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ORIGINAL PAPER

Tracing sediment pathways by zircon fission track analysis: Oligocene marine connections in Central Europe

Cornelia Spiegel · Joachim Kuhlemann · Wolfgang Frisch

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Abstract In this study, we use contrasting zircon fission track age signatures of Alpine detritus and detritus derived from the Variscan realm to trace sediment pathways in Central Europe. Our data show that the Molasse Basin was connected with the Rhine Graben Sea during the Mid-Oligocene, thus joining the North Sea to the Paratethys. Within the Rhine Graben Sea, fairly strong south–north directed currents existed, transporting sand-sized Alpine detritus nearly 300 km towards the north. A connection between the Rhône-Bresse Graben and the Rhine Graben and/or the French Molasse Basin and the Swiss Molasse Basin, by contrast, is not supported by the fission track data. This may be explained by the existence of submarine rises that hampered the transport of sand-sized sediment towards the north/northeast.

Keywords Fission track · Rhine Graben · Rhône-Bresse Graben · Molasse Basin · Paleogeography

Introduction

Identifying formerly existing marine connections and paleocurrent directions has important implications for paleoecologic and climatic studies. Paleogeographic reconstructions, however, are often difficult, particularly if the marine gateways were narrow and the connections only short-lived. A marine connection between the Rupelian Molasse Basin and the Rhine Graben Sea has long been discussed in the literature (Buxtorf and Fröhlicher 1933; Fröhlicher and Weiler 1952; Weiler 1952; Fischer 1965; Büchi 1983; Berger 1995; Reichenbacher 1998; Kuhlemann and Kempf 2002; Picot 2002). This question is of significance because a connection between the Molasse Basin and the Rhine Graben Sea would join the North Sea with the Paratethys in the east and—if a connection existed between the Rhine and the Rhône-Bresse Grabens—also with the Mediterranean Sea in the South (Figs. 1, 2a).

Most previous studies were based on paleontological data, yielding ambiguous results. Missing similarities between foraminifers and ostracodes from the Rupelian Molasse Basin and the Rhine Graben Sea seem to argue against a marine connection (Oertli 1956; Charolais et al. 1980; Huber 1994; Picot 2002). On the other hand, fish species and otolithes of both realms show some affinities, but do not unequivocally prove a marine connection (Leriche 1927; Buxtorf and Fröhlicher 1933; Fröhlicher and Weiler 1952; Reichenbacher 1998). Evidence in favour for a marine linkage is provided by the presence of reworked microfossils derived from the Alps in Rupelian deposits of the Rhine Graben (Fischer 1965).

According to Picot (2002), the Rhine Graben Sea and the Molasse Basin have been connected via narrow marine channels situated in the area of the present-day Jura Mountains during the Rupelian. The specific paleoecologic conditions of these channels in terms of depth and salinity would have precluded the exchange of flora and fauna between both marine realms. This model would explain the apparent contradictions in the

C. Spiegel (✉) · J. Kuhlemann · W. Frisch
Institut für Geowissenschaften, Universität Tübingen,
Sigwartstr. 10, Tübingen 72076, Germany
e-mail: cornelia.spiegel@uni-tuebingen.de

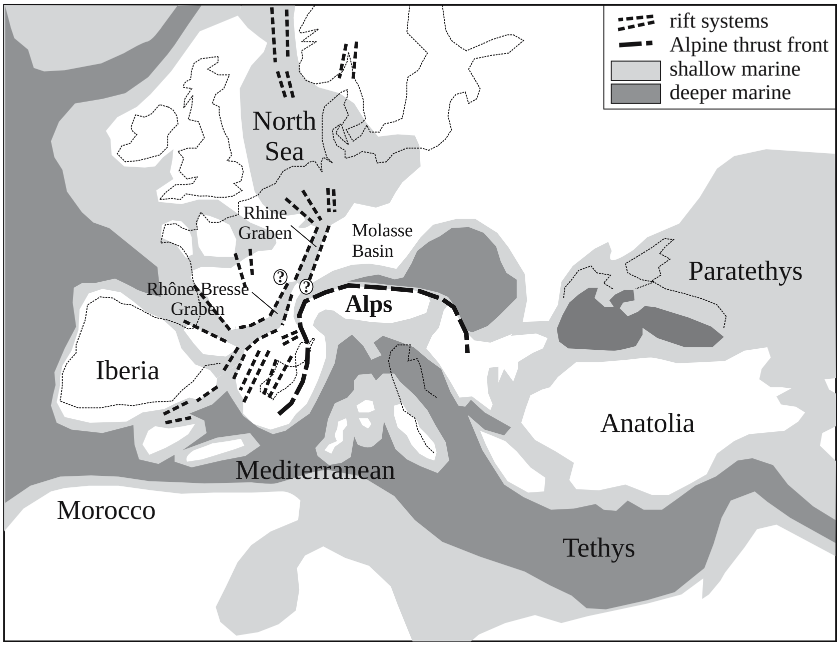


Fig. 1 Sketch map of approximate paleogeographic setting during the Rupelian

paleontologic data. Species which are sensitive to ecologic variations, such as benthic foraminifers and ostracodes, would be precluded from crossing the channels between Molasse Basin and Rhine Graben Sea, whereas active swimmers such as fishes could easily change between both marine realms.

The scope of this study is to provide evidence for or against a Rupelian marine connection between (1) the Rhine Graben and the Molasse Basin, and (2) the Rhine Graben and the Rhône-Bresse Graben, by using fission track dating of single zircon grains. This age-provenance approach is independent of ecological conditions and its suitability for tracing sediment pathways has been tested previously (Köppen and Carter 2000; Cawood et al. 2003; Bernet et al. 2004). Age patterns of Rupelian sediments from the Rhine Graben will be compared to age signatures of potential source areas. Three different scenarios are tested.

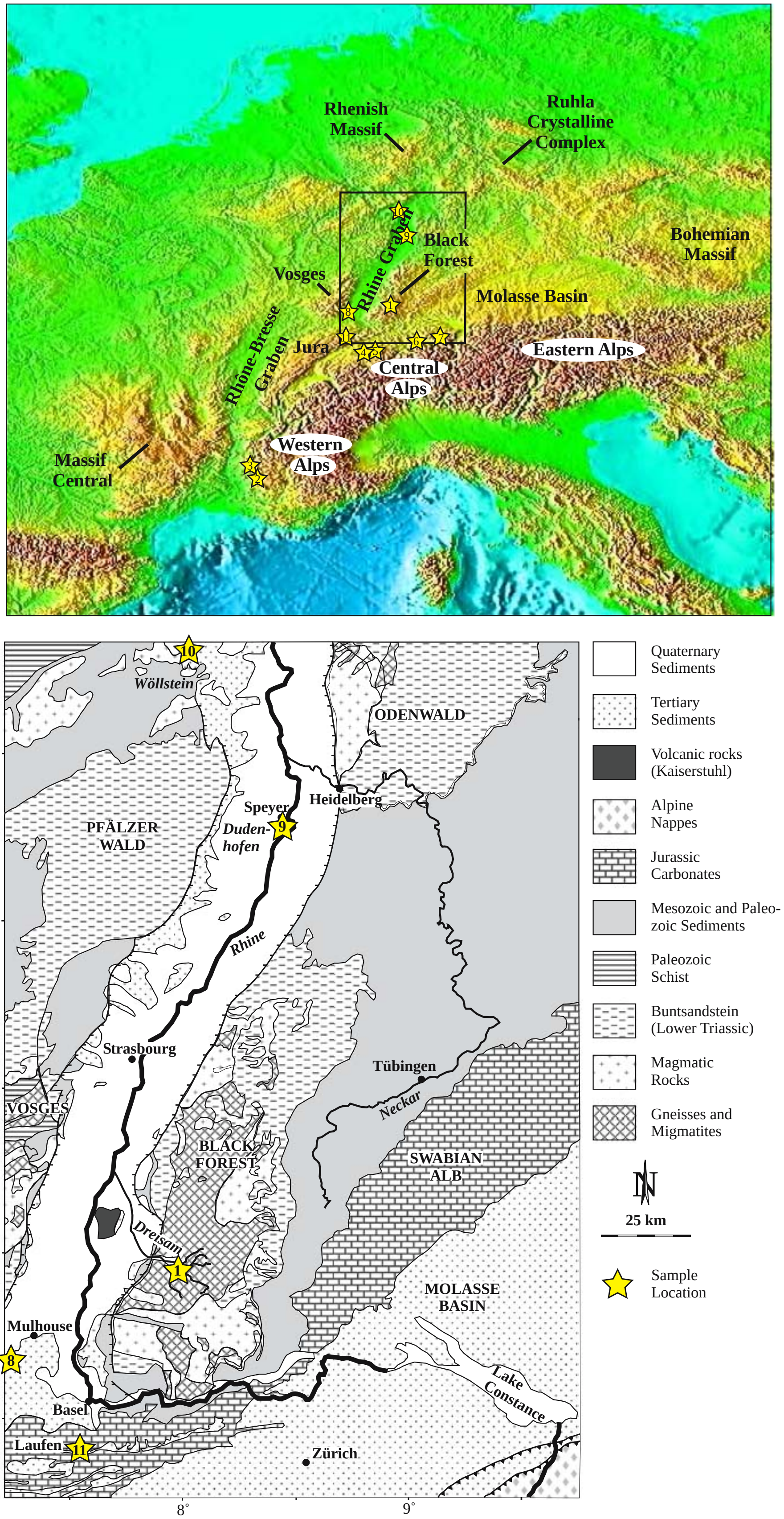
1. No marine connection between the Molasse Basin and the Rhine Graben existed. In this case, Rupelian clastic sediments of the Rhine Graben would originate exclusively from the graben shoulders.
2. A marine connection existed between the Swiss part of the Molasse Basin and the Rhine Graben via the area of the present-day Jura Mountains. In this case, the Rhine Graben sediments would yield a similar age signature as Rupelian sediments from the Swiss Molasse Basin, i.e. they would contain detritus from the Central Alps.
3. A marine connection existed between the Rhine Graben and the Rhône-Bresse Graben. In this case, sediments of the Rhine Graben should yield a similar age signature as Rupelian sediments from the western (French) part of the Molasse Basin, i.e. they would contain detritus from the Western Alps.

Zircon fission track dating: methodology and peak fitting

Zircons were separated according to standard heavy mineral separation techniques, mounted in Teflon and etched in a NaOH–KOH–LiOH eutectic melt for 11–30 h at 180–200°C. At least two mounts per sample with different etching times were analysed. Dating was performed according to the external detector method (Gleadow 1981) and the zeta calibration approach (Hurford and Green 1983; zeta CN2 = 116 ± 2). Fission track analysis was carried out in the Tübingen laboratory (magnification = 1,000 ×) and in the Melbourne laboratory (magnification = 1,600 ×).

The zircon fission track (ZFT) system is sensitive to temperatures between 230 and 330°C (Tagami and Simada 1996). For dating detrital sediments, about 60 single grains per sample are analysed, corresponding to 95% confidence that no fraction ≥ 0.085 is missed (Vermeesch 2004). From the resulting age distributions, single age groups are derived using the binomial peak fitting method (Brandon 1996). To determine the optimal number of age groups, the F test is applied.

Fig. 2 Study area. **a** Digital elevation model of Central Europe showing the Cenozoic Rift System with the Rhône-Bresse Graben and the Rhine Graben, as well as potential source areas in the surrounding regions. For the number of sample locations refer to Table 2. **b** Geological sketch map of the studied area with sample locations. For the number of sample locations refer to Table 2



$P(F)$ gives the probability that random variation alone could produce the observed statistics. $P(F) < \sim 5\%$ is considered to indicate that the improvement in fit by adding a further age group is significant (Brandon 1992, 2002).

Geological setting and sampling strategy

The Rhine Graben is part of the European Cenozoic rift system that crosscuts the European continent from south to north. It is connected to the Rhône-Bresse Graben in the southwest by a set of transform faults. The graben shoulders are formed by the Black Forest in the east and by the Vosges in the west (Fig. 2). Shoulder uplift started in Eocene to Early Oligocene times, as suggested by the deposition of shoulder-derived conglomerates at the eastern and western borders of the Rhine Graben (Duringer 1995).

The southern border of the Rhine Graben is formed by the Jura Mountains, which were folded between 9 and 4 Ma (Becker 2000). Rupelian sediments are preserved in a number of synclines within the Jura Mountains, e.g. the synclines of Moutier, Delemont, and Laufen (Picot 2002).

Deposition in the Rhine Graben started during the middle Eocene and lasted, interrupted by a number of hiatuses, until the present day. The sedimentary sequence shows frequent changes between marine, fluvial, and lacustrine-brackish conditions. For the scope of this study, we only describe Rupelian and early Chattian deposits (see Fig. 3). For a detailed description of the whole sequence we refer to, e.g. Sissingh (1998) or Berger et al. (2005).

During Early Rupelian times, the lacustrine to brackish-marine Pechelbronn formation was deposited in the northern part of the Upper Rhine Graben, while evaporitic conditions in the southern part led to the deposition of the Saliferous Zone formation (Barth 1970). During the Late Rupelian, marine incursions from the north and—as we hope to find out in the course of this study—probably also from the south led to fully marine conditions with water depths in the range of ~100 m (Sissingh 1998). Climatic conditions during this time have been warm and humid (Doebl and Teichmüller 1979; Schaarschmidt 1982). In the southern Rhine Graben, the Grey Marls formation as well as the Foraminifera Marls, Fish Shales, and Meletta Beds have been deposited. The Schleichsand of the northern Rhine Graben is viewed as the coastal-facies equivalent to the Meletta Beds (Bahlo and Tobien 1982; Gad et al. 1990). In general, sedimentation took place in a low-energy environment (Sissingh 1998). However, the Meletta Beds and the Schleichsand contain strongly reworked Cretaceous to Eocene microfossils, indicating relatively strong bottom currents (Fischer 1965). The Meletta Beds became slightly brackish towards the top. During the Early Chattian, brackish to limnic conditions again prevailed, leading to the deposition of the Cyrena Marls.

Between approximately 32 and 29 Ma, the sea in the Swiss Molasse Basin regressed towards the east, leading to deep marine conditions in the eastern part of the basin and shallow marine to fluvial condition in the western part (Berger et al. 2005). Sediment transport in the axis of the Swiss Molasse Basin was directed from west to east. Knowledge on environmental conditions in the French Molasse Basin, southwest of Lac Léman, is scarce, because today, this part of the Molasse Basin is incorporated in the Alpine thrust sheets.

Sampling for this study focused on Late Rupelian deposits (NP23–NP24), because during this time, a marine connection between the Rhine Graben Sea and the Molasse Basin was most likely. Three sandstone samples from the southern, central, and northern Rhine Graben (Mulhouse (8), Dudenhofen (9), Wöllstein (10)) have been collected, thus covering a south–north distance of nearly 300 km along the Rhine Graben (Fig. 2b, Table 1). The Mulhouse and Wöllstein samples are derived from quarries, the Dudenhofen sample is from a borehole (1,652–1,660 m below surface). The Mulhouse and Dudenhofen samples are from the Meletta Beds, while the Wöllstein sample is from the Schleichsand, which is assumed to be the coastal-facies equivalent to the Meletta Beds.

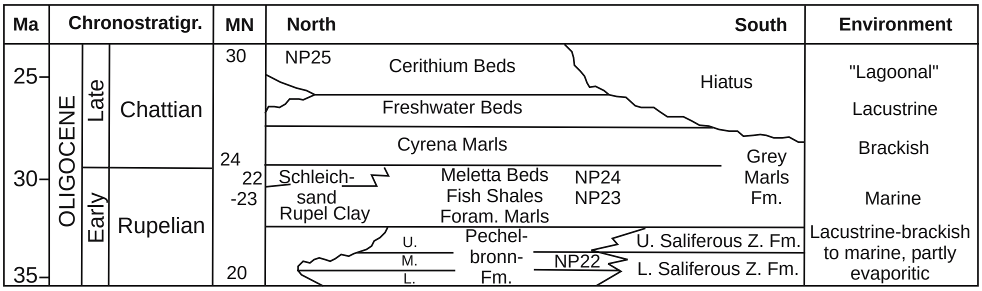


Fig. 3 Stratigraphic sequence and deposition environment of Oligocene sediments from the Rhine Graben (after Sissingh 1998). The dated samples are derived from the Meletta Beds and the Schleichsand. MN refers to mammal biostratigraphy, NP to nannoplankton biostratigraphy

Table 1 Results of zircon fission track analysis

Sample no.	Location	Lithology	Stratigraphy	Counted grains	U-cont. (ppm)	Spontaneous		Induced		$P(\chi^2)$ (%)	Dosimeter		Central age (Ma ± 1σ)
						ρ_s	n_s	ρ_i	n_i		ρ_d	n_d	
1	Dreisam/Black Forest	Sand	Recent	57	339	306	6,747	42	933	18	4.56	4,552	189 ± 8
8	Mulhouse	Sandstone	Meletta B.	56	221	128	3,662	27	789	0	4.7	8,928	125 ± 9
9	Dudenhofen	Sandstone	Meletta B.	54	397	285	5,917	43	897	0	4.0	1,793	148 ± 12
10	Wöllstein	Sandstone	Schleichsand	60	422	289	6,945	51	1,223	0	4.35	4,552	143 ± 11
11	Laufen/Jura	Sandstone	Septarienton	51	446	415	6,155	48	718	0	3.92	1,793	188 ± 18

For locations see Fig. 2. Zircon fission track ages were calculated using dosimeter glasses CN-2 with $\zeta_{CN-2} = 116 \pm 2$. Dating was performed according to the external detector method (Gleadow 1981). n = number of counted tracks, ρ = track density (x10^5 tracks/cm^2). $P(\chi^2)$ is the probability of obtaining χ^2 value for n degrees of freedom (where n = number of crystals – 1)

In addition, one sample from the Laufen syncline of the Jura Mountains was collected (11, see Fig. 2b). It belongs to the Septarienton, which is, according to Picot (2002), again equivalent to the Meletta Beds. The Laufen sample, however, is dated as nannofossil zone NP 22 (Picot 2002), while the Meletta Beds are generally dated as NP 23 to NP 24. Therefore, the sample from the Jura Mountains is slightly older than the samples from the Rhine Graben.

ZFT age signatures of potential source areas

The most important prerequisite for using age signatures as provenance markers is that potential source areas yield different age patterns so that their age-provenance signals can be distinguished from each other. Depending on marine connections in the circum-Alpine area, Rupelian sediments of the Rhine Graben may contain detritus from the Alpine realm (i.e. Central and Western Alps), and from Variscan Europe and its Mesozoic sedimentary cover (i.e. the graben shoulders and their surrounding regions). In the following, we will show that the different potential source areas can be distinguished due to their ZFT age signature (Fig. 4).

Variscan Europe plus Mesozoic cover sequences

Black Forest and the Vosges

The Black Forest and the Vosges form the flanks of the Rhine Graben system. Thus, it is reasonable to assume that they are a major source for the graben sediments, particularly for the southern Rhine Graben. Both comprise Variscan basement rocks (gneisses and granitoids) and Mesozoic cover sequences. The latter consists mainly of Triassic sequences. The sedimentary succession ended during the Middle Jurassic, reaching a maximum thickness of less than 2 km. During the Jurassic, both basement and cover rocks experienced intense hydrothermal activity (Wernicke and Lippolt 1997; Brockamp et al. 2003). ZFT ages of the Black Forest and the Vosges range between 164 and 247 Ma, but are predominantly Jurassic (Timar-Geng et al. (2006); Fig. 4). Heating during Tertiary rifting of the Rhine Graben obviously did not affect the ZFT age signature (Timar-Geng et al. 2006).

In addition to the literature data, we collected one sample of recent river sand from the Dreisam River of the southern Black Forest (1, Fig. 2b, Table 1). The reason why we used a detrital sample instead of bedrocks is because the sand provides an overview of the age pattern integrated over the whole catchment area, whereas bedrock samples only yield point-like information. The locality was chosen because it is situated in a part of the Black Forest, which is deeply incised and shows the highest local relief. Thus, we expect this sample to have recorded the youngest cooling history of the Black Forest.

Zircon fission track dating yielded an age of 189 ± 8 Ma (Tables 1 and 2, Fig. 4). Since the sample passes the χ^2 test at the 5% level (i.e. $P(\chi^2) > 5\%$), we assume only one age group and do not apply peak fitting. This age is in line with the published data by Timar-Geng et al. (2006) and underpins the importance of Jurassic hydrothermal activity in the Black Forest.

Triassic sediments

Large parts of southern Germany are covered with Triassic sediments. The Triassic is subdivided into the Lower Triassic (Buntsandstein), Middle Triassic (Muschelkalk), and Upper Triassic (Keuper). The Middle Triassic mainly consists of carbonate rocks, which are not likely to contain larger amounts of zircon. Therefore, detritus derived from Middle Triassic rocks will not influence ZFT age patterns of Rhine Graben sediments.

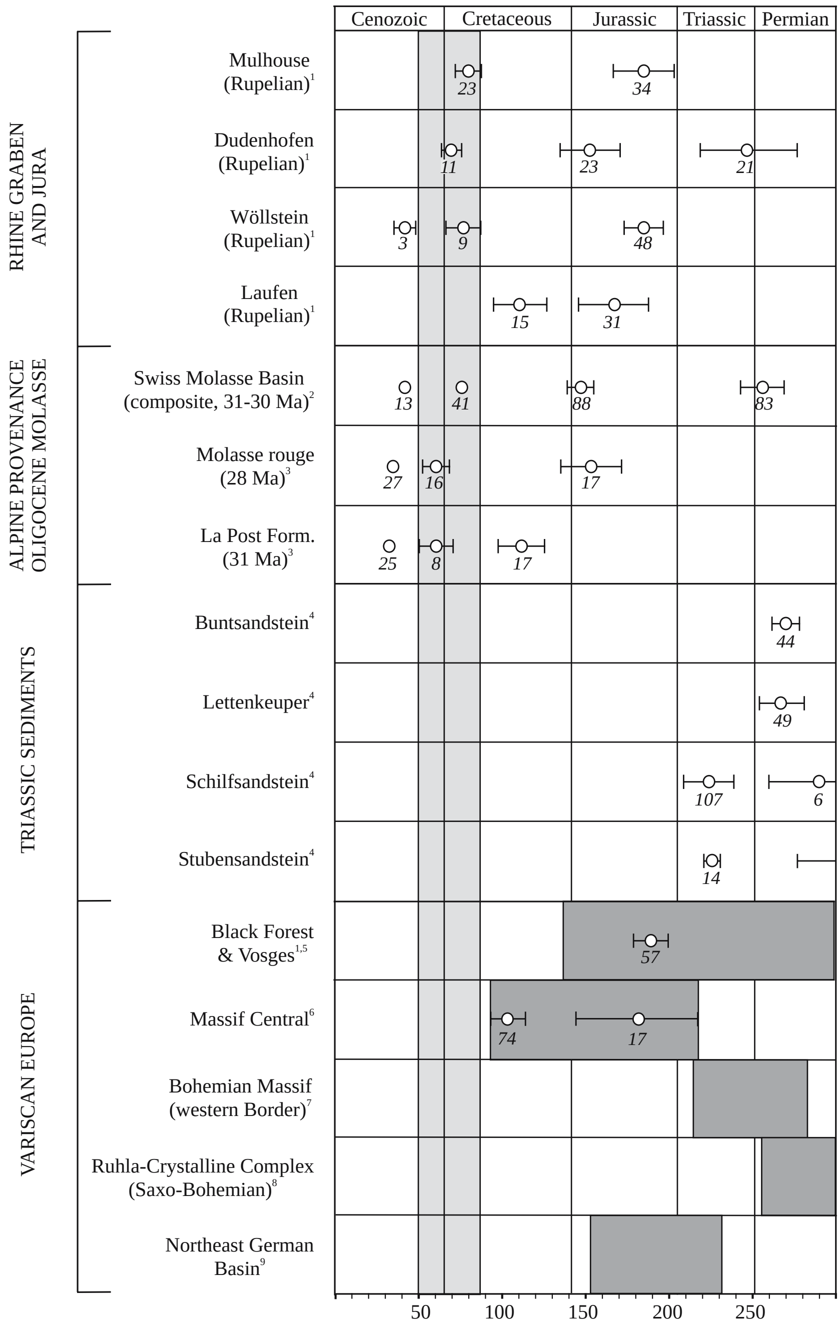


Fig. 4 Modelled zircon fission track age groups of detrital samples from the Rhine Graben, the Jura Mountains, and potential source regions, with sample locations and deposition age (*in parenthesis*). *Error bars* refer to the 1–σ confidence level; *italic numbers* refer to the number of grains contained in each age group. *Dark-grey* shaded area = age range of bed rock samples from potential source regions compiled from literature. *Light-grey* shaded area = range of age groups characteristic for Alpine provenance. *1* This study, *2* after Spiegel et al. (2000, 2001), *3* after Bernet (2002), *4* after Köppen and Carter (2000), *5* after Timar-Geng et al. (2006), *6* after Bernet et al. (2004), *7* after Hejl et al. (1997), *8* after Thomson and Zeh (2000), *9* after Jacobs and Breitkreuz (2003)

ZFT age signatures of Lower and Upper Triassic sediments from different localities in Germany, Switzerland, and Poland were studied by Köppen and Carter (2000), yielding three age groups of approximately 225, 270, and > 300 Ma (Fig. 4).

Massif Central

The Massif Central borders the Rhône-Bresse Graben (Fig. 2). If the Rhine Graben was connected to the Rhône-Bresse Graben during the Rupelian, it would be likely that detritus from the Massif Central was deposited in the Rhine Graben. A sand sample from the modern Ardèche river, which drains the Massif Central contains two ZFT age groups of 103 ± 11 and 181 ± 37 Ma, as well as a minor age component of 24 ± 4 Ma (Bernet et al. 2004). The latter is probably related to volcanic activity, but, since it obviously reflects a thermal event that took place after the Late Rupelian, it is not relevant for this study.

Table 2 Results of peak fitting for the analysed samples

Sample	Location			Stratigraphy	Modelled age groups				
1	Dreisam River	Black Forest	River bed	Recent			189 ± 8 *n* = 57		
2	Molasse Rouge	Western Foreland	Outcrop	28 Ma	34 ± 3 *n* = 27	60 ± 8 *n* = 16	153 ± 18 *n* = 17		
3	La Poste Fm.	Western Foreland	Outcrop	31 Ma	32 ± 3 *n* = 25	60 ± 10 *n* = 16	111 ± 14 *n* = 17		
4	Honegg-Napf	Swiss Molasse Basin	Outcrop	31 Ma	42 ± 3 *n* = 13	76 ± 4 *n* = 41	147 ± 8 *n* = 88	256 ± 13 *n* = 83	
5	Honegg-Napf	Swiss Molasse Basin	Outcrop	30 Ma					
6	Rigi-Hohröne	Swiss Molasse Basin	Outcrop	30 Ma					
7	Speer	Swiss Molasse Basin	Outcrop	31 Ma					
8	Mulhouse	Rhine Graben	Quarry	Meletta B.		80 ± 6 *n* = 23	185 ± 14 *n* = 34		
9	Dudenhofen	Rhine Graben	Drillcore	Meletta B.		70 ± 6 *n* = 11	153 ± 18 *n* = 23	248 ± 29 *n* = 21	
10	Wöllstein	Rhine Graben	Quarry	Schleichsand	42 ± 5 *n* = 3	76 ± 8 *n* = 9	185 ± 9 *n* = 48		
11	Laufen	Jura Mountains	Outcrop	Septarienton			111 ± 16 *n* = 15	167 ± 21 *n* = 31	433 ± 72 *n* = 9

For locations see Fig. 2

Samples 2 and 3 are from Bernet (2002), samples 4–7 are compiled from Spiegel et al. (2000, 2001) and remodelled for this study

Bohemian Massif

Because currents in the Rupelian Molasse Basin were directed from west to east, the Bohemian Massif is not likely to have provided detritus to the Rhine Graben sediments. ZFT ages from the western border of the Bohemian Massif, however, range between 215 and 283 Ma (Heyl et al. 1997; Fig. 4).

Northern Germany: North-German Basin, Ruhla Crystalline Complex

Source Regions of samples from the Northern Rhine Graben (Wöllstein, Dudenhofen) may be situated in northern Germany. Carboniferous sediments from the North-German Basin yield ZFT ages between 152 and 231 Ma (Jacobs and Breitkreuz 2003). ZFT ages of the Ruhla Crystalline Complex, which is part of the Mid-German Crystalline rise, range between 256 and 305 Ma (Thomson and Zeh 2000; Fig. 4).

The Odenwald and the Rhenish Massif

Both, Odenwald and Rhenish Massif are adjacent to the Rhine Graben and are thus likely to have provided detritus to the graben sediments. No ZFT ages exist so far from both areas. However, apatite fission track ages (temperature sensitivity between ~110 and 60°C) from the Odenwald range between 70 and 105 Ma, while K/Ar ages on biotite (temperature sensitivity ~300 ± 50°C) are older than 315 Ma (Wagner 1968).This suggests ZFT ages (temperature sensitivity 230–330°C) that are presumably older than ~Late Cretaceous for the Odenwald.

The Rhenish Massif yields apatite fission track ages between 136 and 291 Ma (Karg et al. 2005). Because the apatite fission track system is sensitive to lower temperatures than the ZFT system, ZFT ages are always older than their corresponding apatite fission track ages, suggesting ZFT age > 136 Ma for the Rhenish Massif. A sample from the modern Rhine river at Rotterdam contains a significant ZFT age group of 155 ± 23 Ma, which is less pronounced in a sample taken upstream from the Rhenish Massif (Bernet et al. 2004).

In summary, the available data suggests that ZFT ages derived from Variscan Europe and its sedimentary cover are generally older than ~100 Ma.

Alpine realm

The Alps formed in response to the convergence between the African/Adriatic and the European plate.

They experienced two distinct orogenic cycles: one during the Cretaceous with top to the W-NNW imbrication and one during the Tertiary with top to the N-NNW movements (e.g. Schmid et al. 1996). The Tertiary orogenic cycle was accompanied by igneous and volcanic activity, which started in Eocene times and culminated during the Oligocene (Dunkl 1990; von Blanckenburg 1992; Ruffini et al. 1997; Brügel et al. 2000).

Central Alps

The age signature of the Rupelian Central Alps is reflected by the age pattern of the Rupelian sediments of the Swiss Molasse Basin. ZFT ages of different fan systems of the Swiss Molasse Basin were published by Spiegel et al. (2000, 2001) and were compiled for this study. The reason for compiling the data was to get an integrated Central Alpine age signal and to exclude disturbances by local sources. The resulting data set contains 225 single zircon ages. Peak fitting yields four major age groups: 256, 147, 76, and 42 Ma (Figs. 4, 5). The first two age groups are in the same range as ages from Variscan Europe and can hence not be used as tracers to indicate Alpine provenance. The Late Cretaceous (76 Ma) age group, in contrast, is significantly younger than ages derived from Variscan Europe and its Mesozoic cover sequences and can thus be used to trace transport pathways of Alpine-derived detritus. The Eocene (42 Ma) age group may reflect an Eocene exhumation period (Dunkl et al. 2002) or volcanic activity (Winkler et al. 1990; Dunkl 1990). However, since Eocene volcanism was not limited to the area of the Alps but was widespread in Central Europe, Eocene ages are not characteristic for the Alpine realm and will thus not be used as a tracer for Alpine provenance (see Seck 1983; Jacoby 1997; Keller et al. 2002).

Western Alps

ZFT ages of Oligocene deposits from the Western Molasse Basin adjacent to the Western Alps were published by Bernet (2002). Similar to the sediments of the Swiss Molasse Basin, these contain a Late Cretaceous age group that is characteristic for Alpine provenance. Additionally, sediments from the Western Molasse Basin contain a distinct Oligocene age group (34–32 Ma), which reflects Oligocene magmatic activity in the Alps (Fig. 4 and Table 2). These Oligocene ages do not occur in the Swiss Molasse Basin (Spiegel et al. 2000, 2001). Therefore, the occurrence of Oligocene ZFT ages can be used to distinguish between Western Alpine and Central Alpine provenance.

Results of ZFT dating

For results of ZFT analysis see Tables 1 and 2, and Figs. 4, 5. As described in the section "Variscan Europe plus Mesozoic cover sequences", the sample from the Black Forest river sand yielded a ZFT age of 189 ± 8 Ma. The three samples from the Late Rupelian Rhine Graben sediments yield the following age patterns.

1. All samples contain Jurassic age groups. These can either be derived from the Alps or from the graben shoulders, or from both sources.
2. All samples contain a Late Cretaceous age group (70–80 Ma), which can only originate from the Alps.
3. The relative importance of the Late Cretaceous age group decreases towards the north, i.e. with increasing distance from the Alps. The Mulhouse sample (8) from the southern Rhine Graben contains 40% of Late Cretaceous ages, whereas the Wöllstein sample (10), nearly 300 km to the north, only contains about 15% Late Cretaceous ages.
4. None of the samples contain Oligocene age groups.

The Laufen sample from the Jura Mountains, by contrast, yields a Silurian age group, a Jurassic, and an Early Cretaceous age group. The Silurian age group points to a provenance from erosion of the lower Triassic Buntsandstein, which in turn originated in Fennoscandia (Köppen and Carter 2000). Lower Triassic sediments covered large parts of southwest Germany, including the Black Forest and the Vosges.

Late Rupelian paleogeographic setting

On the basis of our fission track data, we can now come back to the three potential paleogeographic scenarios described in the first paragraph of this paper (Fig. 6).

The first scenario assumes no Late Rupelian connection between the Molasse Basin and the Rhine Graben Sea. The presence of Alpine detritus, as indicated by the Late Cretaceous age groups contained in the Rhine Graben sediments, clearly excludes this scenario.

The second scenario involves a communication between the Swiss Molasse Basin and the Rhine Graben via the area of the present-day Jura Mountains

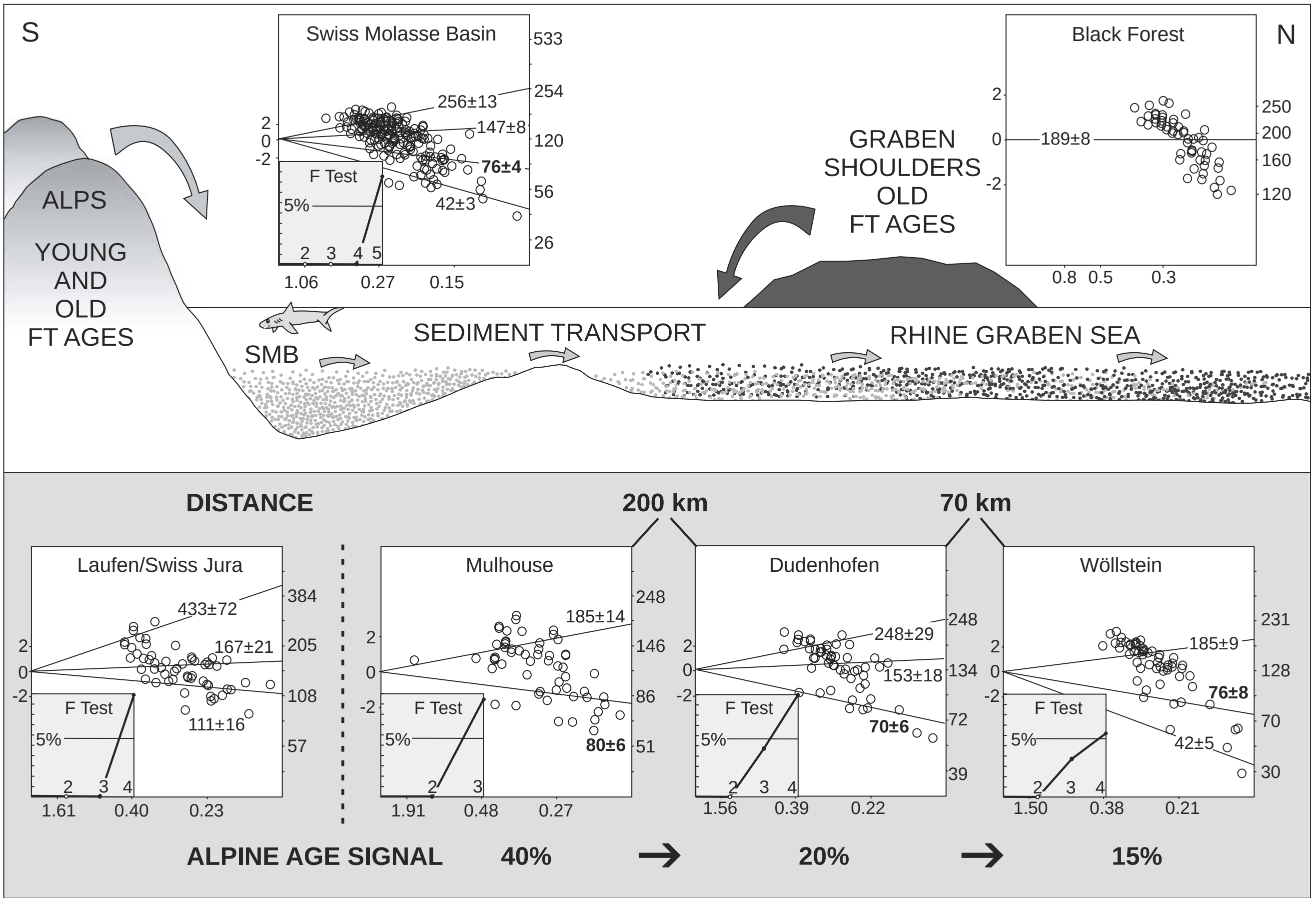


Fig. 5 Schematic section of the connection between Swiss Molasse Basin (SMB) and the Rhine Graben Sea, and the corresponding zircon fission track age signatures. Fission track ages are illustrated as radial plots (Galbraith 1990), showing the precision of the individual grain ages on the *x*-axis and the fission track age on the (*right*) *y*-axis. *Grey-shaded inset* results of the *F* test (Brandon 1992). *x-axis* number of peaks fitted; *y-axis* probability (%) for *F* test. *P*(*F*) < 5%, indicated by the *vertical line*, shows that the added peak is significant

(Figs. 1, 5, 6). This paleogeographic setting is supported by the fission track data. The Late Cretaceous ages contained in the Rhine Graben sediments obviously originated from the Central Alps, thus indicating (1) a connection between the Swiss Molasse Basin and the Rhine Graben, and (2) a transport of Alpine detritus of nearly 300 km towards the north. The latter suggests fairly strong south–north directed currents, which is in line with the presence of strongly reworked microfossils in the Meletta beds.

The most likely location for the marine connection is across the area of the present-day Jura Mountains (see Picot 2002). Therefore, we would expect the Laufen sample to contain similar age groups as the samples from the Swiss Molasse Basin. This is, however, not the case. Two reasons may explain this: (1) the marine connection was in fact located in the area of the Jura Mountains, but not along the Laufen syncline, or (2) because the Laufen sample is slightly older than the samples from the Rhine Graben and the marine connection was only short-lived, the Laufen sample may have been deposited when the marine connection was still not established. In short, the fission track data indicate a communication between the Swiss Molasse Basin and the Rhine Graben, but the exact position of this connection remains unclear.

The third scenario assumes a late Rupelian connection between the Rhône-Bresse Graben and the Rhine Graben and/or the Swiss Molasse Basin, thus connecting the North Sea with the Mediterranean Sea. This setting is supported by paleontological data, suggesting faunal exchange between both realms (Reichenbacher 1998). The ZFT data, however, suggests that no sand-sized detritus was transported from the Western Molasse Basin to the Rhine Graben or to the Swiss Molasse Basin, because otherwise, we would

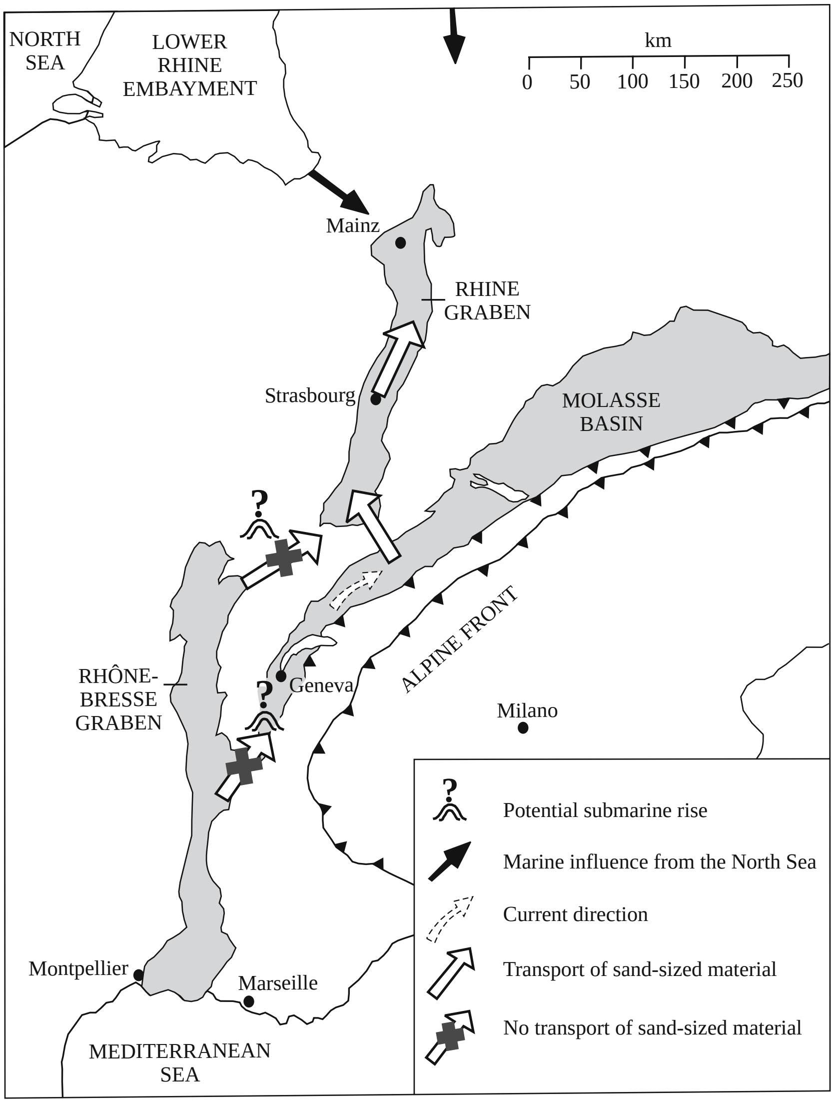


Fig. 6 Sketch map of the Rhône-Bresse Graben, the Rhine Graben, and the Molasse Basin, illustrating the paleogeographic settings discussed in the text. Modified after Reichenbacher (1998). The potential submarine rises were tentatively positioned at the junctions of the Rhône-Bresse Graben with the Rhine Graben and the Swiss Molasse Basin, but may have been situated further south

expect to find detritus from the Western Alps (i.e. an Oligocene age group) in the sediments of the Rhine Graben and the Swiss Molasse Basin, respectively. This apparent contradiction between paleontologic and ZFT data may be explained by a paleogeographic setting that involves a deep-marine environment in the southwestern foreland of the Western Alps, and a submarine rise between the Rhône-Bresse Graben and the Rhine Graben as well as between the Western Molasse Basin and the Swiss Molasse Basin (Fig. 6). The latter must have been situated approximately south of Geneva. This setting would allow a faunal exchange but would preclude coarser-sized material from being transported from the Rhône-Bresse Graben into the Rhine Graben and from the Western Molasse Basin towards the northeast into the Swiss Molasse Basin. The existence of such submarine rises, however, cannot be proven by other evidence and thus remains speculative.

Conclusions

In this study we used detrital ZFT data of late Rupelian sediments to reconstruct marine connections in Central Europe during the mid-Oligocene. The following can be derived from our data.

1. Alpine detritus can be traced for nearly 300 km along the Rhine graben, indicating a Late Rupelian marine connection between the Swiss Molasse Basin and the Rhine Graben Sea that linked the North Sea to the Paratethys.
2. In the Rupelian Rhine Graben Sea, fairly strong south–north directed currents occurred.

3. A connection between the Rhine Graben and the Swiss Molasse Basin via narrow marine channels across the Jura Mountains, as proposed by Picot (2002), seems very likely, but cannot ultimately be proven by ZFT data.
4. According to the fission track data, no sand-sized material transport from the Western Molasse Basin to the Rhine Graben and the Swiss Molasse Basin took place. This may be explained by the presence of submarine rises that hampered the sediment transport towards the north and northeast.

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