

# Keuper (Late Triassic) sediments in Germany – indicators of rapid uplift of Caledonian rocks in southern Norway

Josef Paul, Klaus Wemmer and Florian Wetzel

Paul, J., Wemmer, K. & Wetzel, F. 2009: Keuper (Late Triassic) sediments in Germany – indicators of rapid uplift of Caledonian rocks in southern Norway. *Norwegian Journal of Geology*, vol. 89, pp 193-202, Trondheim 2009, ISSN 029-196X.

K/Ar ages of detrital Keuper micas in the Central European Basin provide new information about the provenance of siliciclastic sediments. All samples of the Erfurt Formation (Lower Keuper) and the Stuttgart Formation (Middle Keuper) indicate Caledonian (445 - 388 Ma) ages. These sediments originate from the Caledonides of southern Norway. The older Fennoscandian Shield and the Russian Platform did not supply any material. In combination with zircon fission track data, we show that uplift of the Caledonides of southern Norway accelerated dramatically during the Carnian, most likely as a result of rifting of the Viking Graben. This push of Scandinavian-derived sediments ceased in the Upper Keuper (Rhaetian). Instead of Scandinavian sediments, micas of Panafrican age were transported from southeast Poland and Slovakia into the Central European Basin. Only micas in the vicinity of the south German Vindelician High and the Bohemian Block have Variscan ages.

J. Paul, K. Wemmer, F. Wetzel: *Geowiss. Zentrum der Georg-August Universität Göttingen, Goldschmidt-Str.3, D 37077 Göttingen, Germany, e-mail corresponding author: jpaul@gwdg.de*

## Introduction

As a result of hydrocarbon exploration, knowledge of Norwegian offshore sedimentary basins has increased dramatically, whereas the corresponding onshore evolution is scarcely known, mainly due to the lack of sediments. Only by fission track thermochronology is it possible to gain information about the uplift of southern Norway (Andriessen & Bos 1986; Zeck et al. 1988; Rohrman et al. 1994; 1995, Hendriks et al. 2007). An additional method to complement the knowledge about uplift and erosion are investigations of the eroded and transported grains at their new locations. Provenance of siliciclastic sediments can be determined by the isotopic age of detrital white mica (Wetzel 1991; Huckriede et al. 2004).

During the Early Triassic, sediments of the Buntsandstein were mainly transported into the Central European Basin from Variscan areas in the southwest (French Massif Central), south (Vindelician Massif), and southeast (Bohemian Massif), according to measurements of cross bedding, distribution of grain sizes and K/Ar ages of detrital micas (Paul et al. 2008). Siliciclastic sediments of the Muschelkalk (Middle Triassic) were also delivered into the basin from the Vindelician Massif. With the onset of the Keuper, there was an abrupt change in the transport direction. Due to Cimmerian movements, sediments were transported from Scandinavia towards the south. This is the so-called “Nordic Keuper” of southern

Germany. Wurster (1964) and Beutler (2005) assumed that the eroded material originated from Scandinavia, but the exact provenance was not known.

Isotopic K/Ar ages of detrital white micas from Keuper sediments of the Central European Basin enable the provenance, sediment pathways, and thermochronology of the source areas to be reconstructed.

Clastic sediments of the Lower Keuper (Erfurt Formation), the Stuttgart and the Arnstadt Formations of the Middle Keuper, and the Upper Keuper (Exter Formation) contain a sufficient amount of large white micas for analysis (Fig.1). Unfortunately, dateable grains are lacking in the mudstones and evaporites of the Middle Keuper.

The aim of the present study is to demonstrate that Lower and Middle Keuper sediments of Central Europe originate from the Caledonian mountain range of southern Norway. Further, that a rapid uplift of these areas during the Late Triassic is required to match the times of cooling in Norway and deposition in Germany.

## Geological Setting

The Fennoscandian shield consists almost entirely of Precambrian rocks. In south Sweden, rocks related to the Gothian Orogeny (1.75 – 1.55 Ga) were reworked and heated by the **Sveconorwegian** Orogeny (1.1 – 0.9

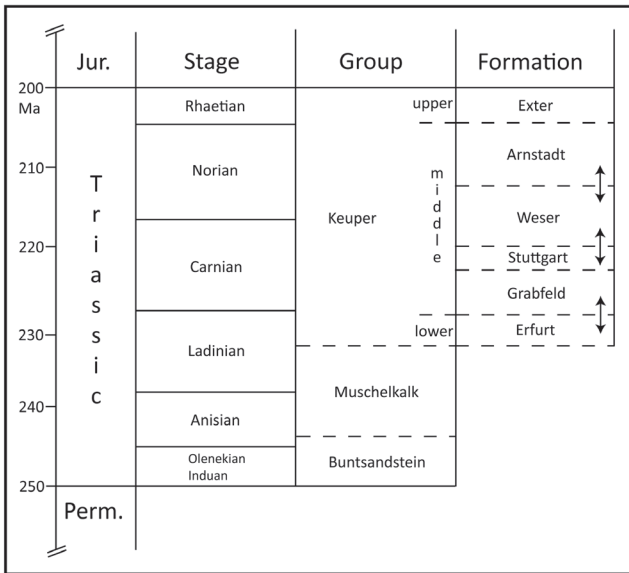


Fig. 1 Stratigraphy and depositional ages of the German Triassic. The age and the exact correlation of the Keuper formations are not yet fixed in detail. After the Geologic Time Scale (Gradstein et al. 2004) and explanations of the Stratigraphic Table of Germany (Menning et al. 2005).

Ga; Starmer 1993, Bingen et al. 2005, 2007). A phase of erosion followed, which culminated in the development of the sub-Cambrian peneplain which was about 200 m higher than the recent surface of the land (Lidmar-Bergström 1996). The Lower Palaeozoic sedimentary cover was less than some hundreds of metres as shown by down-faulted remnants preserved in some places like grabens. Upper Palaeozoic sediments are only preserved in the Oslo rift system which was active from late Carboniferous to the Permian (Olaussen et al. 1994; Larsen et al. 2008). In Sweden, no Devonian or younger Palaeozoic sediments have been recorded. Modelling of apatite fission-track thermochronology resulted in a possible maximum thickness of less than 2.5 km for Devonian to Permian rocks (Cederbom et al. 2000, Cederbom 2001, Larson et al. 2006). Hendriks & Redfield (2005, 2006) rejected this interpretation of fission track data and stated that there is no evidence for the existence of such a deep foreland basin. In any case, temperatures of 350°C are not reached in Phanerozoic sediments of south Sweden and the Baltic area.

At the time of the Keuper, potential source areas which were consolidated by the **Panafrican** Orogeny (which is termed the Cadomian Orogeny in West and Central Europe) were the Małopolska and the Lysogory Massifs (570 - 520 Ma) in Poland, the Teplà-Barrandian (610 - 490 Ma) and the Brunovistulian (650 - 540 Ma) in the Czech and Slovak Republics (Blümel 1995; Chab et al. 1995; Finger et al. 1995; Bełka et al. 1997). Other areas, like the London-Brabant Massif, were also affected by the Cadomian Orogeny, but later orogenies like the Caledonian and Variscan Orogenies reset the radiometric systems.

The **Caledonian** Orogeny took place between 520 and 390 Ma (Ziegler 1990; Roberts 2003) and affected a nearly 2000 km long belt from the Appalachians through Great Britain to northern Norway. The cooling ages of muscovites and biotites corresponding to the exhumation of the Western Gneiss Region and associated nappe rocks of southern Norway are dated at 415 - 380 Ma using <sup>40</sup>Ar/<sup>39</sup>Ar dating techniques (Fossen & Dallmeyer 1998; Fossen & Dunlap 1998; Root et al. 2005; Johnston et al. 2007; Kylander-Clark et al. 2007). Other areas affected by the Caledonian Orogeny are the Mid-European Caledonides extending from England to the Sudetic Mts. in Poland. The already consolidated London-Brabant Massif was caledonized, involving the thermal overprinting of earlier stages.

During the **Variscan** orogeny (370 - 300 Ma) the Massif Central, the Rhenish Massif, the Bohemian Massif and the Vindelician Massif were formed. Again, the radiometric age of the Bohemian Massif, which was consolidated by the Cadomian Orogeny is partly rejuvenated by the Variscan Orogeny (Schäfer 1997). The late Variscan granites especially affected the thermochronology. Sediments from the Rhenish Massif yielded K/Ar ages of

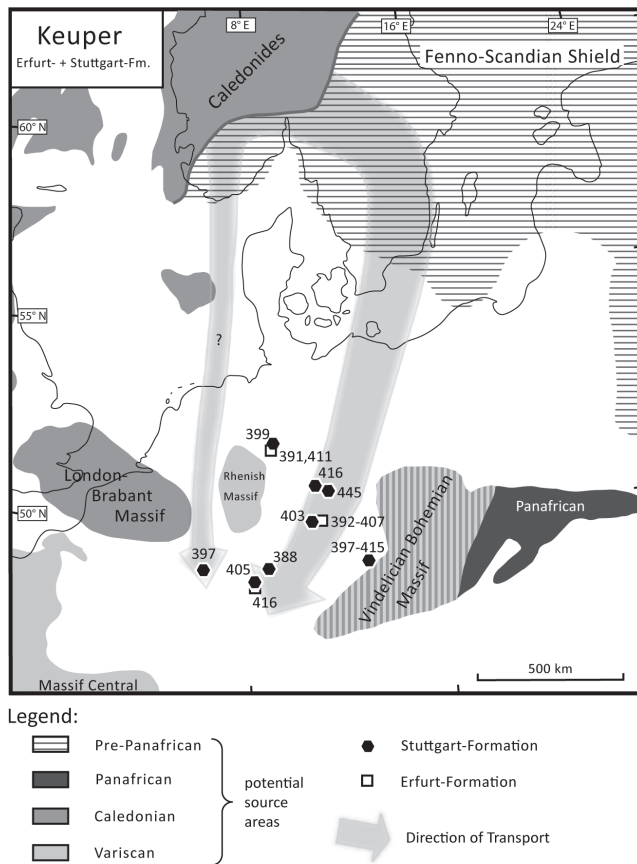


Fig. 2. Palaeogeography, source areas and radiometric ages of detrital micas of the Erfurt Fm. and the Stuttgart Fm. (Lower and Middle Keuper) in central Europe. Palaeogeography modified after Ziegler (1990) and Beutler & Nitsch (2005).

detrital micas between 650 and 370 Ma (Neuroth 1997; Huckriede et al. 2004).

Northeast of the Central European Basin, the large Fennoscandian Block and the Russian Platform extended from southeast Norway across Sweden and the Baltic to Belorussia and eastern Poland (Ziegler, 1990; Beutler & Nitsch 2005; Fig. 2). The western part of the Scandes were occupied by the Caledonides. Other potential source areas were the Vindelician and Bohemian Massifs, and the French Massif Central. Between these massifs, there were gateways to the Tethys, for instance, the Moravian and the Burgundy Gateway. The Viking Graben between Norway and the Hebrides formed part of the Atlantic Rift System. Between the Rhenish and the London-Brabant Massif, there was the Trier gate connecting the Netherlands and North Sea areas with the newly-formed Paris Basin (Bourquin & Durand 2006).

With the onset of the Keuper, fluvial sediments from Scandinavia prograded into the Central European Basin forming large deltas with associated barrier islands and lagoons (Fig. 3).

In the lower part of the Middle Keuper, fluvial activity decreased due to drier climatic conditions. Sabkhas, gypsum and salt were deposited in the centre of the basin. A humid intermezzo, marked by the Stuttgart Formation, saw the return of fluvial sediments. A large system of rivers transported sedimentary loads from Scandinavia to Switzerland and further south into the Tethys (Wurster 1964). The upper part of the Middle Keuper, the Weser Formation and the Arnstadt Formation, consists again of dolomitic and gypsum sabkhas and salt deposits in northern Germany. The Upper Keuper (Exter Formation) is characterized by mudstones and sandstones that have a complicated facies pattern resulting from tectonic movements. According to Beutler & Nitsch (2005), sediments of the Exter Formation in south and central Germany were derived from the Vindelician hinterland, whereas sediments in northern Germany and Thuringia originated, as seen in their heavy minerals, from Fennoscandia or the Vindelician High (Klaue 1969; Häusser & Kurze 1975; Appel 1981).

## Methodology

Muscovite and biotite contain up to 9 % potassium, which includes 0.01167 % of radioactive  $^{40}\text{K}$  decaying to  $^{40}\text{Ar}$  (and  $^{40}\text{Ca}$ ) with a half-life time of  $1.25 \times 10^9$  years. Muscovite preserves the cooling age of its host rock due to high retentivity for argon, whereas biotite suffers from loss of argon during transport and sedimentary history (Clauer 1981). Muscovite is highly resistant to weathering even when transported over long distances into basal areas. It preserves the time when the temperature of the host rock decreased below 350°C (McDougall &

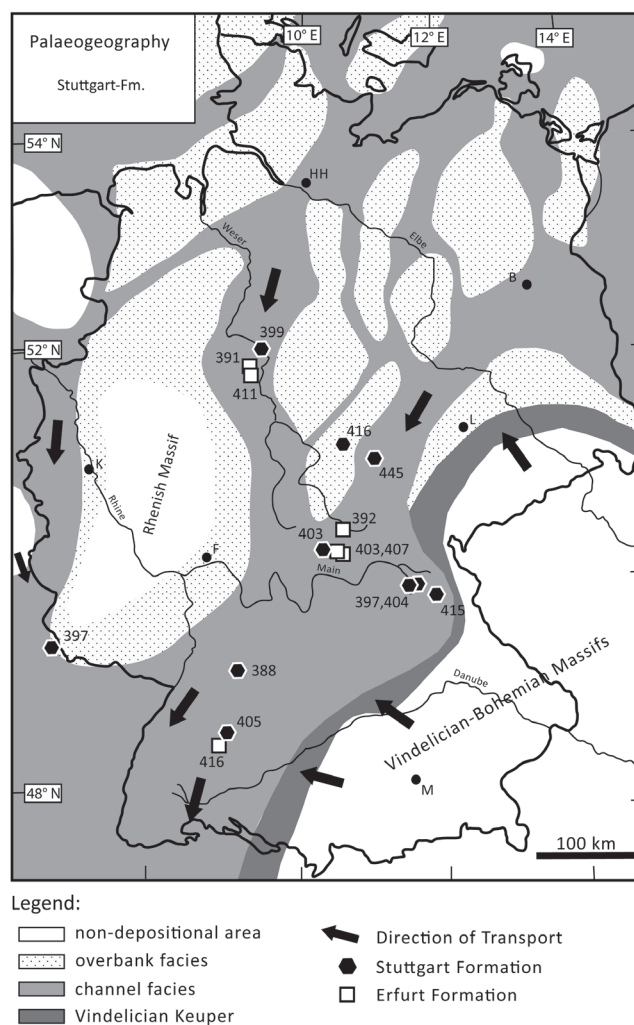


Fig. 3. Palaeogeography and radiometric ages of detrital micas in the Germanic Basin. Erfurt Fm. and Stuttgart Fm. (Lower and Middle Keuper). Palaeogeography modified after Beutler & Nitsch (2005). B = Berlin, F = Frankfurt, HH = Hamburg, K = Köln, L = Leipzig.

Harrison 1999) or 420°C as recommended by von Blanckenburg et al. (1989). K/Ar and Ar/Ar dating of detrital white mica as a tool for the identification of source areas has been used by many authors since the first publication by Fitch et al. (1966).

Sampling localities are given in their stratigraphic order in Table 1. Geographically, the samples are from north, central and southern Germany and Lorraine in eastern France. The samples were crushed, sieved, and the fractions between 200 and 500  $\mu\text{m}$  were used. The micas were enriched by using a countercurrent apparatus which separated well-rounded quartz and other grains from floating phyllosilicates (Welzel 1991). After drying, biotite and chlorite were removed by a Frantz magnetic separator. For the last purification, the micas were handpicked under a binocular microscope. White micas larger than 200  $\mu\text{m}$  were selected for analyses because of their high resistance to weathering. As

Table 1						
Sample	locality	grid	stratigraphy	K <sub>2</sub> O %	age±2σ Ma	
Wz174	Kleinwenkheim	R 35 91 500, H 55 69 900	Erfurt Fm.	9,60	403	9
Wz175	Wemmerichsh.	R 35 90 450, H 55 67 780	Erfurt Fm.	9,50	407	10
Wz176	Bedheim	R 44 04 700, H 55 84 800	Erfurt Fm.	10,05	392	10
JP4	Frommenhausen	R 34 90 300, H 53 66 000	Erfurt Fm., Pflanzensch. Mb.	8,64	416	18
R9/93	Elbrinxen	R 26 54 840, H 51 55 180	Erfurt Fm., Lettenkohlen Mb.	8,27	391	11
R10/93	Nieste	R 26 57 030, H 51 52 680	Erfurt Fm., <i>Anoplophora</i> Mb.	9,08	411	9
Wz120a	Bodenmühle	R 44 72 650, H 55 30 900	Stuttgart Fm.	9,95	397	10
Wz120b.	Bodenmühle	R 44 72 650, H 55 30 900	Stuttgart Fm.	9,07	404	9
Wz125	Scheckenhof	R 44 88 900, H 55 18 400	Stuttgart Fm.	7,03	415	10
Wz162	Unterhof	R 35 97 800, H 55 67 800	Stuttgart Fm.	10,27	403	9
JP1	Heilbronn	R 35 19 750, H 54 44 350	Stuttgart Fm.	8,68	388	8
JP2	Wendelsheim	R 34 95 600, H 53 75 200	Stuttgart Fm.	6,88	405	8
FW-2-07	Erfurt	R 44 31 800, H 56 55 540	Stuttgart-Fm.	9,73	445	20
FW-3-07	Altengottern	R 43 99 802, H 56 72 038	Stuttgart-Fm.	9,96	416	6
FW-6-07	Remelfang	Lorraine, France	Stuttgart-Fm.	10,24	397	5
R8/93	Hämelschenburg	R 27 00 685, H 52 01 830	Stuttgart Fm.	10,19	399	9
Wz 90	Schönbachsm.	R 44 05 600, H 55 43 200	Arnstadt Fm., Coburg Mb.	10,46	315	6
Wz165	Sternberg	R 43 98 700, H 55 70 900	Arnstadt Fm., Coburg Mb.	10,55	311	7
Wz177	Staffelbach	R 44 10 950, H 55 35 100	Arnstadt Fm., Coburg Mb.	10,25	317	8
Wz164	Annabild	R 36 00 600, H 55 71 500	Arnstadt Fm., Burgsands.Mb.	10,14	332	9
Wz 67	Pechgraben	R 44 67 000, H 55 41 600	Exter Fm.	9,58	325	7
Wz 71	Forkendorf	R 44 68 150, H 55 30 250	Exter Fm.	9,43	325	8
Wz115	Ebersdorf	R 44 34 000, H 55 66 300	Exter Fm.	10,16	338	8
Wz168	Großheirat	R 44 26 100, H 55 61 600	Exter Fm.	9,60	345	10
R1/94	Hedeper	R 44 08 180, H 57 70 560	Exter Fm.	9,46	569	6
FW5 07	Seeberg	R 44 13 600, H 56 43 760	Exter-Fm., <i>Contorta</i> Mb.	7,36	507	10

Tab.1: Isotopic ages of detrital Keuper micas (Welzel 1991, Reifferscheidt 1996, Wetzel 2007). R and H are Gauss-Krüger coordinates of the sample locality. The samples are arranged according to their depositional age.

a final treatment, the muscovites were ground under alcohol and the fraction >80 µm recovered by sieving. Using this procedure, the rims that might have suffered Ar loss were removed, and the fresh cores of the minerals analysed (Welzel 1991).

The argon isotopic composition was measured in a pyrex glass extraction and purification assembly coupled to a VG 1200 C noble gas mass spectrometer operating in static mode. The amount of radiogenic <sup>40</sup>Ar was determined by the isotope dilution method using a highly enriched <sup>38</sup>Ar spike from Schumacher, Bern (Schumacher 1975). The spike is calibrated against the biotite standard HD-B1 (Fuhrmann et al. 1987). The age calculations are based on the constants recommended by the IUGS quoted in Steiger & Jäger (1977).

Potassium was determined in duplicate by flame photometry using an Eppendorf Elex 63/61. The samples were dissolved in a mixture of HF and HNO<sub>3</sub> according to the technique of Heinrichs & Herrmann (1990). CsCl and LiCl were added as an ionisation buffer and internal standard, respectively.

The analytical error for the K/Ar age calculations is given at a 95% confidence level (2s). Details of argon and

potassium analyses from the laboratory in Goettingen are given in Wemmer (1991).

The obtained ages of the white mica samples are listed together with their potassium content. In many cases the potassium content can be regarded as an indication for the "freshness" of the muscovite grains. Pure separates of fresh white mica contain between 9.5 and 10.5 % of K<sub>2</sub>O. Lower values can be caused by impurities, e.g. mixing with minor amounts of quartz or other minerals, or by the alteration of the micas. In the latter case, the loss of potassium is always accompanied by a disproportionately high loss of Ar as the noble gas has no chemical bond with the crystal lattice. The altered minerals yield inaccurate younger ages, which can only be interpreted as minimum values for the requested cooling age. A thermal rejuvenation leading to partly reset, younger ages cannot be detected by the K/Ar method, but temperatures needed to reset recrystallisation-free muscovites at ca. 500°C (Villa 1998) can be excluded from the post-Keuper history.

K/Ar dating of fresh cores of muscovite, which did not suffer alteration or thermal rejuvenation leads to ages

comparable to those obtained by Ar/Ar techniques and have to be interpreted in the same manner (McDougall & Harrison 1999 and references therein).

We use the stratigraphic terminology and correlations introduced by the Deutsche Stratigraphische Kommission (2005), Menning et al. (2005), Nitsch (2005), and the International Geologic Time Scale (Gradstein et al. 2004). In older literature the term "Schilfsandstein" was used instead of Stuttgart Formation.

## Results

The isotopic ages of the white mica samples are listed in Table 1. Micas of six samples from the Erfurt Formation and ten samples of the Stuttgart Formation indicate cooling ages in a relatively narrow range between 416 and 388 Ma.

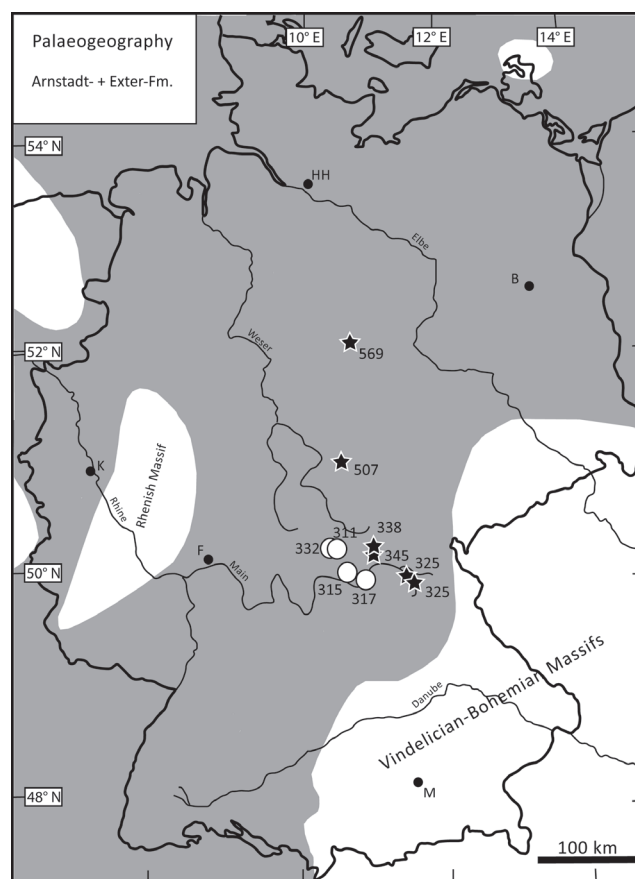
Results of nine age determinations of the Arnstadt Formation and the Exter Formation vary between 569 and 311 Ma. They form a cluster around 330 Ma and two analyses yielded ages of 569 and 507 Ma. The first group of samples is from southern Germany, whereas the two older ones are from northern and central Germany.

## Interpretation

It is obvious that the number of samples is too small for the determination of perhaps complicated transport patterns which may have changed several times over a period of 35 Ma. But the existing 25 age determinations, together with measurements of cross bedding, fission track data, trends of grain sizes, and heavy mineral analyses allow an overview of probable provenance areas.

Surprisingly, all detrital micas of the Erfurt Formation and the Stuttgart Formation from north to south Germany form a unimodal cluster at a weighted mean of 400 Ma (Tab.1). These data fit very well with the cooling ages of the exhuming Caledonian Orogene. The cooling ages of muscovites and biotites from the Western Gneiss Region and associated nappe rocks of southern Norway are dated at 415 – 380 Ma using  $^{40}\text{Ar}/^{39}\text{Ar}$  dating techniques (Fossen & Dallmeyer 1998; Fossen & Dunlap 1998; Root et al. 2005; Johnston et al. 2007; Kylander-Clark et al. 2007).

This Caledonian age of the micas is in marked contrast to the previous Buntsandstein and Muschelkalk strata, which contain Variscan micas (Paul et al. 2008). In spite of tidal or marine influences in south Germany (Gehrmann & Aigner 2002), an admixture of non-Caledonian particles can be excluded for northern Germany and downstream to southern Württemberg. The sediment particles originate from the Caledonides of southwestern Norway. It seems that smaller islands, like the Rhenish Massif, the London-Brabant Massif and the Texel High, did not contribute sedimentary material in large quantities.



Legend:

- non-depositional area
- depositional area
- ★ Exter-Formation
- Arnstadt-Formation

Fig. 4. Palaeogeography, and radiometric ages of detrital micas of the Arnstadt Fm. and the Exter Fm. (Middle and Upper Keuper) in Germany. Palaeogeography modified after Beutler & Nitsch (2005)

One general result of our investigation is that the Fenoscandian shield and the Russian Platform did not contribute material into the interior of the Central European Basin. Most likely, these old massifs were lowlands during the Keuper. The Schilfsandstein River systems transported the sedimentary load from the Norwegian Highland through southern Sweden without picking up any more muscovite (Fig. 2). We suppose that the sediments originate from the Caledonides of southern Norway, as this part is proximate to the Central European Basin. But in principle, we cannot exclude their northern continuation as provenance area.

The Vindelician Keuper of the Erfurt Formation and the Stuttgart Formation occupy only a narrow strip along the old massifs (Fig. 3). This means that both massifs were not elevated during this time, but had rather low reliefs.

The Caledonian ages of the Lower and Middle Keuper sediments are completely missing in the Exter Formation (Fig. 4) indicating a change in provenance area.

In southern Germany, the Variscan Vindelician and Bohemian Massifs were source areas. In northern and central Germany, the micas indicate Panafrican ages. Until now, there are only two analyses, but they are supported by mica ages of Lower und Middle Jurassic sediments in northern Germany, which give more or less similar ages of 655 and 555 Ma (Paul et al. 2008). We assume that these particles were derived from south Polish or Slovakian Panafrican source rocks and were transported westward along the shore of the Bohemian Massif (Fig. 5).

### Discussion

Köppen & Carter (2000) investigated the provenance of Triassic sediments by means of zircon fission-track data. The zircon fission track system is reset by overprinting

at temperatures between 200 and 320°C (Tagami et al. 1996). Köppen & Carter (2000) assumed that the highest palaeotemperatures after deposition had not exceeded 120°C for durations of 10<sup>6</sup>-10<sup>7</sup> years, and therefore the measured zircon fission track ages should record their original provenance signature. For two samples of the Erfurt Formation from southwest Germany and Poland they obtained ages of 263±16 and 270±15 Ma, respectively. The Stuttgart Formation in southwest Germany and Switzerland (three samples) yielded ages of 239±15, 226±15 and 219±31 Ma, whereas the Schilfsandstein (equivalent of the Stuttgart Formation) of southern Poland gave an age of 428±43 Ma. Two samples of the Middle Keuper, the micas of which were derived from the Vindelician High, gave ages of 276±26, and 267±20 Ma, respectively (Köppen & Carter 2000). The depositional ages of the Erfurt Formation, the Stuttgart and the Exter Formations are about 230, 220, and 200 Ma, respectively.

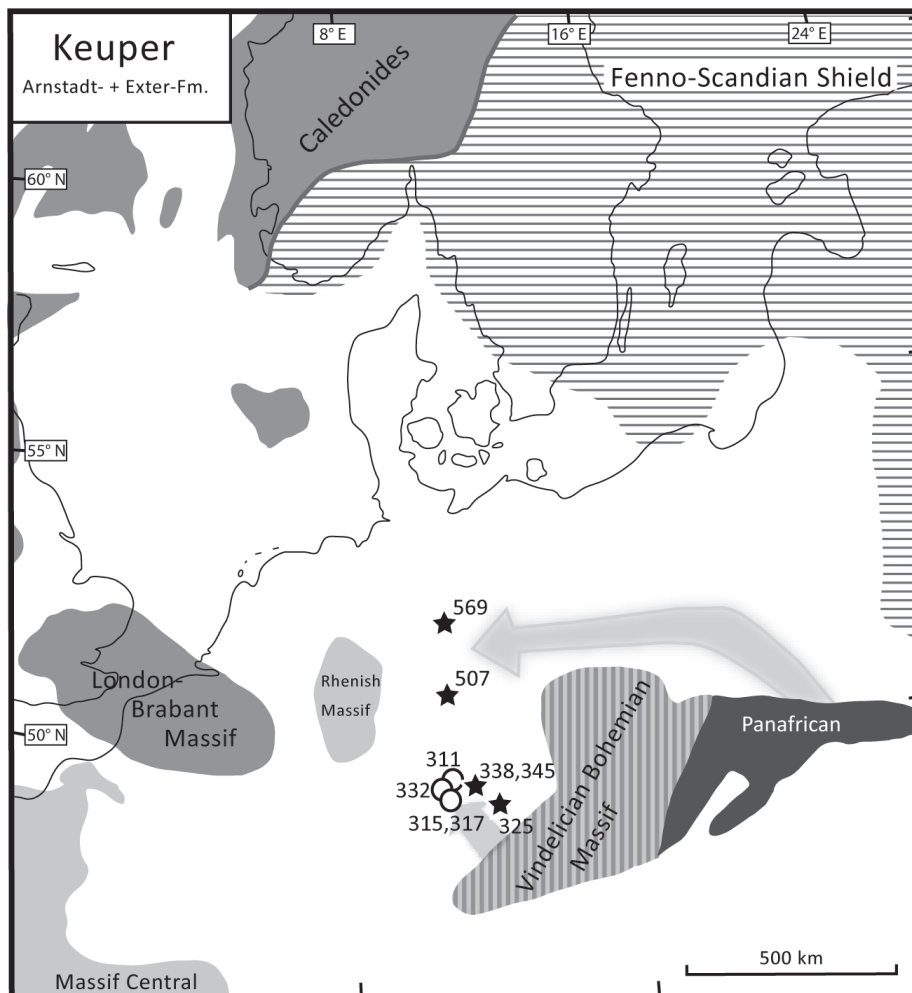


Fig. 5. Palaeogeography, source areas and radiometric ages of detrital micas of the Arnstadt Fm. and the Exter Fm. (Middle and Upper Keuper) in central Europe. Palaeogeography modified after Ziegler (1990) and Beutler & Nitsch (2005).

Legend:

- |  |                |                          |   |                        |  |
|--|----------------|--------------------------|---|------------------------|--|
|  | Pre-Panafrican | } potential source areas | ★ | Exter-Formation        |  |
|  | Panafrican     |                          | ○ | Arnstadt-Formation     |  |
|  | Caledonian     |                          |   | Direction of Transport |  |
|  | Variscan       |                          |   |                        |  |

Köppen & Carter (2000) assumed that the sediments of the Erfurt Formation originated from the Oslo Rift in southern Norway or from lower Permian volcanics that occur at the margins of the Bohemian Massif. The K/Ar ages of the micas that give Caledonian ages, exclude an origin from late Variscan volcanics of the Bohemian Massif. Investigations of zircon fission track thermochronology of the Oslo Rift by Rohrman et al. (1994), Olausen et al. (2004) and Larsen et al. (2008) yielded ages of about 600 Ma for gneisses at the shoulders, about 500 Ma for Silurian and Ordovician sandstones and 290 Ma for Permian magmatic rocks within the rift. The latter ages are due to post-rift heating by hydrothermal circulation. An origin of Keuper micas from south Sweden can be excluded since due to the shallow overburden the critical temperature of 500 to 350°C for re-setting the K/Ar system was not reached. In northeast Germany, the pattern of fluvial channels of the Schilfsandstein river leads from the Baltic Sea towards the southwest (Beutler & Nitsch 2005). Therefore, the rivers from southern Norway flowed in a southeast direction through Sweden and then turned southwesterly over the Baltic Sea towards northeast Germany and as far as Switzerland (Figs. 2, 3). Another possible transport pathway would be across the North Sea, the Netherlands and west of the Rhenish Massif towards the south.

Although the data of Köppen & Carter (2000) contain a large analytical error, it seems clear that - assuming a geothermal gradient of 30°C/km - a rock column of several km was removed in a period of less than 40 Ma in the case of the Erfurt Formation (Ladinian). The exhumation accelerated in the Carnian, during which time up to ten km were eroded in less than 10 Ma, calculated from the data of Köppen & Carter (2000).

Denudation thicknesses of seven to ten kms in the Eidfjord area in southern Norway were calculated by Andriessen & Bos (1986) using apatite fission track thermochronology. But Hendriks et al. (2007) mentioned in a compilation of fission track data of Scandinavia that Andriessen & Bos (1986) did not consider the possibility of annealing fission tracks at temperatures between 60° and 120 °C which is critical for reconstructing the thermal history.

Nevertheless, the zircon fission track ages of the Stuttgart Formation from the southwest part of the Central European Basin are only some millions of years older than the depositional age, and require a very rapid uplift and subsequent exhumation of southwestern Scandinavia from the Ladinian (about 230 Ma) until the Rhaetian (210 Ma). Only in humid periods like those of the Erfurt Formation and Stuttgart Formation, was the fluvial capacity large enough to transport sand-sized particles from Norway to central Europe. In arid times, only mud-sized particles reached Germany. The termination of the southward transport from Scandinavia may be the result of orogenic movements which fundamentally changed

the palaeogeographic setting. At the base and within the Upper Keuper, there are several far-reaching discordances and unconformities which are Early Cimmerian in age (Wienholz 1967; Wolburg 1969; Ziegler 1990; Beutler 2005). Additionally, the formation of basins along the Tornquist-Tesseyre lineament could have prevented the transport of clastics towards central Europe.

Our data support the opinion of Hendriks & Redfield (2006) that there was no deep Caledonian foreland basin in Sweden, as in the middle and late Triassic no detrital mica has been delivered from Fennoscandia to the Central European Basin. Either the sediments were already eroded during the Carboniferous and Permian or there was no deep basin.

The uplift and exhumation of southern Norway seems to be connected to the rifting of the Viking Graben and the Horda Basin in the North Sea which started in the upper Permian or early Triassic (Ziegler 1990). As a syn-rift flank uplift (Cloetingh & Kooi 1992), both shoulders of the rift were uplifted, similar to the Black Forest and Vosges on both sides of the Tertiary Rhine Graben.

The provenance of the Lorraine Schilfsandstein, which has also a Caledonian age, is not clear. The particles may have been transported from the northeast, via east of the Rhenish Massif or they were derived from the northwest through the gateway between the London-Brabant and the Rhenish Massif (Fig. 2). In the latter case also the London-Brabant Massif may be the area of provenance.

The zircon fission track age of the south Polish Schilfsandstein (400 Ma) is difficult to interpret. Most likely, the sediment particles were derived from other sources than the Norwegian Caledonides. Unfortunately, there are no K/Ar ages of detrital white micas from these sediments.

## Conclusions

K/Ar ages of detrital micas are a valuable tool for reconstructing provenance and the pathways of sediments. In combination with fission track data, the thermochronology of the source rocks can be estimated. The Keuper (Ladinian - Rhaetian) of the Central European Basin started with an influx of fluvial sediments from Scandinavia.

Micas in the sediments of the Lower and Middle Keuper yield K/Ar ages of about 400 Ma, the age of exhumation and cooling of the Caledonian Orogen. As older micas could not be detected, it is clear that the Fennoscandian shield and the Russian platform did not contribute material to the Central European Basin, being lowlands during this time. The source area was the south Norwegian Caledonian mountain range. Zircon fission track thermochronology give detrital ages of 266 Ma for the Lower Keuper and 239-219 Ma for the Middle Keuper. Their depositional ages are about 230 and 220 Ma, respectively. From these data a very rapid uplift

and subsequent exhumation of the Caledonian mountain range in south Norway can be inferred. Most likely, this event is connected with the formation of the Viking Graben or – more generally – with the Atlantic Rift system. Micas in the Rhaetian (Upper Keuper) have quite a different origin. They were derived from Panafrican sources in southeast Poland or the Slovakian Republic.

#### Acknowledgements

We thank the following persons for permission to sample in active quarries: Herrn Dipl.-Ing. H. Weigelt, Creaton AG, Großgottern and Herrn Winter, Wienerberger Ziegelindustrie GmbH, Erfurt-Gispersleben. Dr. Herrmann Huckriede, Thüringische Landesanstalt für Umwelt und Geologie, Jena and Prof. Dr. Theo Simon, Landesamt für Geologie und Rohstoffe Baden-Württemberg, Stuttgart, helped to select sampling localities in Thüringen and Baden-Württemberg. Special thanks to Prof. Dr. Gerhard Bachmann, University of Halle, for fruitful discussions. Dr. David Tanner, Leibniz-Institut für Angewandte Geophysik, Hannover, supported us as an English native speaker. The constructive reviews and suggestions of E. S. Rasmussen and an anonymous reviewer are gratefully acknowledged. We appreciate the editorial handling by P. T. Osmundsen.

## References

- Andriessen, P.A.M. & Bos, A. 1986: Post-Caledonian thermal evolution and crustal uplift in the Eidfjordarea, western Norway. *Norsk geologisk Tidsskrift* 66, 243-250.
- Appel, D. 1981: Petrographie und Genese der Sandsteine des Unter- und Mittelrhäts im nördlichen Harzvorland (Ostniedersachsen). *Mitteilungen Geologisches Institut der Universität Hannover* 20, 1-133.
- Belka, Z., Ahrendt, H., Franke, W., & Wemmer, K. 1997: Provenance of clastic material in the Cambrian and Devonian rocks of Palaeozoic terranes of southern Poland; evidence from K/Ar ages of detrital muscovites. *Terra Nostra*, 97/5, 23-27.
- Beutler, G. 2005: 4.3 Diskordanzen im Keuper. In: Deutsche Stratigraphische Kommission (ed.), *Stratigraphie von Deutschland IV. Keuper. Courier Forschungsinstitut-Institut Senckenberg* 253, 85-93.
- Beutler, G. & Nitsch, E. 2005: Paläogeographischer Überblick. In: Deutsche Stratigraphische Kommission (ed.), *Stratigraphie von Deutschland. IV. Keuper. Courier Forschungsinstitut-Institut Senckenberg* 253, 15-31.
- Bingen, B., Nordgulen, Ø. & Viola, G. 2008. A four-phase model for the Sveconorwegian orogeny, SW Scandinavia. *Norwegian Journal of Geology* 88, 43-72.
- Bingen, B., Skår, Ø., Marker, M., Sigmond, E.M.O., Nordgulen, Ø., Ragnhildstveit, J., Mansfeld, J., Tucker, R.D. & Liégeois, J.P. 2005: Timing of continental building in the Sveconorwegian orogen, SW Scandinavia. *Norwegian Journal of Geology* 85, 87-116.
- Blümel, P. 1995: Exotic Metamorphic Nappes. Metamorphic Evolution. – In: Dallmeyer, R.D., Franke, W. & Weber, K. (eds.): *Pre-Permian Geology of Central and Eastern Europe*, 295-308, Springer, Heidelberg.
- Bourquin, S. & Durand, M. 2006: International Field Workshop on “The Triassic of eastern France. 74 pp., Geosciences Rennes.
- Cederbom, C. 2001: Phanerozoic, pre-Cretaceous thermotectonic events in southern Sweden revealed by fission track thermochronology. *Earth and Planetary Science Letters* 188, 199-209.
- Cederbom, C., Larson, S.A., Tullborg, E.-L. & Stiberg, J.-P. 2000: Fission track thermochronology applied to Phanerozoic thermotectonic events in central and southern Sweden. *Tectonophysics*, 316, 153-167.
- Cháb, J., Suchý, V. & Vejnar, Z. 1995: Tepla-Barrandian Zone (Bohemicum). Metamorphic Evolution. – In: Dallmeyer, R.D., Franke, W. & Weber, K. (eds.): *Pre-Permian Geology of Central and Eastern Europe*, 403-410, Springer, Heidelberg.
- Clauer, N. 1981: Strontium and argon isotopes in naturally weathered biotites, muscovites and feldspars. *Chemical Geology* 31, 325-334.
- Cloetingh, S., & Kooi, H. 1992: Intraplate stresses and dynamical aspects of rifted basins. *Tectonophysics* 215, 167-185.
- Deutsche Stratigraphische Kommission (ed.). 2005: *Stratigraphie von Deutschland IV. Keuper. Courier Forschungsinstitut-Institut Senckenberg* 253, 1-296.
- Finger, F., Frasl, G., Dudek, A., Jelínek, E. & Thöni, M. 1995: Igneous Activity (Cadomian Plutonism in the Moravo-Silesian Basement). In: Dallmeyer, R.D., Franke, W. & Weber, K. (eds.): *Pre-Permian Geology of Central and Eastern Europe*, 495-507, Springer, Heidelberg.
- Fitch, F.J., Miller, J.A. & Thompson, D.B. 1996: The palaeogeographic significance of isotopic age determinations on detrital micas from the Triassic of the Stockport-MacClesfield District, Cheshire, England. *Palaeogeography, Palaeoclimatology, Palaeoecology* 2, 281-312.
- Fossen, H. & Dallmeyer, R.D. 1998:  $^{40}\text{Ar}/^{39}\text{Ar}$  muscovite dates from the nappe region of southwestern Norway: dating extensional deformation in the Scandinavian Caledonides. *Tectonophysics* 285, 119-133.
- Fossen, H. & Dunlap, W.J. 1998: Timing and kinematics of Caledonian



- thrusting and extensional collapse, southern Norway: evidence from  $^{40}\text{Ar}/^{39}\text{Ar}$  thermochronology. *Journal of Structural Geology* 20, 765-781.
- Fuhrmann, U., Lippolt, H.J. & Hess, J.C. 1987: Examination of some proposed K-Ar standards:  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses and conventional K-Ar-Data. *Chemical Geology, Isotope Geoscience Section* 66, 41-51.
- Gehrmann, O. & Aigner, T. 2002: Der Schilfsandstein (Obere Trias) bei Heilbronn (S-Deutschland): Hinweise auf tidale Einflüsse. *Neues Jahrbuch für Geologie und Paläontologie. Abhandlungen* 223, 377-403.
- Gradstein, F.M., Ogg, J.G. & Smith, A.G. 2004: A Geologic Time Scale 2004. 489 pp., Cambridge Univ. Press, Cambridge.
- Häusser, I. & Kurze, M. 1975: Sedimentationsbedingungen und Schwerkmineralführung im Mesozoikum des Nordteils der DDR. *Zeitschrift für Geologische Wissenschaften* 3, 1317-1332.
- Heinrichs, H. & Herrmann, A.G. 1990: Praktikum der Analytischen Geochemie. 1-669, Springer, Heidelberg, Berlin.
- Hendriks, B., Andriessen, P., Huigen, Y., Leighton, C., Redfield, T., Murrell, G., Gallagher, K. & Nielsen, S.B. 2007: A fission track data compilation for Fennoscandia. *Norwegian Journal of Geology* 87, 143-155.
- Hendriks, B.W.H. & Redfield, T.F. 2005: Apatite fission track and (U-Th)/He date from Fennoscandia: An example of underestimation of fission track annealing in apatite. *Earth and Planetary Science Letters* 236, 443-458.
- Hendriks, B.W.H. & Redfield, T.F. 2006: Reply to: Comment on "Apatite Fission Track and (U-Th)/He data from Fennoscandia: An example of underestimation of fission track annealing in apatite" by B.H.W. Hendriks and T.F. Redfield. *Earth and Planetary Science Letters* 248, 568-576.
- Huckriede, H., Wemmer, K. & Ahrendt, H. 2004: Palaeogeography and tectonic structure of allochthonous units in the German part of the Rheno-Hercynian Belt (Central European Variscides). *International Journal of Earth Sciences* 93, 414-431.
- Johnston, S.M., Hacker, B.R. & Andersen, T.B. 2007: Exhuming Norwegian ultrahigh-pressure rocks: Overprinting extensional structures and the role of the Nordfjord-Sogn Detachment Zone. *Tectonics* 26, TC5001, doi: 10.1029/2005TC001933.
- Klaau, D. 1969: Sedimentpetrographische Untersuchungen der Rätssandsteine Thüringens. Geologie. Beiheft 64, 1-82.
- Köppen, A. & Carter, A. 2000: Constraints on provenance of the central European Triassic using detrital zircon fission track data. *Palaeogeography, Palaeoclimatology, Palaeoecology* 161, 193-204.
- Kylander-Clark, A.R.C., Hacker, B.R., Johnson, C.M., Beard, B.L., Mahlen, N.J. & Papen, T.J. 2007: Coupled Lu - Hf and Sm - Nd geochronology constrains prograde and exhumation histories of high- and ultrahigh-pressure eclogites from Western Norway. - *Chemical Geology* 242, 137-154.
- Larsen, B., Olausen, S., Sundvall, B. & Heeremans, M. 2008: The Permo-Carboniferous Oslo Rift through six stages and 65 million years. *Episodes* 31, 52-58.
- Larson, S.A., Cederbom, C.E., Tullberg, E.-L. & Stiberg, J.-P. 2006: Comment on "Apatite fission track and (U-Th)/He data from Fennoscandia: An example of underestimation of fission track annealing in apatite" by Hendriks and Redfield [Earth Planet. Sci. Lett. 236 (443-458)]. *Earth and Planetary Science Letters* 248, 561-568.
- Lidmar-Bergström, K. 1996: Long term morphotectonic evolution in Sweden. *Geomorphology* 16, 33-59.
- McDougall, I. & Harrison, T.M. 1999: Geochronology and Thermochronology by the  $^{40}\text{Ar}/^{39}\text{Ar}$  Method, 269 pp., Oxford Univ. Press, Oxford.
- Menning, M., Gast, R., Hagdorn, H., Käding, K.-C., Simon, T., Szurli, M. & Nitsch, E. 2005: Zeitskala für Perm und Trias in der Stratigraphischen Tabelle von Deutschland 2002, zykl stratigraphische Kalibrierung der höheren Dyas und Germanischen Trias und das Alter der Stufen Radium bis Rhaetium 2005. *Newsletter on Stratigraphy* 41, 174-210.
- Neuroth, H. 1997: K/Ar-Datierungen an detritischen Muskoviten - „Sicherungskopien“ orogener Prozesse am Beispiel der Varisciden. *Göttinger Arbeiten zur Geologie und Paläontologie* 72, 143 pp.
- Nitsch, E. 2005: Der Keuper in der stratigraphischen Tabelle von Deutschland 2002. Formationen und Folgen. *Newsletter on Stratigraphy* 41, 159-172.
- Olausen, S., Larsen, B. & Steel, R. 1994: The Upper Carboniferous - Permian Oslo Rift; basin fill in relation to tectonic development. *Memoir of the Canadian Society of Petroleum Geologists* 17, 175-197.
- Paul, J., Wemmer, K. & Ahrendt, H. 2008: Provenance of siliciclastic sediments (Permian - Jurassic) of the Central European Basin. - *Zeitschrift der deutschen Gesellschaft für geologische Wissenschaften* 159, 641-650.
- Reifferscheidt, H. 1996: K/Ar-Altersdatierungen an detritischen Muskoviten des Zechstein bis Dogger (Hessen, Thüringen, Niedersachsen). Unpubl. diploma thesis, University of Göttingen, 55 pp.
- Roberts, A. 2003: The Scandinavian Caledonides: event chronology, palaeogeographic settings and likely modern analogues. *Tectonophysics* 365, 283-299.
- Rohrman, M., van der Beek, P. & Andriessen, P. 1994: Syn-rift thermal structure and post-rift evolution of the Oslo Rift (south east Norway): New constraints from fission track thermochronology. *Earth and Planetary Science Letters* 127, 39-54.
- Rohrman, M., van der Beek, P., Andriessen, P. & Cloetingh, S. 1995: Meso-Cenozoic morphotectonic evolution of southern Norway: Neogene domal uplift inferred from apatite fission track thermochronology. *Tectonics* 14, 704-718.
- Root, D.B., Hacker, B.R., Gans, P.B., Ducea, M.N. & Mosenfelder, J.L. 2005: Discrete ultrahigh-pressure domains in the Western Gneiss Region, Norway: implications for formation and exhumation. *Journal of Metamorphic Geology* 23, 45-61.
- Schäfer, J., Neuroth, H., Ahrendt, H. & Dörr, W. 1997: Accretion and exhumation at a Variscan active margin recorded in the Saxothuringian flysch. *Geologische Rundschau* 87, 599-611.
- Schumacher, E. 1975: Herstellung von 99,9997%  $^{38}\text{Ar}$  für die  $^{40}\text{K}/^{40}\text{Ar}$  Geo-chronologie. *Geochronologica Chimia*, 24: 441-442.
- Starmer, I. 1993: The Sveconorwegian orogeny in southern Norway, relative to deep crustal structures and events in the North Atlantic Proterozoic supercontinent. *Norsk Geologisk Tidsskrift* 73, 109-132.
- Steiger, R.H. & Jäger, E. 1977: Subcommission on Geochronology: Convention on the Use of Decay Constants in Geo- and Cosmochronology. *Earth and Planetary Science Letters* 36, 359-362.
- Tagami, T., Carter, A. & Hurford, A.J. 1996: Natural long-term annealing of the zircon fission-track system in Vienna Basin deep borehole samples: constraints upon the partial annealing zone and closure temperature. *Chemical Geology* 130, 147-157.
- von Blankenburg, F., Villa, I.M., Baur, H., Morteani, G. & Steiger, R.H. 1989: Time calibration of a PT-path from the Western Tauern Window, Eastern Alps: the problem of closure temperatures. *Contributions to Mineralogy and Petrology* 101, 1-11.
- Villa, I.M. 1998: Isotopic closure. *Terra Nova* 10, 42-47.
- Welzel, B. 1991: Die Bedeutung der K-Ar-Datierungen an detritischen Muskoviten für die Rekonstruktion tektonometamorpher Einheiten im orogenen Liefergebiet - ein Beitrag zur Frage der varistischen Krustenentwicklung in der böhmischen Masse. *Göttinger Arbeiten zur Geologie und Paläontologie* 49, 61 pp.
- Wemmer, K. 1991: K/Ar-Datierungsmöglichkeiten für retrograde Deformationsprozesse im spröden und duktilen Bereich - Beispiele aus der KTB-Vorbohrung (Oberpfalz) und im Bereich der Insubrischen Linie (Nord-Italien). - *Göttinger Arbeiten zur Geologie und Paläontologie* 51, 61 pp.
- Wetzel, F. 2007: Provenance-Analyse an detritischen Muskoviten des mitteleuropäischen Keupers anhand von K/Ar-Datierungen. Unpubl. bachelor thesis, University of Göttingen, 48 pp.
- Wienholz, R. 1967: Über den Bau des Untergrundes im Nordost-deutschen Flachland. *Jahrbuch für Geologie* 1, 1-87.

- Wolburg, J. 1969: Die epirogenetischen Phasen der Muschelkalk- und Keuperentwicklung Nordwestdeutschlands mit einem Rückblick auf den Buntsandstein. *Geotektonische Forschungen* 32, 1-65.
- Wurster, P. 1964: Geologie des Schilfsandsteins. *Mitteilungen des Geologischen Staatsinstitutes Hamburg* 13, 1-144.
- Zeck, H.P., Andriessen, P.A.M., Hansen, K., Jensen, P.K. & Rasmussen, B.L. 1988: Paleozoic paleo-cover of the southern part of the Fennoscandian shield –fission track constraints. *Tectonophysics* 149, 61-66.
- Ziegler, P.A. 1990: Geological Atlas of Western and Central Europe. 238 pp. (2<sup>nd</sup> ed.), Shell, Den Haag.