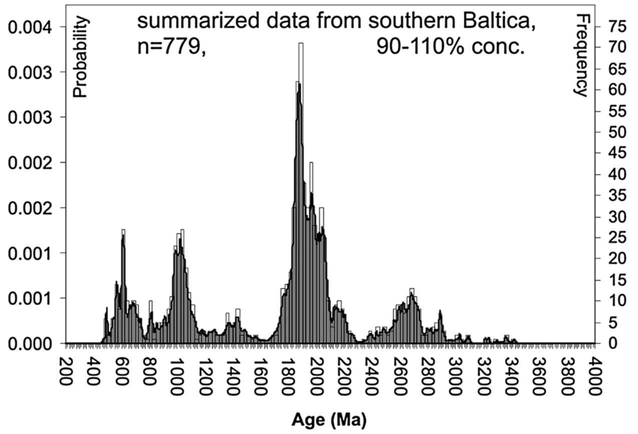


Fig. 9 AgeDisplay diagram showing U–Pb detrital zircon data representative for southern Baltica (Telemarkia and adjoining areas). The diagram comprises 779 single zircon U–Pb analyses compiled from the literature: Johansson et al. (1993); Andersen et al. (2002a, b, 2007, 2011); Bingen et al. (2002, 2008); Rohr et al. (2004); Lundmark et al. (2007); and Lamminen (2011). Probability of the diagram is based on 1-sigma errors (Sircombe 2004). All measurements with a degree of concordance between 90 and 110% were regarded as concordant and used for this diagram

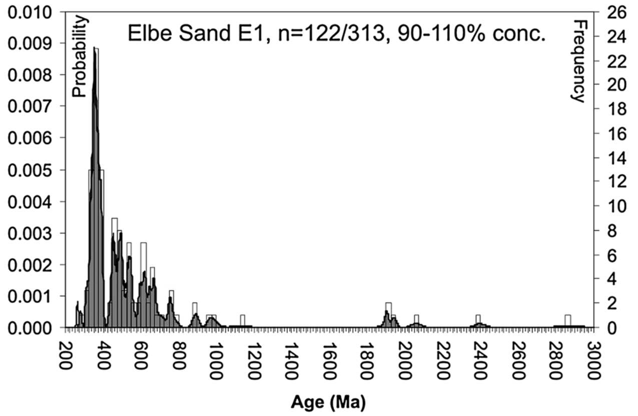


Fig. 10 AgeDisplay diagram of sample E1, representing a recent river sand from the Elbe River taken at Bad Schandau in Saxony close to Schmilka. Probability of the diagram is based on 1-sigma errors (Sircombe 2004). All measurements with a degree of concordance between 90 and 110% were regarded as concordant and used for this diagram. n = number of concordant analyses/number of all analyses made for this sample. ^{206}Pb/^{238}U ratios were used for all ages below 1000 Ma, whereas for older grains ^{207}Pb/^{206}Pb-ages were used. Data from Gärtner (2011). These data represent the detrital zircon U–Pb age record for the Bohemian Massif

K–S test results and first implications of the data

The presented detrital U–Pb zircon ages within this study differ from sample to sample, although they all represent parts of the German Central European Basin, which was formed in Mesozoic times. Therefore, they all show ages typical for the Cadomian and Variscan of Germany (e.g. Linnemann 2008; Linnemann et al. 2010).

For the Mesozoic sediments of Germany, a local provenance is generally assumed, resulting from mixing various sources provided by the basement and overlying sediments. Therefore, reported detrital zircon ages for the Schmilka section are not surprising, except for the uppermost sample (Sk 2–2) which yields an unexpected high amount of Proterozoic zircon ages very untypical for this area (Figs. 4, 5, 6).

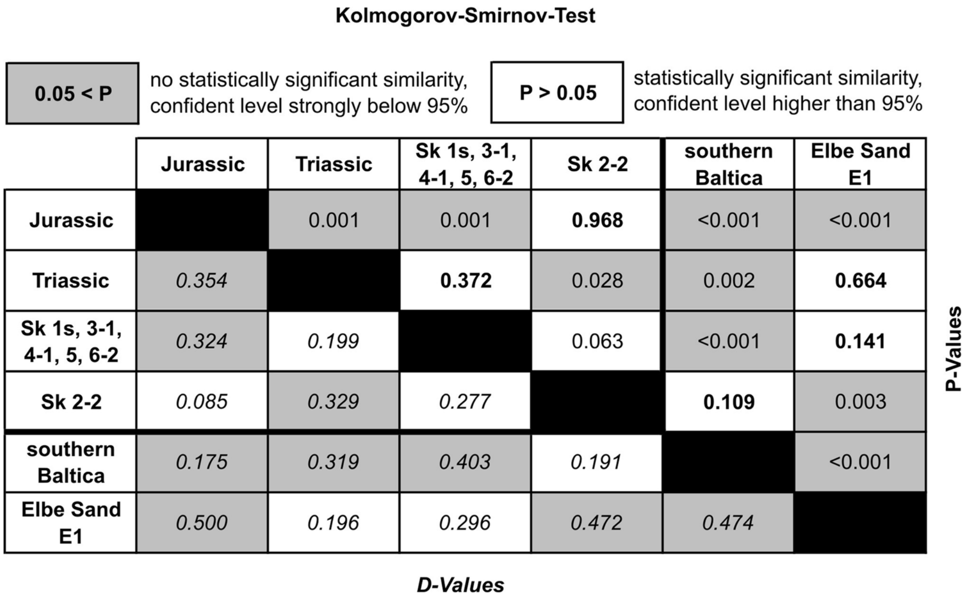
To understand the assumptions based on this dataset, two additional sample sets based on published data are necessary. Both are shown as AgeDisplay plots (Figs. 9, 10) using the same age ranges as the plots for the sandstones from the Schmilka section in Fig. 4 to make them comparable.

The first one in Fig. 9 shows an AgeDisplay plot of compiled ages of the southern Baltica area known from the literature (references see figure caption). The gathered data resembles the Telemarkia terrane and adjoining areas.

The second one on Fig. 10 shows the AgeDisplay plot of zircon grains from a sample taken from the recent sand of the Elbe River near Bad Schandau (close to Schmilka). The data is taken from Gärtner (2011). This sample represents the typical ages of the Bohemian Massif within the complete drainage area of the Elbe River (see Gärtner 2011). There is a lack of Mesoproterozoic ages.

To put possible assumptions on a statistical base, a Kolmogorov–Smirnov test (K–S test) was done to show similarities between the different samples (Fig. 11). The samples Sk 1 s, Sk 3-1, Sk 4-1, Sk 5 and Sk 6-2 were summarized to one group as they all show the same detrital zircon age record (Fig. 4). The two Upper Triassic (Thuer 7, Bayern 1–1) samples and the two Middle Jurassic (WOB 1, Bayern 2) samples were also grouped to “Jurassic” and “Triassic”, respectively. Only sample Sk 2–2 represents a single “group”. To allow a statistically secured similarity study between the samples and their possible source areas, “southern Baltica” and “Elbe Sand E1” were also included into the K–S test. Since the Proterozoic (Lower Neoproterozoic to Paleoproterozoic) ages are the base for the differentiation of possible source areas for sample Sk 2–2 in this study, we excluded all ages younger than 900 Ma for all samples from the K–S test.

There are statistically significant similarities between Sk 2–2 (uppermost sample of the Schmilka section) with the Jurassic ($P = 0.968$) and southern Baltica ($P = 0.109$) samples. The statistical similarity between sample Sk2-2 and Jurassic is significantly higher than between Sk 2–2 and southern Baltica. Surprisingly, the southern Baltica age group shows no statistically secured similarity with the Jurassic age group ($P < 0.001$, Fig. 11). Therefore it is



Kolmogorov-Smirnov-Test

0.05 < P: no statistically significant similarity, confident level strongly below 95%

P > 0.05: statistically significant similarity, confident level higher than 95%

	Jurassic	Triassic	Sk 1s, 3-1, 4-1, 5, 6-2	Sk 2-2	southern Baltica	Elbe Sand E1
Jurassic		0.001	0.001	**0.968**	<0.001	<0.001
Triassic	*0.354*		**0.372**	0.028	0.002	**0.664**
Sk 1s, 3-1, 4-1, 5, 6-2	*0.324*	*0.199*		0.063	<0.001	**0.141**
Sk 2-2	*0.085*	*0.329*	*0.277*		**0.109**	0.003
southern Baltica	*0.175*	*0.319*	*0.403*	*0.191*		<0.001
Elbe Sand E1	*0.500*	*0.196*	*0.296*	*0.472*	*0.474*	

P-Values

D-Values

Fig. 11 Results of the Kolmogorov–Smirnov test with errors and excluding ages < 900 Ma. The strong statistically significant similarity between sample Sk 2–2 and the Jurassic samples is striking. Also the high similarity between the lower samples of the Schmilka section with the Elbe Sand E1 sample is remarkable. See text for further explanations and interpretation

assumed that the source area between the detrital zircons found in the Jurassic samples differs from the source of the southern Baltica samples, although both datasets result in a statistically secured similarity value when compared with sample Sk 2–2. This similarity is based on detrital zircon grains with Neo- to Paleoproterozoic ages, which are present in both, the Jurassic as well as the southern Baltica, samples. The detrital zircon age record for sample Sk 2–2 is a mixture of local and exotic material, which blurs the original source area information. This can explain the similarities of this sample to Jurassic as well as southern Baltica samples seen from the statistical point of view (K–S test). The Jurassic sandstones summarized in the Jurassic group for the K–S test, represent a mixture of local and exotic material, too, which explains the statistically high similarity with Sk 2-2 and the low to non-similarity to southern Baltica.

According to Shaw et al. (2014), the K–S test fails for samples from the same source with age heterogeneities at a given scale, which end up in different proportions for each sample. This can also be a reason for the disparity for the Jurassic and the southern Baltica samples in the K–S test (Fig. 11).

All five Schmilka samples below Sk 2–2 resemble the group of Triassic samples of Germany ($P = 0.372$) and the "Elbe Sand E1" ($P = 0.141$) sample (Fig. 11), representing the general zircon age distribution of the Bohemian Massif (e.g., Drost et al. 2004; Drost 2008; Linnemann et al. 2010). Also, sample "Elbe Sand E1" shows its highest statistically significant similarity to the Triassic group ($P = 0.664$), and a high similarity to the group of Schmilka samples (Sk 1 s, Sk 3-1, Sk 4-1, Sk 5 and Sk 6-2, $P = 0.141$).

These results allow a new interpretation on the source of the cretaceous sandstones of the Elbe valley.

Discussion and interpretation

Discussion on the contribution of local material

For all samples of the Schmilka section, the main age peaks are represented by Variscan and Cadomian ages (Fig. 4). These are typical ages for the Bohemian Massif in general (e.g. Drost et al. 2004; Drost 2008; Hofmann et al. 2009; Linnemann et al. 2008, 2010, Fig. 10). The most prominent age peak for all Schmilka sandstones occurs between c. 330 and c. 360 Ma (i.e. Variscan, Fig. 4). Variscan ages are typical for the units lying south-west of the Bohemian Cretaceous Basin as well as for units along the Elbe Zone (e.g. Hofmann et al. 2009). In the metamorphic units of the Krkonoše Mountains (N) and in the Jizerske Hory (SE), Variscan ages prevail, too. Mixing of different source areas in pre-Cretaceous times cannot be excluded.

Studies of Tröger (1964, 2008); Voigt and Tröger (1996), Voigt (1995, 2009); Wilmsen et al. (2011) and others show that the Upper Cretaceous sedimentary input into the Elbe valley came from the Lausitz Block and its cover sequences. The spatial distribution of conglomerates within the Upper Cretaceous sedimentary rocks gives evidence that the main source area was situated at the north-western basin margin (Lausitz Block, Voigt 2009). Composition of these conglomerates is completely determined by well-rounded quartz pebbles and a variety of sedimentary rocks such as sandstones, limonitic ironstones and some limestones. Medium grade metamorphic rocks, such as gneisses and mica schists, which are typical of the recent Krkonoše high, do not occur.

The K–S test (Fig. 11) shows that the lowermost five samples of the Schmilka section (Sk 6-2, Sk 1 s, Sk 5, Sk 4-1 and Sk 3-1) resemble the zircon populations known from the Bohemian Massif (represented by sample Elbe Sand E1, Gärtner 2011, Fig. 10) and zircon ages known from detrital Triassic samples (Fig. 7). Therefore, most part of the Schmilka section reflects the local basement and cover rocks of the Lausitz Block.

The rocks of the Lausitz Block are dominated by Cadomian units (e.g. Linnemann 2008). Therefore, detrital zircon grains bearing Cadomian ages (c. 540 to 560 Ma) were found as expected in the Schmilka section (Fig. 4). The basement of the Lausitz Block is dominated by Lower Cambrian granodiorites at c. 540–550 Ma and Proterozoic greywackes with detrital zircon ages between 600 Ma and 2.2 Ga (e.g. Linnemann 2008; Hofmann et al. 2009; Linnemann et al. 2010). Based on this knowledge an increasing amount of 540–550 Ma ages acting as a “tracer” for the Lausitz Block basement was expected from the base to the top of the Schmilka section. Interestingly, the obtained U–Pb data (Figs. 4, 5, Table ESM 1) show no such trend. Instead, the age spectra of all five Turonian samples (Sk 6-2, Sk 1 s, Sk 5, Sk 4-1 and Sk 3-1) show a uniform age distribution with nearly no ages between 540 and 550 Ma (varying numbers between zero and two, see boxes in AgeDisplay diagrams in Fig. 4).

The Lausitz Block experienced uplift along the Lausitz Thrust (Figs. 1, 2), relative to the Elbe valley (halfgraben structure), in the Cenomanian to Turonian (Lange et al. 2008; Danisik et al. 2010). Due to this, its former cover of sedimentary rocks became eroded and re-deposited into the Elbe valley.

The Schmilka section represents an inverse redeposition of the sedimentary cover on top of the Lausitz Block with no contribution of the Lausitz Block basement.

Discussion on the contribution of exotic material

In contrast to the lowermost five Schmilka samples, the topmost sample of the Schmilka section Sk 2–2 shows neither a statistical highly significant similarity to local material of the Bohemian Massif (to sample E1, $P = 0.003$) nor to the Triassic samples ($P = 0.028$, Fig. 11). As shown in Fig. 11, there is only a slightly statistical similarity between sample Sk 2–2 and all underlying samples of the Schmilka section (Sk 1 s, Sk 3-1, Sk 4-1, Sk 5 and Sk 6-2). This similarity (P value 0.063) can be explained by mixing with local material that also contributed to the other five samples of the Schmilka section. However, the significant amount of Proterozoic ages on the topmost sandstone of the Schmilka section (sample Sk 2–2) cannot be explained by the erosion of sediments containing local material that rested on top of the Lausitz Block. As mentioned before, the Upper Triassic Keuper sandstones should represent a northern to north-eastern source (Wurster 1964; Paul et al. 2008). Nevertheless, the U–Pb zircon data (Fig. 7) show only very few (Meso-) Proterozoic ages and contain mainly ages that point to local sources. Therefore, the Upper Triassic Keuper might have contributed to the source rocks for the five lowermost Schmilka samples (Sk

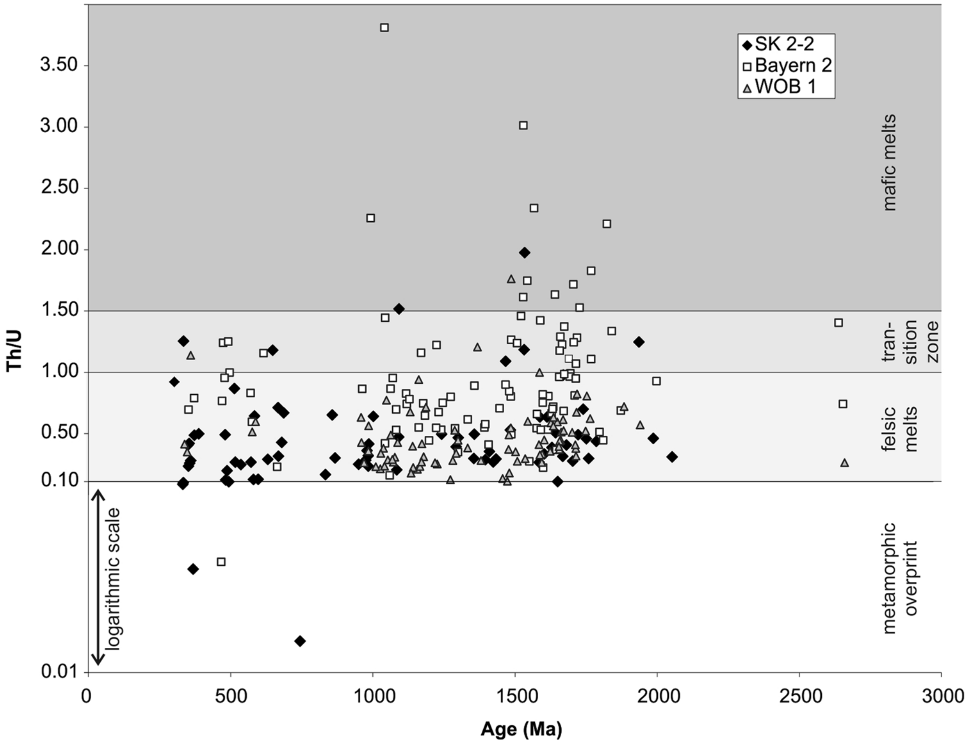


Fig. 12 Th/U versus age diagram for zircon grains from sample Sk 2–2 (top of Schmilka section, sandstone e) in comparison with those of the two Jurassic samples WOB 1 and Bayern 2. It is visible that all three samples not only coincide in U–Pb ages but also in Th/U ratios. The majority plots in the range of origin from felsic melts

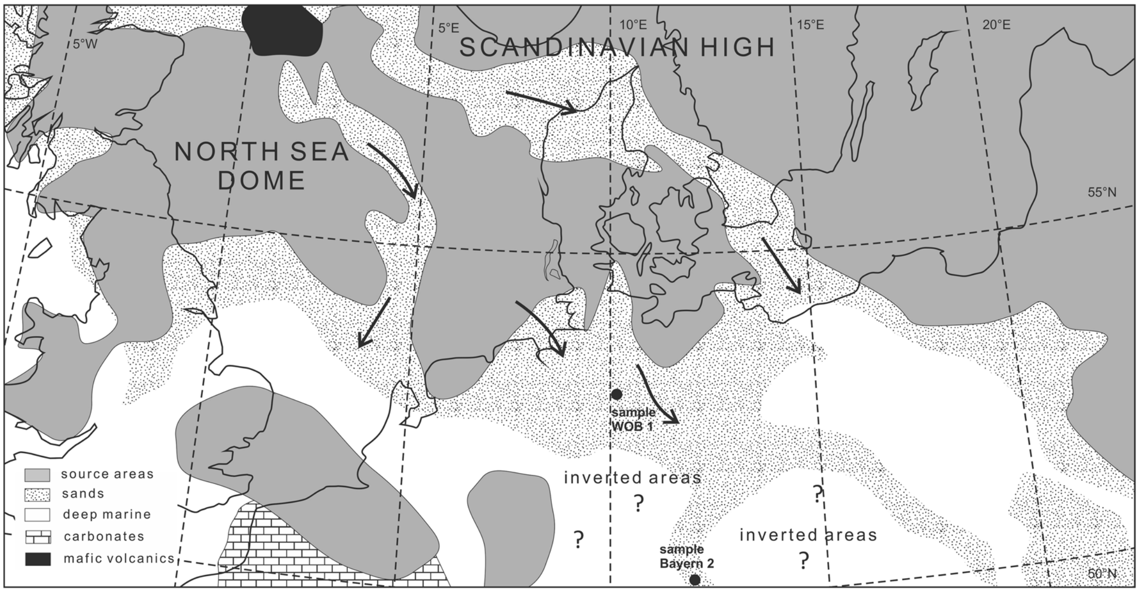


Fig. 13 Reconstruction of land-sea distribution during the Middle Jurassic based on Ziegler (1990) showing the uplifted area of the North Sea dome. Arrows indicate directions of sediment supply. Sample points of the two presented Jurassic sandstones are indicated

1 s, Sk 3-1, Sk 4-1, Sk 5 and Sk 6-2), but can be excluded as solitary source for sample Sk 2–2.

Apart from this, the only sedimentary Mesozoic rocks that are likely to have once covered the Lausitz Block and that are known to contain Proterozoic detrital zircon ages in high amounts, are the iron-rich Dogger sandstones from the Middle Jurassic (Fig. 8). Also, the K–S test confirms the strong similarity between the source of these sandstones and the source for the top sample of the Schmilka section (Fig. 11, $P = 0.968$).

Not only the U–Pb ages of the detrital zircon grains coincide for sample Sk 2–2 and the Middle Jurassic samples Bayern 2 and WOB 1, but also the Th/U ratios (see Fig. 12: majority of analyses plot within the field of originally felsic melts).

Paleogeographic reconstructions of Central Europe for the Middle Jurassic show a plume related updoming of crust in the recent North Sea area (e.g. Ziegler 1990; Hesselbo 2000, Fig. 13). In the literature, this is referred to as the "North Sea Dome" (Ziegler 1990). The structure was related to the initial break-up of the Atlantic Ocean. The overall sedimentary transport direction in Central Europe during the Middle Jurassic was from the north towards the south (indicated by the arrows in Fig. 13, Ziegler 1990), allowing material from the southern Baltica area and the exposed rocks of the North Sea Dome to be eroded and redeposited within the German Mesozoic basin. The northern areas were a major sediment source area for Middle Jurassic deposits. The dome structure (North Sea Dome) exhumed unknown crustal units and provided them for erosion during the Middle Jurassic. Continental clastic deposits probably first accumulated at the margins of the dome and then were eroded and transported further to the south into the German Mesozoic Basin. It is unclear, if the detrital zircon grains found in the presented Jurassic samples (Fig. 8) were delivered directly from the southern Baltica area and/or from the North Sea Dome, or if they represent a mixture of both.

A comparison of the detrital zircon age records of the Mesozoic rocks of Central Europe (Germany) presented in this study (Figs. 4, 7, 8) shows that the detrital zircon age pattern of the Middle Jurassic sandstones (Fig. 8) is unique. The occurrence of the same conspicuous age spectrum in Middle Jurassic samples of northern (sample WOB 1) as well as southern (sample Bayern 2) Germany is remarkable. It shows that these sands were distributed across Germany in areas that are separated by several hundred kilometres. Surely, such a far transport is associated with sorting and mixing of minerals. Nevertheless, both analysed Middle Jurassic rock samples (Bayern 2, WOB 1) were similar in grain size, colour, general rock structure and detrital zircon U–Pb age record (Fig. 8). For both sample sites, another source, apart from the North Sea Dome and the Scandinavian High (southern Baltica), providing the required detrital zircon age pattern, is not known so far. For Europe, these Meso- and Paleoproterozoic ages are very prominent for the southern Baltica region (e.g. see references used for Fig. 9 in the figure caption). Because they yield this exotic detrital zircon age record, the Middle Jurassic (Dogger) sandstones represent a perfect marker horizon for investigations on basin inversion.

According to the statistics, the top of the Schmilka section (Sk 2–2, sandstone e) and the Jurassic samples are very likely to resemble the same source area. However, a direct connection of the Cretaceous sediments to the Baltica (Boreal) realm, as it was the case for the Jurassic, is neither known nor documented in any sediments of the Elbtal Group. The only reasonable explanation would be the Upper Cretaceous erosion of a Middle Jurassic sandstone cover resting on the Lausitz Block. A complete Mesozoic cover including Middle Jurassic sediments on top of the Lausitz Block is a new idea, but as sedimentary rocks of similar age were found along the Lausitz Thrust in Saxony (e.g. Pietzsch 1963), it can be easily conceivable.

These assumptions result in a new idea regarding the sedimentary cover of the Lausitz Block and the time of its (stepwise) erosion.

Conclusions on the Mesozoic cover of the Lausitz Block

As pointed out before, the sandstones of the Elbe valley (Elbtal Group) represent the re-deposited sedimentary cover of the Lausitz Block in inverse order. The basement rocks of the Lausitz Block cannot be the source for the Upper Cretaceous sandstones of the Schmilka section. The sedimentary cover resting on the Lausitz Block must have been younger than the Cadomian basement, but also older than the Turonian samples of the Elbtal Group sandstones (Fig. 14). This cover most probably comprised Permian to Lower Cretaceous sediments (Fig. 14).

Remnants of Permian and Mesozoic rocks are known only from sparse occurrences on the Lausitz Block and along the Lausitz Thrust (Fig. 2, e.g. Pietzsch 1963; Lobst 1993). A cover of Triassic sedimentary rocks prior to the uplift of the Lausitz Block along the Lausitz Thrust was assumed by other authors already (e.g. Pietzsch 1963). The age spectra of the Triassic samples from Germany (Fig. 7) roughly fit to the age spectra of the lowermost Schmilka section samples (Sk 1 s, Sk 3-1, Sk 4-1, Sk 5 and Sk 6-2). This is confirmed by a P value of 0.372 (Fig. 11), which represents a high statistical similarity. But the K–S test in this study is based on zircon ages older than 900 Ma for all samples. Therefore, younger ages are not included in this statistical analysis. The Triassic samples Thuer 7 and Bayern 1–1 show young zircon ages between 230 and 250 Ma (Fig. 7) that are completely missing in the Cretaceous samples of the Schmilka section (Fig. 4). In addition, the Triassic samples show no considerable amount of Meso- and Paleoproterozoic zircon ages and can therefore also not be the source for the uppermost sample of the Schmilka section (Sk 2–2, sandstone e, Schmilka Formation, Lower Coniacian). This means that the Triassic samples can be excluded as possible source for the detrital zircons found in the Upper Cretaceous sandstones of the Schmilka section.

It can be concluded that Triassic and Permian sedimentary units did not contribute to the detritus that formed the Upper Cretaceous sedimentary rocks of the Schmilka section because the detrital zircon age signal of the Middle Jurassic samples occurs in the highest preserved units of the Schmilka section. Moreover, based on the presented data, a cover of Middle Jurassic Dogger sandstones resting on the Lausitz Block is the only reasonable source providing Meso- and Paleoproterozoic ages for the uppermost sandstone of the Schmilka section. A mixture of Jurassic sandstones (detritus from the north: southern Baltica, North Sea Dome) and local material (Bohemian Massif, Lausitz Block) can explain the age spectra found for sandstone e (sample Sk 2–2, Fig. 4).

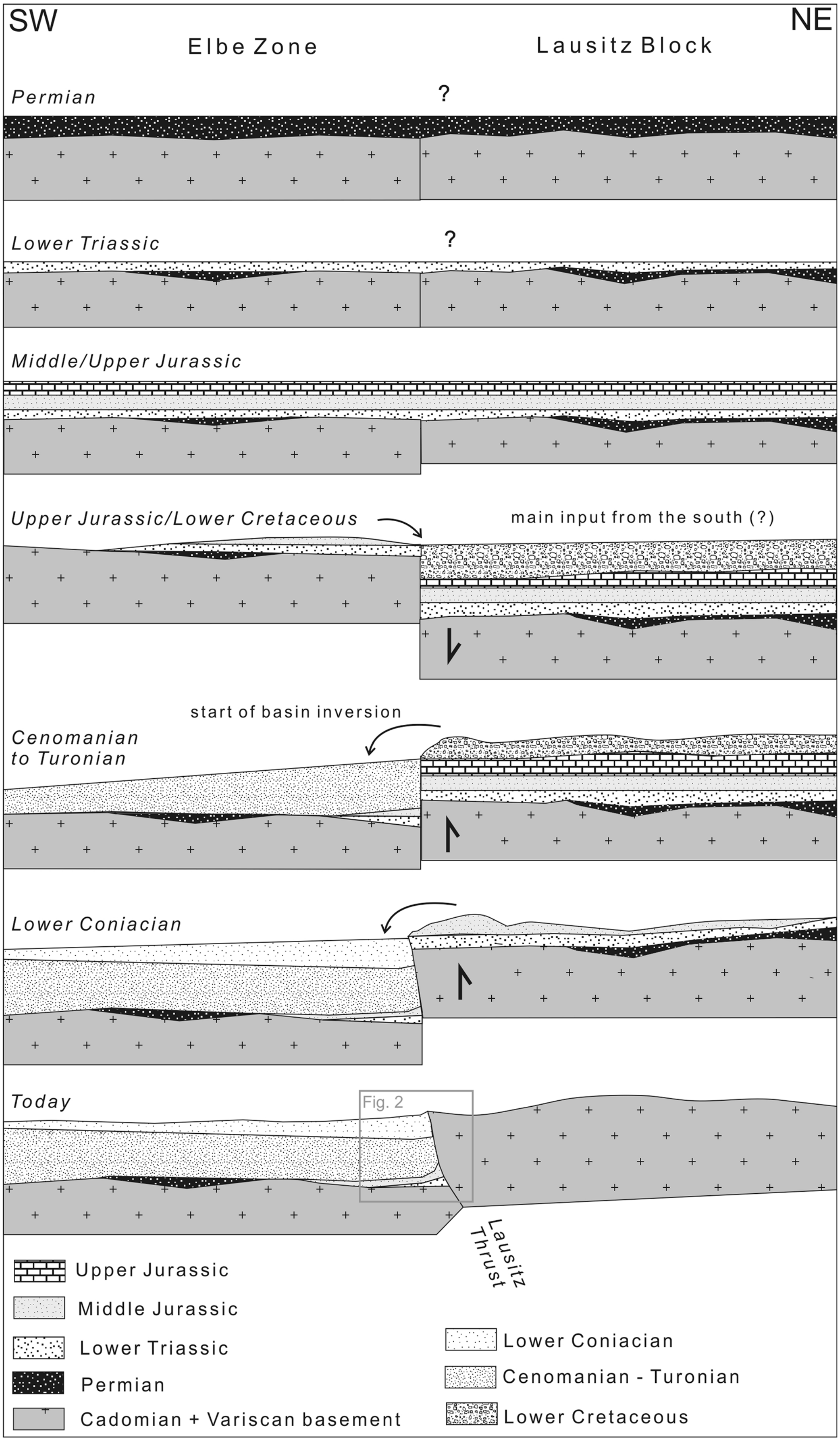
Although other authors (e.g. Pietzsch 1963) already assumed a Jurassic cover for some areas of Saxony in particular and Central Europe in general, these Jurassic sandstones have never been considered as a possible source area for the Cretaceous sedimentary rocks of the Elbtal Group. The occurrences of Jurassic deposits, comprising the upper Middle to middle Upper Jurassic, along the Lausitz Thrust in Saxony confirm this interpretation.

From this interpretation follows the conclusions that the lower units of the Upper Cretaceous basin fill (Elbtal Group, represented by samples Sk 1 s, Sk 3-1, Sk 4-1, Sk 5 and Sk 6-2) must consist of reworked sediments younger than Middle Jurassic (post-Middle Jurassic sediments). This upper part of the former Lausitz Block cover had to become eroded prior to Coniacian erosion and redeposition of Middle Jurassic sediments into the Elbe valley (Fig. 14). The lowermost sandstones of the Schmilka section (Sk 1 s, Sk 3-1, Sk 4-1, Sk 5 and Sk 6-2) might represent reworked Lower Cretaceous sediments (Fig. 14), which is a completely new interpretation.

It is assumed that Triassic and Permian sedimentary rocks, lying below the Jurassic deposits covering the Lausitz Block, were eroded later (post-Coniacian). Permian and Triassic sediments might have contributed to the clastic sedimentary rocks in the Santonian and Campanian, just like the basement of the Lausitz Block itself. These Santonian and Campanian units were probably eroded in the latest Cretaceous and Lower Paleogene as reaction of the maximum uplift of inversion-related basins of Central Europe (Voigt 2009).

Conclusions and summary

- From analysed sandstones from the Upper Triassic and the Middle Jurassic of Germany only the latter ones contained a significant amount of Meso-and Paleoproterozoic ages, representing a Scandinavian source (North Sea Dome, southern Baltica).
- The sudden input of Meso-and Paleoproterozoic ages in the Middle Jurassic sedimentary rocks was caused by the uplift of the North Sea dome due to the opening of the Atlantic Ocean.


SW
NE
Elbe Zone
Lausitz Block
Permian
?
Lower Triassic
?
Middle/Upper Jurassic
Upper Jurassic/Lower Cretaceous
main input from the south (?)
start of basin inversion
Cenomanian to Turonian
Lower Coniacian
Today
Fig. 2
Lausitz Thrust
Upper Jurassic
Middle Jurassic
Lower Triassic
Permian
Cadomian + Variscan basement
Lower Coniacian
Cenomanian - Turonian
Lower Cretaceous

◂**Fig. 14** Model of tectonic inversion and syntectonic redeposition of the Mesozoic cover of the Lausitz Block based on Voigt (1995, 1996, 2009) and own results. Uplift of the Lausitz Block along the Lausitz Thrust started in the lower Upper Cretaceous (Cenomanian). From that time on, the Lausitz Block as a part of the Lausitz–Krkonoše High (WestSudetic Island) and its Mesozoic cover were the main source areas for the sandstones of the Elbtal Group. Erosion of Middle Jurassic (Dogger) siliciclastic sedimentary rocks started in the Lower Coniacian. Older (Permian and Triassic) sedimentary rocks and the basement of the Lausitz Block did not contribute to the formation of Upper Cretaceous deposits in Saxony and where not at the surface at that time

- The Scandinavian source can be traced in Middle Jurassic samples from northern as well as from southern Germany, indicating that these sands were distributed across the whole of Germany, and probably Central Europe.
- The high input of Meso- and Paleoproterozoic detrital zircon ages represent a singular event in the Mesozoic sedimentary record of Central Europe, characterizing the Dogger sandstones. This makes the Middle Jurassic Dogger sandstones to a perfect marker for the Cretaceous European basin inversion.
- The Upper Cretaceous (Lower Turonian to Lower Coniacian) sandstones of the Schmilka section (Elbtal Group) in the Elbe valley in Saxony show a distinct change in their U–Pb detrital zircon age spectra in the uppermost sample (sandstone e), represented by an increased amount of Meso- and Paleoproterozoic ages.
- The Lausitz Block to the north of the Elbe valley was a part of the West-Sudetic Island and covered with Permian, Triassic, Jurassic and most probably Lower Cretaceous sedimentary rocks. These were the source rocks that became eroded and re-deposited as the Upper Cretaceous sandstones of the Elbtal Group.
- Middle Jurassic sedimentary rocks that presumably covered the Lausitz Block were the source rocks for the Lower Coniacian sandstone e on top of the Schmilka section. This indicates that Triassic and Permian sedimentary rocks, lying below the Jurassic ones did not contribute to the Cretaceous sedimentary rocks of the Schmilka section.
- Erosion of these Jurassic sedimentary rocks started not earlier than in Lower Coniacian (Fig. 14).
- The lower part of the Schmilka section (Turonian sandstones) must therefore represent a reworked post-Jurassic Lausitz Block cover, which most probably was Lower Cretaceous.
- Triassic and Permian sedimentary rocks, lying below the Jurassic deposits on the Lausitz Block, were eroded later (post-Coniacian), and probably contributed together with the basement of the Lausitz Block itself to the clastic sedimentary rocks in the Santonian and Campanian. These were eroded again during uppermost Cretaceous and lower Paleogene.
- The zircon grains from the sandstones of the Schmilka section experienced at least their second cycle of recycling during the Upper Cretaceous sedimentation.

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