

Bettina Reichenbacher · Daniel Kälin · Jürg Jost

A fourth St. Gallen Formation cycle (?) in the Karpatian Upper Marine Molasse of central Switzerland

Received: 29 December 2004 / Accepted: 10 March 2005 / Published online: 10 June 2005
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Abstract The Mauensee section in the Molasse Basin (North Alpine Foreland Basin) of central Switzerland represents one of the best continuously exposed outcrops of the St. Gallen Formation of the Upper Marine Molasse. A similarly well-exposed section is at Schmiedrued, situated about 15 km to the north. Biostratigraphic analysis of mammal and fish faunas shows that both sections are of Early Karpatian age. Palaeoecological analysis of the biota indicates an oligohaline intercalation within the marine part of the sections. This is additionally confirmed by the oxygen isotopic compositions of fish otoliths from the Mauensee section. The overlying marine sequence may represent a fourth cycle in the St. Gallen Formation that might perhaps indicate a Karpatian transgression from the Mediterranean Sea, which has not previously been recognized. Biostratigraphic comparison shows that the sedimentation of the Upper Freshwater Molasse began at the base of the Karpatian in southwest Germany and eastern Switzerland, and in the Middle Karpatian in central Switzerland. The presence of a Karpatian marine sedimentation area in central Switzerland may explain that the terrestrial sedimentation of the Upper Freshwater Molasse began at such different times.

Keywords Molasse · Switzerland · Karpatian · Mammals · Otoliths · Oxygen and carbon isotopes

Introduction

The Molasse Basin is a part of the western Paratethys and forms the main part of the northern foreland basin of the Alps. It extends from near Lake Geneva in Switzerland, through southern Germany, across into Lower Austria. The Molasse Basin deposits include marine and non-marine sediments; these range in age from Upper Eocene/Lower Oligocene to Upper Miocene. The clastic input is derived largely from the Alps, but partially also from the Bohemian Massif and other sources in the north. The fill is up to 5000 m thick in the parts of the basin closest to the Alps. It decreases towards the north and can be no more than a few metres thick in the basin's most north-westerly regions.

The stratigraphic succession in the Molasse Basin is conventionally subdivided into two transgressive–regressive megacycles. Each of these starts with marine deposits and ends with freshwater deposits. The lithostratigraphic units in the first megacycle are the Lower Marine Molasse (Kiscellian), the Lower Brackish Molasse, and the Lower Freshwater Molasse (Egerian). The lithostratigraphic units in the second megacycle, to which the present study refers, are the Upper Marine Molasse (Eggenburgian to Early Karpatian), the Upper Brackish Molasse (Late Otnangian), and the Upper Freshwater Molasse (Karpatian to Pannonian). The two megacycles cannot readily be recognized in the eastern part of the Molasse Basin in Germany (east of Munich) and in the Molasse Basin in Austria. In these areas, marine conditions prevailed into the Late Lower Miocene (e.g., Lemcke 1988; Bachmann and Müller 1991; Doppler et al. in press).

All of the major lithostratigraphic units in the Molasse Basin are at least partially heterochronous, which makes a basin-wide chronostratigraphy difficult. Recently, several biostratigraphical, magnetostratigraphical and geochronological studies were carried out, mainly in the part of

This paper is dedicated to Erik Flügel. He always was open and attentive for all topics of palaeontology. We will never forget him.

B. Reichenbacher (✉)
Department of Earth and Environmental Sciences, Section
Palaeontology and GeoBioCenter,
Ludwig-Maximilians-University,
Richard-Wagner Str. 10,
D-80333 Munich, Germany
e-mail: b.reichenbacher@lmu.de
Tel.: +49-89-21806603
Fax: +49-89-21806603

D. Kälin
Rainweg 2A,
CH-3314 Schalunen

J. Jost
Bärenhubelstraße 10,
CH-4800 Zofingen

the Molasse Basin in Switzerland (e.g., Schlunegger et al. 1996, 1997a, b, 2001; Kälin 1997; Kempf et al. 1997, 1999; Kempf and Matter 1999; Kälin et al. 2001; Strunck and Matter 2002; Kempf and Pross 2005). These studies have strongly improved the time-resolution attainable in the successions there, and have produced datasets that have been used as the basis for recognizing relations between basin development, sediment supply and the tectonic evolution of the Alps (Schlunegger et al. 1997a, 2001; Kuhlemann and Kempf 2002). The chronostratigraphical correlation between these Swiss Molasse successions and those in southern Germany is nevertheless still in need of improvement. The substantial uncertainties in basin-wide correlation have led to considerable controversies, especially with regard to the dynamics of the basin's depositional history. Some authors have argued, that the sedimentary history of the basin was determined principally by Alpine tectonic processes and resulting uplift (e.g., Schlunegger et al. 1997a; Kempf et al. 1999; Kuhlemann 2000; Kuhlemann and Kempf 2002); other authors have argued that eustatic sea-level changes were the principal controls (e.g., Lemcke 1988; Jin 1995; Zweigel et al. 1998). It is remarkable that the tectonic and eustatic events documented in the basin-fill seem so commonly to have been contemporary, but this may be due to the relative imprecision of the basin-wide chronostratigraphic correlation as mentioned above (see also discussion in Sissingh 1997, 1998, 2001; Zweigel et al. 1998).

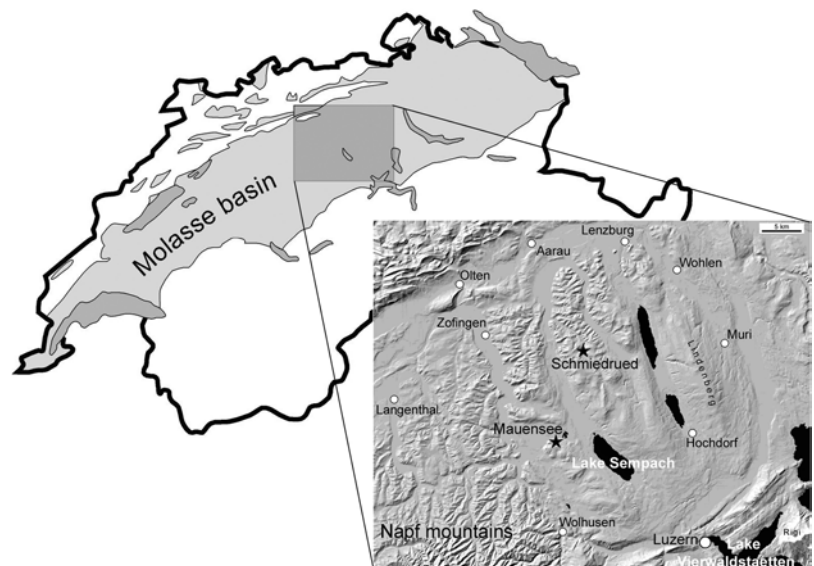
The aim of this present paper is to provide some new data that lead to a better understanding of the sedimentary history in the northern Alpine foreland basin during the Late Lower Miocene. These data bear on a previously unknown marine-oligohaline-marine sequence within the Karpatian Upper Marine Molasse of the Mauensee and Schriedrued sections in central Switzerland (Fig. 1), both of which were discovered by J.J.

Geological setting

The transgression of the sea into the Molasse Basin in the Lower Miocene came from two directions: from the Mediterranean in the southwest and from the Central Paratethys in the east (e.g., Büchi and Schlanke 1977; Berger 1985; Homewood et al. 1986; Rögl 1998; Sissingh 2001; Bieg et al. 2003, *in press*). The transgression started during the Burdigalian (Eggenburgian) about 19–20 Ma ago (e.g., Strunck 2001), and probably reflected the eustatic rise of sea level at that time (Lemcke 1988; Sissingh 1997; Zweigel et al. 1998). The sea-level highstand occurred during the Late Burdigalian (Otnangian) (Buxtorf 1901; Gall 1975; Schwerd et al. 1996; Hug et al. 1997).

The mainly siliciclastic sediments of the Upper Marine Molasse are up to several hundred metres in thickness. Conventionally, the Upper Marine Molasse is subdivided into two transgressive–regressive fining-upward cycles, with a hiatus between. The hiatus is dated with reference to the magnetostratigraphic charts (Berggren et al. 1995; Cande and Kent 1995) as about 18.3–17.8 Ma in the Molasse Basin of eastern Switzerland (Kempf et al. 1999) and as about 18.1–17.7 Ma in central Switzerland (Schlunegger et al. 1997a, b). In Switzerland, the cycles are composed respectively of the Luzern Formation and the St. Gallen Formation; the former was correlated with the Eggenburgian in age, the latter with the Otnangian to Early Karpatian (e.g., Keller 1989, 1990; Schlunegger et al. 1997a, b). In southwestern Germany, the cycles are composed of the so-called Heidenlöcher Beds and “Sand Shales”, and of the overlying Baltringen Beds and “Fine Sand Series” (Lemcke et al. 1953; Hagn 1961; Wenger 1987). It must be noted that there is uncertainty in the correlation of the cycles between Switzerland and South Germany, especially for the Eggenburgian and Lower Otnangian (cf. Hagn 1961; Wenger 1987).

Fig. 1 Geographic location of the Mauensee and Schriedrued sections in central Switzerland.



During the Middle Otnangian, the sea retreated from the southwest German part of the Molasse Basin, but marine conditions prevailed longer (perhaps for some 100,000 years) in Switzerland and in the southeast German part of the basin (most recently Schwerd et al. 1996; Schlunegger et al. 1996; Kempf et al. 1997, 1999; Reichenbacher et al. 1998; Kälin et al. 2001). Since Kiderlen (1931), the regression from the southwest German Molasse Basin is commonly considered having been accompanied by the incision of the channel-like “Graupensandrinne” along the northern edge of the basin. Most authors consider the “Graupensandrinne” as the incision of a river that drained into the sea, which still existed in the Swiss part of the Molasse Basin (e.g., Reichenbacher et al. 1998). This river removed either partly or completely the Upper Marine Molasse that had existed beforehand in its valley. According to this opinion, the “Graupensandrinne” initially was filled by fluvial to estuarine gravels and sands (Grimmelfingen Beds) and later by the brackish marls of the Kirchberg Formation, which would reflect a last transgression of the Swiss Molasse Sea during the Late Otnangian (e.g., Kiderlen 1931; Schlickum 1963; Lemcke 1972, 1988; Doppler 1989; Reichenbacher 1989, 1993; Luterbacher et al. 1992; Asprien and Aigner 2000). The Late Otnangian age for the Kirchberg Formation is supported by biostratigraphic data on mammals and fish otoliths. However, according to Tipper et al. (2003), there is no sedimentological or faunal evidence that the erosion that produced the Graupensand channel actually was fluvial. Tipper et al. (2003) propose as an alternative explanation for the origin of the “Graupensandrinne” that it was incised by submarine erosion. If that is correct, no hiatus need to be present between the top of the Upper Marine Molasse and the bottom of the Brackish Molasse. However, this interpretation makes it difficult to explain the records of lacustrine carbonates, calcretes, clasts of “Albstein”, tuffs and red marls at the basis of the Upper Brackish Molasse and on the floor of the Graupensand channel (Lemcke et al. 1953; Hofmann 1967; Nägele 1962; Zöbelein 1985). They would require that the submarine channel of the “Graupensandrinne” was exposed terrestrially at some places along its length.

The Mauensee and Schmiedrued sections

The Mauensee and Schmiedrued sections are located west and north of Lake Sempach (Fig. 1). Each section exposes the upper part of the St. Gallen Formation (Upper Marine Molasse), and one section (Mauensee) exposes also the lower part of the Upper Freshwater Molasse. The exposures are along the steep slopes of deeply incised, small creeks. The Mauensee section was investigated during September and October 2000, the Schmiedrued section during February 2004.

The Mauensee section represents a thickness of about 72 m of Molasse sediments (Fig. 2). A 7-m thick conglomerate bank forms the base of the section. Over this lie 32 m of poorly fossiliferous sandstones. The few fossils occurring in these sandstones are mainly plant fragments; there

are also some marine fossils, such as sharks teeth and bryozoans in bed 24. The sandstone sequence is overlain by a mudstone–limestone complex some 3.7 m thick, which contains freshwater and terrestrial molluscs. Above this is a thin conglomerate bed (bed 55), which is followed in turn by a 24.5-m thick siliciclastic sequence. This sequence includes sandstones with rare marine fossils; within the sandstones there are intercalated thin layers of gravels and boulders. The top of the Mauensee section is formed of black marls, sandstones and mudstones, with freshwater and terrestrial molluscs.

The Schmiedrued section is similar to the Mauensee section because it is made up of sequences consisting of marine siliciclastics as well, which are separated by a 4-m thick mudstone–limestone complex containing freshwater and terrestrial molluscs. In addition, the Schmiedrued section shows that there is an erosive contact at the base of the thin conglomerate layer overlying the mudstone–limestone complex.

Materials and methods

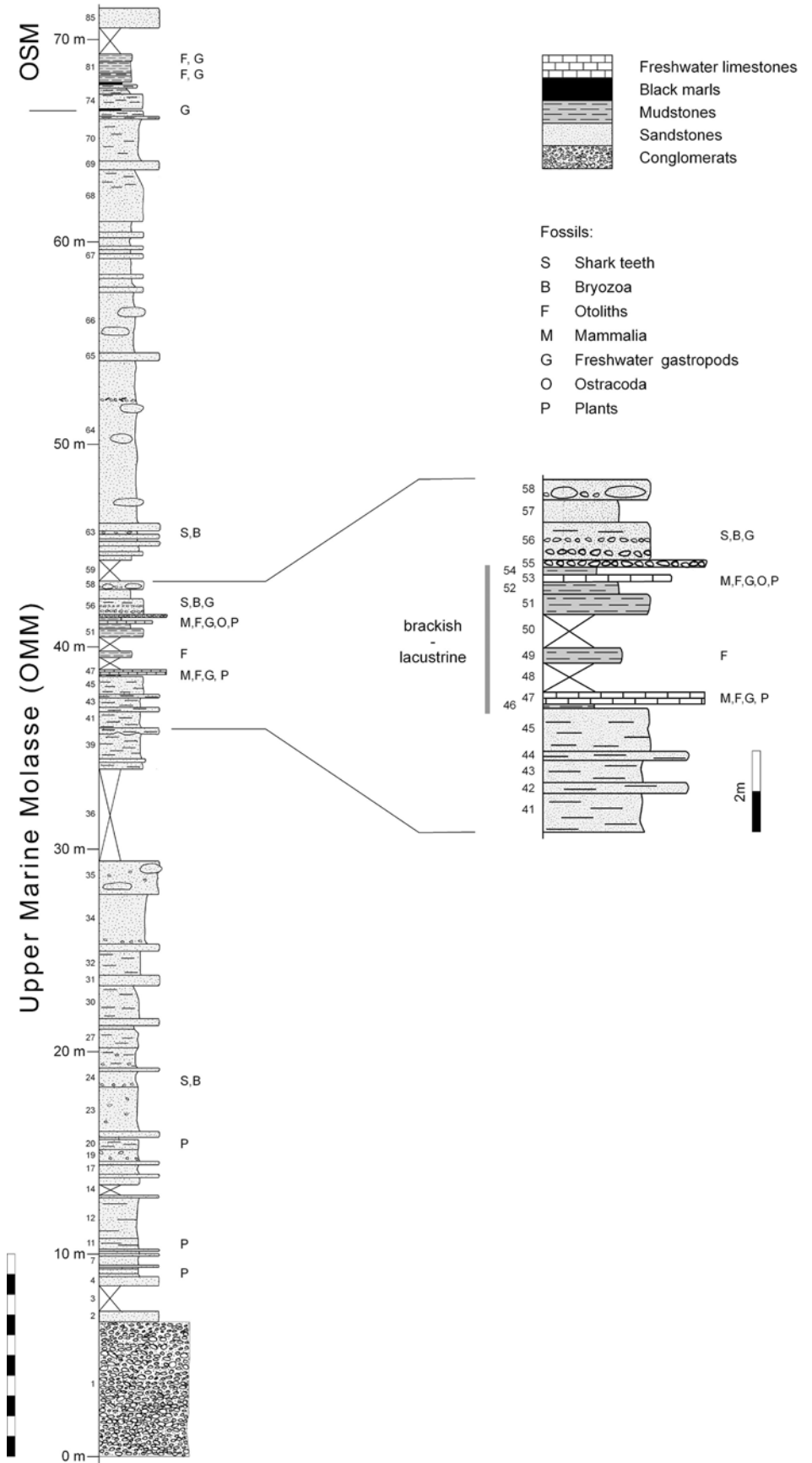
Sample preparation

A total of 660 kg sediment was collected by J.J. from ten beds of the Mauensee section (Table 1); of this material, 300 kg came from bed 52. About 100 kg sediment was collected from the Schmiedrued section. The samples were disaggregated first by being treated with gasoline. They were then washed through 0.3, 0.4, 0.5 and 1.0 mm sieves, and all microfossils recovered were picked out under a stereomicroscope. With one exception, all of the size fractions were picked for all of the samples; the exception was the 0.3–0.4 mm fraction from bed 52, which was picked only partly. The fossils recovered from the Mauensee samples included charophytes, seeds, bryozoans, bivalves, gastropods, ostracods, fish remains (otoliths, teeth), the remains of amphibians and reptiles, and mammal teeth. For the purpose of the present paper, only fish remains and mammal teeth have been studied in detail. The remaining elements of the biota will be described in a separate paper.

Biostratigraphy

The biostratigraphy of non-marine sections in the Molasse Basin is based mainly on small mammals, charophytes (e.g., Berger 1999), and fish otoliths. For the Mauensee and Schmiedrued sections, the mammal and otolith zonations were applied. Among the mammals, it is mainly the rodents that are important; among the fishes, the cyprinodontiform and perciform taxa are especially useful. The mammal zonation is based generally on the MN-biostratigraphy described by Mein (1975, 1989). More detailed mammal zonations are also available for the Swiss and Bavarian Molasse (Engesser and Mödden 1997; Kälin 1997; Heissig 1997), but only in Switzerland these

Fig. 2 The Mauensee section: the sediments, fossils, and bed numbers.



zonations are supported by magnetostratigraphic data (e.g., Kempf et al. 1997). The otolith zonation was established by Reichenbacher (1999) for non-marine aquatic deposits in the western Paratethys, in which classical marine microfossils are absent and terrestrial mammal fossils are rare. This otolith zonation can be calibrated against the mammal zonation, and it has been successfully applied by Mödden et al. (2000), Uhlig et al. (2000) and Reichenbacher et al. (2004a, b).

Palaeoecology

The palaeoecology of fossil mammals and fish species can be reconstructed readily, provided that the assumptions involved in the actualistic method are valid: these are that a fossil species required similar ecological conditions to the nearest-related Recent species. The actualistic approach is especially well suited for Miocene and younger palaeo-ecosystems, because close relationships exist between many fossil and Recent species.

Stable isotope analysis

Stable oxygen and carbon isotopic compositions of *Gobius* otoliths were measured in order to try to get a better understanding of that genus' palaeoecology ($n=18$; see Table 2). The consistency in the composition of the aragonite of the otoliths from the Mauensee section was demonstrated using Fourier Transform Infrared spectroscopy (FTIR). This enabled diagenetic alteration of those otoliths to be ruled out. Each sample used for the stable isotope study was a single complete otolith weighing 0.15–0.3 mg. The otolith was first washed in an ultrasonic bath with distilled water, air-dried, and finally examined under a binocular microscope to ensure that no sedimentary matrix has remained. The isotopic measurements were carried out using a THERMO/Finnigan MAT Delta-plus isotope ratio mass spectrometer coupled to a THERMO/Finnigan Gasbench II sample preparation unit. The isotope ratios are given in the conventional delta notation ($\delta^{13}\text{C}/\delta^{18}\text{O}$) relative to VPDB (Vienna PeeDee Belemnite standard). The standard deviation for repeated measurements of laboratory standard material (limestone) is better than 0.10‰, for both stable oxygen and carbon isotopes.

Results and interpretation

Biostratigraphy

Detailed mammal-based zonation of the Miocene is generally best carried out using the extinct rodent group eomyids, especially the genera *Ligerimys* and *Keramidomys*. However, representatives of this group are not found in the Mauensee section. Age control can be obtained instead by using the size-evolution of the hamster *Megacricetodon*. The First Appearance Datum (FAD)

of *Megacricetodon collongensis* falls in mammal zone MN4b, thus the presence of this species in the Mauensee section shows that the section is not older than MN4b. The *M. collongensis*—*M. lappi* lineage (which is based on rapid size-evolution with distinctly enlarged molars) can be used for more detailed age control (Fig. 3). The *M. collongensis* specimens from the Mauensee section are smaller than those from the Hirschthal locality in Aargau in central Switzerland (Hürzeler 1932); consequently they can be taken to be slightly older than those from Hirschthal. It is in Hirschthal that the so-far biggest (and therefore youngest) specimens of the eomyid *Ligerimys florancei* have been found (Engesser 1990). This species is an index species for MN4, therefore Hirschthal represents the so-far youngest part of MN4b. This suggests that the Mauensee section is also of Late MN4b age, although—as mentioned—it is slightly older than Hirschthal.

According to lithostratigraphic, biostratigraphic and magnetostratigraphic data, mammal zone MN4b ranges from the Late Otnangian up into the Early Karpatian (e.g., Steininger 1999). The otolith zonation allows the separation of the Otnangian part of MN4b from the Karpatian part of MN4b. The index fish fossil for the Otnangian is the glassfish *Dapalis formosus*; its FAD and LAD define the Otnangian otolith zone OT-M4 (Reichenbacher 1999). The Karpatian is characterized by the otolith zone OT-M5 (older part), which includes the FAD of *Gobius latiformis* and the co-occurrence of *G. latiformis* and *Hemitrichas martinii*; this latter species dies out during the Early Karpatian (Reichenbacher et al. 2004a). *G. latiformis* and *H. martinii* are present in both the Mauensee and Schmiedrued sections, but there are no species of *Dapalis* there (Table 1; Fig. 4). Consequently, the oligohaline intercalations in the Mauensee and Schmiedrued sections belong to the otolith zone OT-M5 (older part), which correlates with the Early Karpatian. It should be stressed that the absence of *Dapalis* is not due to specific ecological conditions, because the ecology of the Mauensee fish fauna (without *Dapalis*) and that from the Upper Brackish Molasse (with *Dapalis*) can be considered as very similar due to the accompanying fauna and flora (Reichenbacher 1989, 1993). Moreover, the occurrence of the carp species *Palaeocarassius mydlovarensis* supports a Karpatian age for the Mauensee and Schmiedrued sections because this species is restricted to the Karpatian (Böhme and Reichenbacher 2003).

Palaeoecology of the mammals and the fishes

The mammal fauna found in beds 46 and 52 in the Mauensee section includes just nine species; it is therefore of low diversity. The most abundant species is the hamster *Megacricetodon collongensis*. Other species include the glirid *Miodyromys* aff. *aegercii* and the lagomorph *Prolagus oeningensis*. The remaining taxa are rare: *Galerix* sp., Soricidae indet., Talpidae indet., Insectivora indet., another indeterminate cricetid, and *Heteroxerus*. Mammal faunas of the same age are known from several localities in the Upper

Table 1 The fish fauna from the Mauensee section. Species that also are present in Schmiedrued are marked with *. N, number of specimens; x, some hundred specimens of pharyngeal teeth; cf.,

determination on the species-level questionable. OSM, Upper Fresh-water Molasse (“Obere Süßwassermolasse”).

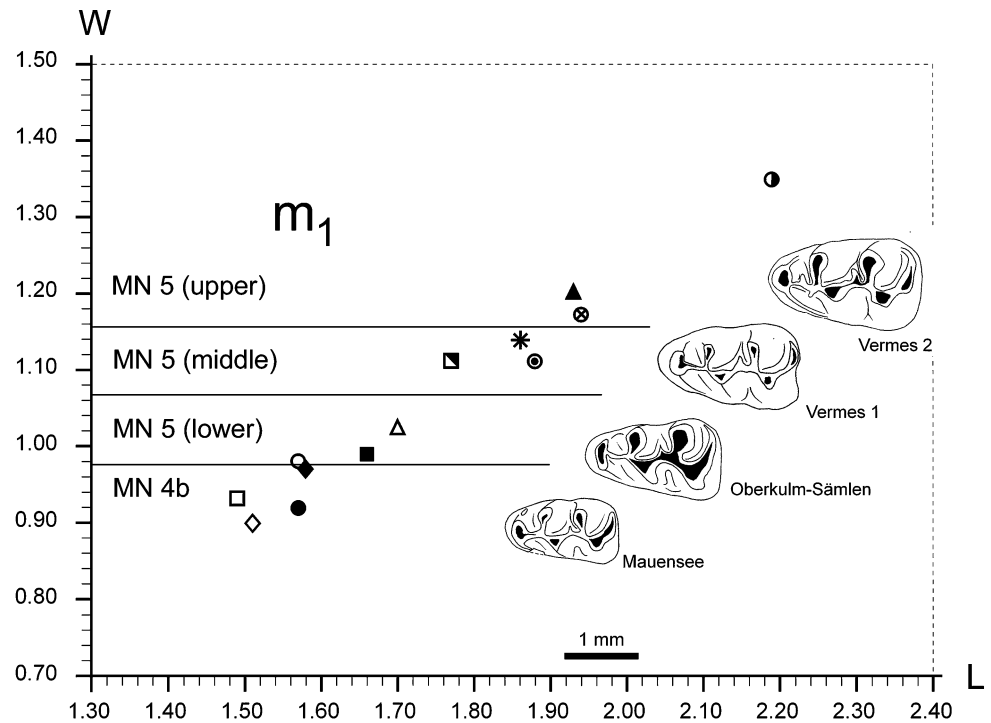
	Upper Marine Molasse (OMM)								OSM	
	marine	lacustrine-oligohaline			?	marine		lac.-oligoh.		
Number of layer	24	46	47	49	52	54	56-58	63	80	82
Amount of sample (kg)	(50)	(70)	(80)	(10)	(300)	(10)	(70)	(30)	(20)	(20)
<i>Dasyatis</i> sp.	1									
<i>Dasyatis</i> cf. <i>rugosa</i>								2		
<i>Rhinobatos</i> sp.	1						2			
<i>Scyliorhinus</i> sp.	1									
<i>Synodontaspis acutissima</i>	1							1		
<i>Synodontaspis</i> sp.							1			
Carcharhinidae indet.	1						2			
Selachier indet.	4						4			
<i>Palaeocarass. mydlovarensis</i>		x	x	cf.	x					cf.
<i>Palaeoleuciscus</i> sp.		x	x	x	x				x	x
Leuciscinae indet.				x	x					
* Cyprinidae indet. (Lapilli)		33	100	2	1050				1	
<i>Mugil</i> sp.					2					
* <i>Hemitrichas martinii</i>		13	40	4	1800				2cf.	6
* <i>Prolebias weileri</i>		10	16	1	680				8	6
* <i>Aphanolebias konradi</i>		7	19		680				15	20
* <i>Gobius latiformis</i> / div. spec.		71	270	17	10700				27	39
* <i>Channa elliptica</i> / sp. juv.			1 / 2		2 / 27				1 / 3	1 / 1
<i>Channa</i> n.sp.			2		5					2

Marine Molasse, e.g., from Tägernastrasse, Hüenerbach, Hubertingen, and Hirschthal (Bolliger 1992; Kälin 1997). These faunas have a much higher diversity, however, and thus special environmental conditions for the Mauensee mammals must be postulated.

Mammal faunas of similar composition and similarly low diversity are known from the Upper Badenian lake sediments of Le Locle (Kälin et al. 2001). In these faunas the dominant taxa also include one hamster species (*Megacricetodon minor*), one glirid (*Miodiromys aegercii*) and one lagomorph (*Prolagus*). At Le Locle—just as in the Mauensee section—rodent groups that are supposed to have lived in forests are either completely missing (the eomyids) or are rare (the sciurids and glirids). Moreover, the mammal-bearing sediments of Le Locle are very similar in their lithofacies to those of the Mauensee section. Kälin et al. (2001) postulated for Le Locle a large lake in a savanna-like landscape. Therefore, we assume that a large lake may also have existed in the Mauensee area in a more or less similar environment. Nevertheless, the question remains of how the mammal fossils were transported into the lake sediments. It may be that the mammals lived on islands in the lake, or it may be that they were the food remains of predators such as of crocodiles or birds.

The fish fauna found in the Mauensee section (Table 1) can be regarded as autochthonous because (a) delicate shark teeth and aragonitic fish otoliths are mainly well preserved, and (b) there is no evidence of size-sorting. Teeth of sharks and rays were recovered from the sandstone beds 24, 56 to 58, and 63. The occurrence of these fossils indicates a marine environment during the deposition of these beds, a conclusion which is supported by the presence of bryozoans and barnacles. Other fish remains, especially otoliths, are missing in these beds. This, however, is probably a result of taphonomic processes, because in siliciclastic sediments, aragonitic otoliths are often destroyed by corrosion. Otoliths are abundant in the marls of the beds 46–52 that have yielded the mammals, and also in the marls at the top of the Mauensee section (Table 1). The bulk of these otoliths belong to small fishes like the gobies *Gobius dopp-leri*, *G. gregori*, *G. latiformis*, *G. aff. multipinnatus*, the atherinid *Hemitrichas martinii*, and the tooth-carps *Prolebias weileri*, *Aphanolebias konradi* and *A. gubleri*. Furthermore, three species of carps could be recognized based on pharyngeal teeth and otoliths: these are *Palaeocarassius mydlovarensis*, *Palaeoleuciscus* sp., and Leuciscinae. Big predatory fish species like the snakehead (*Channa*) and the grey mullet (*Mugil*) are rare.

Fig. 3 Size increase of the first lower molar (m_1) within the lineage *Megacricetodon collongensis* (Mein 1958) – *M. bavaricus* Fahlbusch, 1964 – *M. aff. bavaricus* – *M. lappi* (Mein 1958). The oldest member *M. collongensis* develops into the distinctly larger *M. bavaricus* (Lower MN5), and subsequently into *M. lappi* (terminal MN5). (L, length; W, width).



● Vieux-Collonges*	MN 5 (uppermost ¹)	<i>M. lappi</i>	n= 100
▲ Rämigraben	MN 5 (upper)		n= 20
⊙ Vermes 2	MN 5 (upper)		n= 11
* Vermes 1	MN 5 (middle)	<i>M. aff. bavaricus</i>	n= 18
⊙ Tobelholz	MN 5 (middle)		n= 5
■ Hüllistein	MN 5 (middle)		n= 24
△ Oberkulm-Sämlen	MN 5 (lower)		n= 19
■ Langenmoosen*	MN 5 (lower)	<i>M. bavaricus</i>	n= 34
○ Buchberg	MN 5 (lower)		n= 24
◆ Hirschthal	MN 4b		n= 7
● Mauensee	MN 4b	<i>M. collongensis</i>	n= 6
□ Hüenerbach	MN 4b		n= 5
◇ Hubertingen	MN 4b		n= 8

* typ localities:

Vieux-Collonges, *Megacricetodon lappi*
 Vieux-Collonges, *Megacricetodon collongensis*
 Langenmoosen, *Megacricetodon bavaricus*

¹ karstic fissure filling with both MN 4 and MN 5 (uppermost) age.

The fish fauna from beds 46 to 52 does not contain any stenohaline marine species, as even the grey mullet is known to migrate occasionally from the sea into rivers and other freshwater habitats. In contrast, so-called freshwater fish are abundant in the fauna, such as the carp species and the snakehead (cf. Gaudant et al. 2002; Sach et al. 2003; Böhme 2004). However, the co-occurrence of gobies, atherinids, and tooth-carps is indicative for an oligoha-

line environment (see Reichenbacher 1993) with a salinity of about 0.5–3.0 g l⁻¹. It is known from recent habitats that many so-called freshwater molluscs and fish are able to survive also in oligohaline waters (Remane 1958). Thus it can be assumed that the “freshwater”-fish and the other “freshwater” biota from the Mauensee and Schriedrued sections could also thrive in an oligohaline water body.

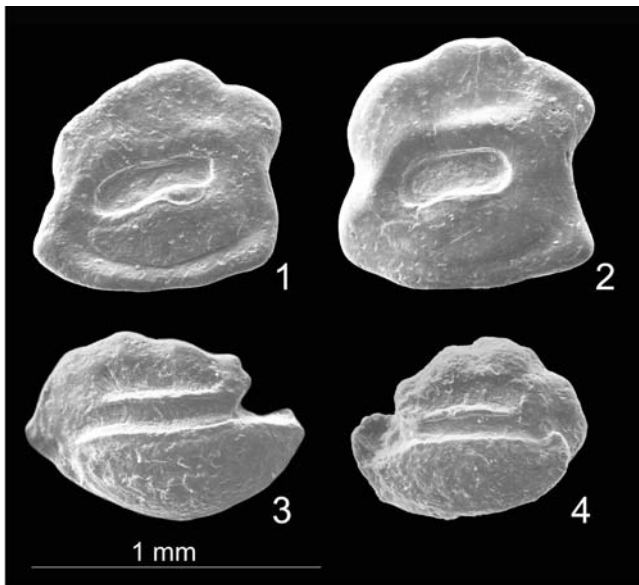


Fig. 4 The biostratigraphically most important fish species *Gobius latiformis* (1–2) and *Hemitrichas martinii* (3–4) from the oligohaline intercalations in the Mauensee and Schmiedruef sections. SEM-pictures of a left sagitta (3) and three right sagittae.

The fish assemblage from the overlying Upper Freshwater Molasse is almost identical with that from beds 46 to 52. The lowest Upper Freshwater Molasse therefore corresponds again to an oligohaline habitat, despite the appearance of the “freshwater” biota. Similar oligohaline conditions have been described for the lowermost Upper Freshwater Molasse near Lake Constance (Reichenbacher 1993).

Four pieces of evidence suggest that the environment in which the sediments of the Mauensee section were laid down was a large lake: (1) the high diversity of the fish fauna from beds 46 to 52, (2) the presence of several sympatric benthic *Gobius* species, (3) the abundance of different pelagic fishes (three species of tooth carp, one atherinid), (4) the occurrence of three top predators (two *Channa* species and the grey mullet). The Mauensee fish fauna is much more diverse and complex than that from the lake at Le Locle. There are no small pelagic fishes at Le Locle, and among the benthic species only *Gobius latiformis* has been found (Reichenbacher and Weidmann 1992). The Mauensee lake obviously was larger and deeper than the Le Locle lake, and thus was capable of supporting many more habitats and complex food chains.

In summary, the fish and mammal faunas from beds 46 to 52 evidence a change from a marine environment to an oligohaline lake within the Karpatian Upper Marine Molasse. The connection to the open sea obviously was interrupted, and the remaining water body freshened rapidly due to precipitation and river inflow. The fact that the oligohaline deposits are thin suggests that this event probably was short. Subsequently, there occurred a flooding from the sea, and the oligohaline lake became again marine (beds 56–70).

Stable isotope data

For stable isotope investigation exclusively diagenetically unaltered otoliths were used (see methods).

Saccular otoliths (also termed sagittae) grow incrementally within the auditory system of teleost fish, and they display daily and yearly bands (e.g., Woydack and Morales-Nin 2001). Thus they preserve a record of the fish’s growth rate, environmental parameters such as temperature and salinity, and metabolic state (e.g., Wurster and Patterson 2001). Kalish (1991a, b), Patterson et al. (1993), and Thorrold et al. (1997) have demonstrated that the $\delta^{18}\text{O}$ -values of saccular otoliths are closely comparable to the $\delta^{18}\text{O}$ -values of the ambient water body. In contrast, the $\delta^{13}\text{C}$ -values of saccular otoliths are not only controlled by the ambient water body, but also by metabolic effects and somatic growth of the fish and also by the otolith precipitation rate (Kalish 1991a, b; Gaudie 1996; Thorrold et al. 1997).

The saccular otoliths of gobies are well suited for oxygen isotope studies in Molasse deposits, for two reasons. First, gobies are benthic fishes and do not migrate much; thus the $\delta^{18}\text{O}$ -values of goby otoliths reflect the salinity and temperature of a water body well. Second, goby otoliths are the most abundant otoliths in the Miocene Molasse, which makes possible the collection of sufficient numbers of otoliths that enable statistical analysis of isotopic data.

Table 2 summarizes the results of the stable isotope analysis. The mean $\delta^{18}\text{O}$ -values of the goby otoliths from beds 47 and 52 are about -2.0‰ and the mean $\delta^{13}\text{C}$ -values are about -7‰ . The standard deviations are comparable with those found in a similar study of otoliths from an Eocene lake (Grimes et al. 2003).

When comparing the $\delta^{18}\text{O}$ -values from the Mauensee section with data from other Molasse sections, it is important to keep in mind that the oxygen isotopic composition depends both on salinity and on water temperature. Salinity effects can be seen by comparing the $\delta^{18}\text{O}$ -values from the Mauensee section (oligohaline) with those from the time-equivalent Bodman section (freshwater) in the southwest German Molasse Basin (Reichenbacher et al. 2004a). The goby otoliths from Mauensee are about 1‰ enriched in ^{18}O compared to those at Bodman (Table 2), which could result from a warmer water body and/or a higher salinity at Mauensee. However, it can be assumed that the water body at Mauensee was not warmer (compared with Bodman) because the climatic conditions and the air and water temperatures should have been similar at both places referring to their geological situation, similar lake environment and water depth and time equivalence. Instead, the enriched ^{18}O -values at Mauensee should reflect the higher (oligohaline) salinity there, as indicated by the palaeoecological interpretation of the fish fauna.

The $\delta^{13}\text{C}$ -values of the goby otoliths from Mauensee are about 3‰ lighter than those from Bodman, and they are also lighter than those from Illerkirchberg (Table 2), a locality for which water of the same salinity can be assumed. It has been hypothesized that $\delta^{13}\text{C}$ -values of otoliths are strongly influenced by the trophic structure of the

Table 2 Stable isotope analyses: mean values and standard deviations for the measured samples from the Mauensee section (beds 47 and 53) and from sections in the southwest German Molasse Basin

This study	Samples (<i>n</i> = number of otoliths)	$\delta^{18}\text{O}$ (in ‰)	$\delta^{13}\text{C}$ (in ‰)
OMM	Mauensee, bed 47: <i>Gobius</i> sp. (<i>n</i> =5)	-1.81±0.83	-6.75±2.53
OMM	Mauensee, bed 52: <i>Gobius</i> sp. (<i>n</i> =13)	-2.09±0.73	-7.85±1.22
Data from Reichenbacher (2004a)			
OBM	Illerkirchberg: <i>Gobius</i> sp. (<i>n</i> =3)	-0.75±1.90	-4.4±0.80
OSM	Bodman: <i>Gobius</i> sp. (<i>n</i> =5)	-2.8±1.40	-4.0±1.20

ambient water body (e.g., Kalish 1991a, b; Reichenbacher et al. 2004a). Moreover, there has been found a positive correlation between $\delta^{13}\text{C}$ -values in biogene carbonates and productivity (e.g., Mutti and Hallock 2003). Therefore the low $\delta^{13}\text{C}$ -values of the Mauensee goby otoliths may indicate an oligotrophic structure for the Mauensee lake.

Discussion and conclusion

The biostratigraphic analysis of mammal and fish faunas indicates an Early Karpatian age for both the Mauensee and

(Reichenbacher et al. 2004a). OMM, Upper Marine Molasse; OSM, Upper Freshwater Molasse; OBM, Upper Brackish Molasse.

the Schmiedrued sections. Palaeoecological study of the mammals and the fish points to a thin but significant oligohaline intercalation within the marine sediments in both of the sections; this is additionally confirmed by analysis of the oxygen isotope composition of the fish otoliths from the Mauensee section. Thus it is obvious that the marine connection to the open sea was interrupted during the time of this oligohaline intercalation, leaving behind an isolated lake.

Two different events could be responsible for the change from marine to oligohaline and again to marine conditions: (1) a sedimentological “event” or (2) a sea-level change due

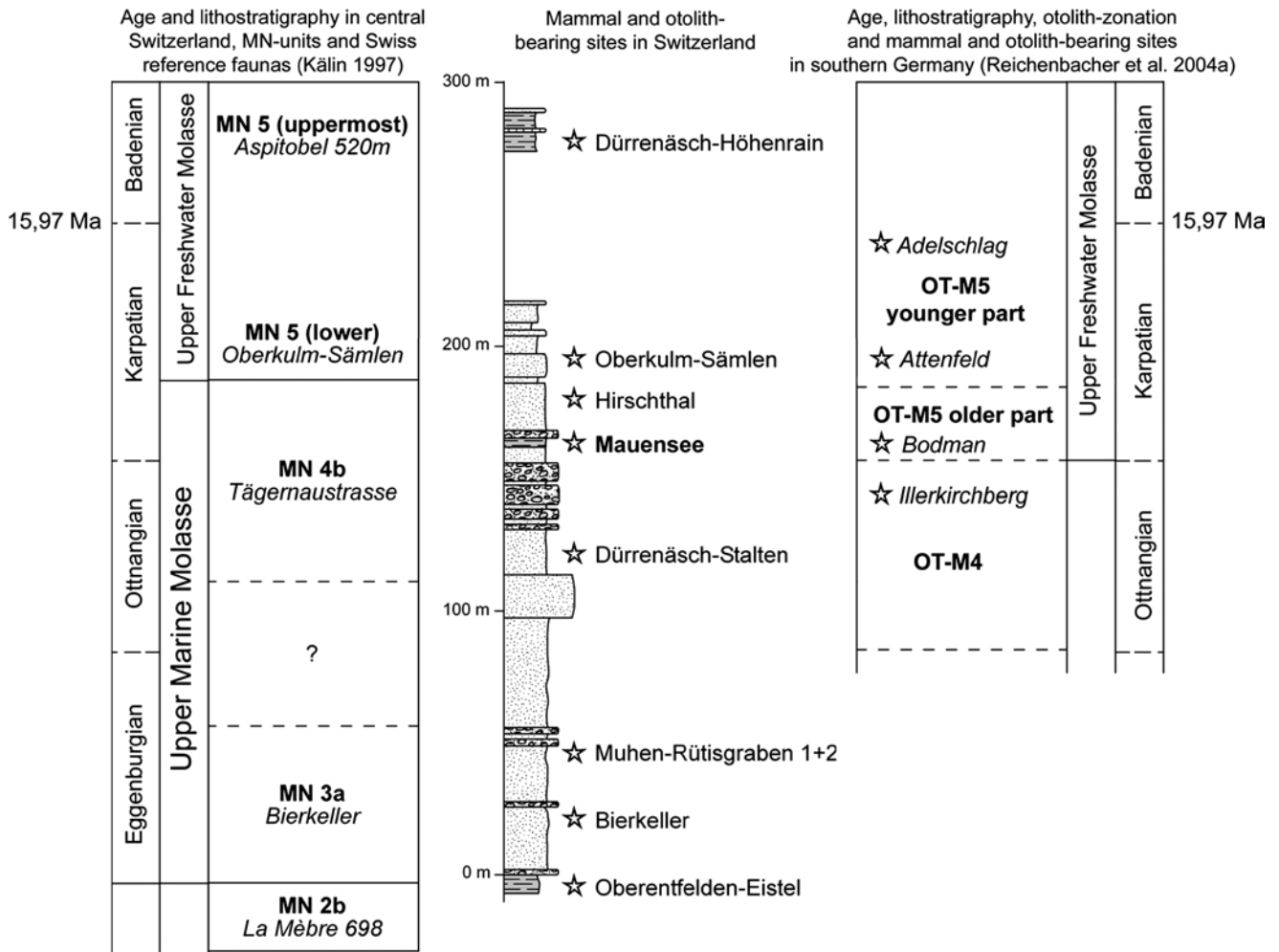


Fig. 5 Age, lithostratigraphy, biostratigraphy and correlation of the Late Otnangian and Karpatian Molasse deposits from central Switzerland to southern Germany. Note the diachronous beginning of the Upper Freshwater Molasse.

to eustatics or tectonics. A sedimentological event might have happened if some large near-coastal water body had become isolated as a result of coastal sedimentation processes (e.g., storms). In that case, the change back to marine conditions was due to the re-opening of the connection between this bay (now a lake) and the sea. On the first glance, this explanation seems reasonable because the sections represent a near-shore environment at the eastern margin of the Napf fan-delta, where high sediment supply might have created a restricted lagoonal environment that developed into an oligohaline lake. In this case, no tectonic or eustatic event would be involved and the marine-oligohaline-marine sequences of the Mauensee and Schmiedrued sections would not be correlative with any other event in the Molasse Basin. However, the fish assemblages in the oligohaline sediments do not support a locally restricted, near-shore lagoon, because in such an environment also stenohaline-marine fishes and a variety of marine-euryhaline species would be expected. Instead, a diverse oligohaline to freshwater fish fauna is present in Mauensee and Schmiedrued. It contains freshwater taxa (e.g., *Palaeocarassius mydlovariensis*, *Aphanius konradi*, *A. gubleri*) that are widespread from southwest Germany to central Switzerland (Reichenbacher 1993; Reichenbacher et al. 2004a). Such a fish fauna indicates an extended inland water system, and some distance from the coast. Consequently, it seems to be a more probable explanation that the marine-oligohaline-marine sequence was due to a sea-level change, which caused a vast regression in central Switzerland, and which was followed by a recurrent transgression. In that case, a correlation with other sections in Switzerland and probably also in the southwest German part of the Molasse Basin should be expected, which will be discussed in the following.

In eastern Switzerland, the St. Gallen Formation (this includes the younger part of the Upper Marine Molasse) consists of three small cycles, each of them starting with coarse conglomerate flows and ending with a regressive sequence of fine-grained clastics and a subsequent hiatus (Keller 1989; Schlunegger et al. 1997b). For the present study, the second and third of these small cycles are the most interesting ones. Conglomerate beds, derived from the Napf and Hörnli fans, characterize the beginning of the second small cycle. Such conglomerates appear also within the Baltringen Beds in southwest Germany, and on this basis it has been suggested that the second small cycle of the St. Gallen Formation correlates with the Baltringen Beds and the overlying “Fine Sand Series” (Hofmann 1967; Büchi and Schlanke 1977; Lemcke 1985). The subsequent hiatus may then correspond to the terrestrial period in southwest Germany during which the “Graupensandrinne” was incised (Schreiner 1966; Hofmann 1967). The third of the St. Gallen Formation small cycles starts with the coarse conglomeratic flows of the so-called “Grenzagnelfluh” (e.g., Büchi 1955). The pebbles and boulders in these flows derive mainly from the Napf fan, and they are widely distributed; for instance, they are found near Lake Constance, where they outcrop at the base of the Kirchberg Formation of the Upper Brackish Molasse (e.g., Werner 1975; Schreiner 1976).

Consequently, the Kirchberg Formation of the Upper Brackish Molasse has been correlated with the third St. Gallen Formation small cycle (Büchi and Schlanke 1977; Reichenbacher 1993). Recent bio- and chronostratigraphic data additionally support this correlation, as the third St. Gallen Formation small cycle has been dated as Late Otnangian to Early Karpatian (Schlunegger et al. 1997a), and the Kirchberg Formation as Late Otnangian (Reichenbacher et al. 1998). Up to date, the third St. Gallen Formation small cycle was not known from the Molasse Basin of central Switzerland, probably due to the lack of biostratigraphically dated sections. It should be added that Gall (1975) had proposed the occurrence of a third small cycle in southwest Germany and along the southern border of the Suebian Alb. However, this small cycle, which appears according to Gall (1975) within the “Fine Sand Series”, has never been studied with regard to its biostratigraphy or basin-wide correlation. At present, it can only be speculated if it is a lateral facies equivalent of the Kirchberg Formation of the Upper Brackish Molasse or if the Kirchberg Formation is then a younger, fourth cycle.

As the Mauensee and Schmiedrued sections are evidently of Early Karpatian age (on the basis of their mammal and fish faunas), they seem correlatable with the third small cycle of the St. Gallen Formation in eastern Switzerland (on the basis of the litho-, bio- and chronostratigraphy discussed earlier). Consequently, the oligohaline intercalations in the Mauensee and Schmiedrued sections can be interpreted as belonging to the regressive phase of the third St. Gallen Formation small cycle.

The fish fauna from the oligohaline strata at Mauensee and Schmiedrued is of the same age as the fish fauna from the lowermost Upper Freshwater Molasse in southwest Germany (Reichenbacher et al. 2004a: Bodman locality). Thus it can be assumed that the regressive phase of the third St. Gallen Formation small cycle may have caused the beginning of the lowermost Upper Freshwater Molasse sedimentation in eastern Switzerland and southwest Germany (Fig. 5). The marine sequence above the oligohaline strata at the Mauensee and Schmiedrued sections apparently represents a previously unknown fourth St. Gallen Formation cycle, which took place during the Karpatian. According to Hardenbol et al. (1998), these third and fourth St. Gallen Formation cycles happened during globally transgressive times. The fourth cycle might perhaps indicate a Karpatian transgression from the Mediterranean Sea, which has not previously been recognized. As no equivalent marine sediments are known from eastern Switzerland and southern Germany, this Karpatian transgression would evidently have reached only into the area of central Switzerland. This stopping of the transgression there would possibly have been due to the palaeotopography; tectonic activity is unlikely to have been responsible, because it was low at that time (Kempf and Matter 1999; Schlunegger et al. 2001; Hay et al. 2002). It may be the presence of a marine area in central Switzerland in the Karpatian that explains why the terrestrial sedimentation of the Upper Freshwater Molasse began at different times in southwest Germany and eastern Switzerland and in central Switzerland.

Acknowledgements John Tipper (Univ. Freiburg) helped with a critical review of an earlier version and improved our English. Oliver Kempf (Technical Univ. Braunschweig), Thomas Tütken (Univ. Lausanne) and an anonymous reviewer gave additional helpful advice. M. Böhme (Univ. Munich and GeoBioCenter) determined the pharyngeal teeth of the carps. U. Struck (Univ. Munich and GeoBioCenter) assisted with the stable isotope analysis and interpretation. T. Fehr and A. Rocholl (both Univ. Munich) carried out the FTIR analysis. To all go our sincere thanks. This study was supported by the Deutsche Forschungsgemeinschaft (Re 1113/9-1) and the GeoBioCenter (LMU).

References

- Asprion U, Aigner T (2000) Facies- und Georadar-Analyse in der süddeutschen Graupensandrinne. *N Jb Geol Paläont Abh* 218:321–342
- Bachmann GH, Müller M (1991) The Molasse basin, Germany: evolution of a classic petroliferous foreland basin. In: Spencer AM (ed) *Generation, accumulation, and production of Europe's hydrocarbons*, vol 1. Special Publication of European Association of Petrol Geosciences, pp 263–276
- Berger JP (1985) La transgression de la Molasses marine supérieure (OMM) en Suisse occidentale. *Münchner Geowiss Abh A* 5:1–208
- Berger JP (1999) Redefinition of European Oligo-Miocene charophyte biozonation. *Aust J Bot* 47:283–296
- Berggren WA, Kent DV, Swisher CC III, Aubry MP (1995) A revised Cenozoic geochronology and chronostratigraphy. In: Berggren WA, Kent DV, Hardenbol J (eds) *Geochronology, time scales and global stratigraphic correlations: a unified temporal framework for a historical geology*. *SEPM Spec Publ* 54:129–212
- Bieg U, Suess MP, Thomas M, Kuhlemann J, Cordero F (2003) Global M 2 Simulation for the Early Miocene delivering border conditions for a forthcoming tidal simulation of the Circum-Mediterranean realm. *Zbl Geol Paläont Teil I* 3/4:259–276
- Bieg U, Suess MP, Kuhlemann J (in press) Simulation of tidal flow and circulation pattern in the Burdigalian Seaway (Upper Marine Molasse, Early Miocene). *IAS Spec Publ*
- Böhme M (2004) Migration history of air-breathing fishes reveal Neogene atmospheric circulation pattern. *Geology* 32:393–396
- Böhme M, Reichenbacher B (2003) Teleost fishes from the Karpatian (Lower Miocene) of the Western Paratethys. In: Brzobohaty R, Cicha I, Kovac M, Rögl F (eds) *The Karpatian – an Early Miocene Stage of the Central Paratethys*. Masaryk University Brno, pp 11–14
- Bolliger T (1992) Kleinsäugerstratigraphie in der miozänen Hörnlichüttung (Ostschweiz). *Documenta Naturae* 75:1–296
- Büchi UP (1955) Zur Geologie der Oberen Meeresmolasse von St. Gallen. *Eclogae Geol Helv* 48:257–321
- Büchi UP, Schlanke S (1977) Zur Paläogeographie der schweizerischen Molasse. *Erdöl/Erdgas-Z* 93:57–69
- Buxtorf A (1901) Geologie der Umgebung von Gelterkinden im Basler Tafeljura. *Beitr geol Karte Schweiz NF* 11:1–106
- Cande SC, Kent DV (1995) Revised calibration of the geomagnetic polarity time scale. *J Geophys Res* 100:6093–6095
- Doppler G (1989) Zur Stratigraphie der nördlichen Vorlandmolasse in Bayerisch-Schwaben. *Geol Bavar* 94:83–133
- Doppler G, Heissig K, Reichenbacher B (in press) Zur Gliederung des Tertiärs im süddeutschen Molassebecken. *Newsl Strat* 41
- Engesser B (1990) Die Eomyidae (Rodentia, Mammalia) der Molasse der Schweiz und Savoyens. *Schweiz Paläont Abh* 112:1–144
- Engesser B, Mödden C (1997) A new version of the Biozonation of the Lower Freshwater Molasse (Oligocene and Aegianian) of Switzerland and Savoy on the basis of fossil mammals. In: Aguilar JP, Legendre S, Michaux J (eds) *Actes du Congrès Biochrom'97*. *Mém Trav EPHE Inst Montpellier* 21:475–499
- Gall H (1975) Der III. Zyklus der Oberen Meeresmolasse (Helvet) am Südrand der Schwäbisch-Fränkischen Alb. *Mitt Bayer Staatssamml Paläont Hist Geol* 15:179–205
- Gaudant J, Weidmann M, Berger JP, Bolliger T, Kälin D, Reichenbacher B (2002) Recherches sur les dents pharyngiennes de Poissons Cyprinidae de la Molasse d'eau douce oligo-miocène de Suisse (USM, OSM) et de Haute-Savoie (France). *Rev Paléobiol* 21:371–389
- Gauldie RW (1996) Biological factors controlling the carbon isotope record in fish otoliths: principles and evidence. *Comp Biochem Physiol B* 115:201–208
- Grimes ST, Matthey DP, Hooker JJ, Collinson ME (2003) Paleogene paleoclimate reconstruction using oxygen isotopes from land and freshwater organisms: the use of multiple paleoproxies. *Geochim Cosmochim Acta* 67:4033–4047
- Hagn H (1961) Die Gliederung der Oberen Meeresmolasse nördlich vom Überlinger See (Bodensee) in mikropaläontologischer Sicht. *Jh Geol Landesamt Baden-Württemb* 5:293–321
- Hardenbol J, Thierry J, Farley MB, Jacquin T, de Graciansky PC, Vail PR (1998) Mesozoic and Cenozoic sequence chronostratigraphic framework of European Basins. In: de Graciansky PC, Hardenbol J, Jacquin T, Vail PR (eds) *Mesozoic and Cenozoic sequence stratigraphy of European Basins*. *SEPM Spec Publ* 60:3–13
- Hay WD, Soeding E, DeConto RM, Wold CN (2002) The Late Cenozoic uplift—climate change paradox. *Int J Earth Sci* 91:746–774
- Heissig K (1997) Mammal faunas intermediate between the reference faunas of MN4 and MN6 from the Upper Freshwater Molasse of Bavaria. In: Aguilar JP, Legendre S, Michaux J (eds) *Actes du congrès Biochrom'97*. *Mém Trav EPHE Inst Montpellier* 21:537–546
- Hofmann F (1967) über die Tertiärbildungen im Kanton Schaffhausen. *Mitt Naturf Ges Schaffhausen* 28:171–210
- Homewood P, Allen PA, Williams GD (1986) Dynamics of the Molasse basin of western Switzerland. In: Allen PA, Homewood P (eds) *Foreland basins*. *Spec Publ IAS* 6:199–219
- Hürzeler J (1932) Die Helvétien-Tortonien-Grenze im aargauischen Mittelland. *Eclogae Geol Helv* 25:266–269
- Hug W, Berger JP, Clement I, Kälin D, Weidmann M (1997) Miocene fossiliferous paleokarst (MN 4) and OSM deposits (MN 5 -?) near Glovelier (Swiss Jura Mountains). Abstracts, *Groupe Molasse 1997*, Fribourg
- Jin J (1995) Dynamic stratigraphic analysis and modeling in the south-eastern German molasse basin. *Tübinger Geowiss Arbeiten A* 24:1–153
- Kalish JM (1991a) Carbon-13 and oxygen-18 isotopic disequilibria in fish otoliths. Metabolic and kinetic effects. *Mar Ecol Progr Ser* 75:191–203
- Kalish JM (1991b) Oxygen and carbon stable isotopes in the otoliths of wild and laboratory-reared Australian *Salmon arripis-trutta*. *Mar Biol* 110:37–48
- Kälin D (1997) The mammal zonation of the Upper Marine Molasse of Switzerland reconsidered – a local Biozonation of MN 2–MN 5. In: Aguilar JP, Legendre S, Michaux J (eds) *Actes du congrès Biochrom'97*. *Mém Trav EPHE Inst Montpellier* 21:515–535
- Kälin D, Berger JP, Engesser B, Weidmann M (2001) Paläontologie et âge de la Molasse d'eau douce supérieure neuchâtelois. *Schweiz Paläont Abh* 121:63–99
- Keller B (1989) Fazies und Stratigraphie der Oberen Meeresmolasse (Unteres Miozän) zwischen Napf und Bodensee. Inaugural Dissertation, *Phil-Naturwiss Fak Univ, Bern*, 402 pp
- Keller B (1990) Wirkung von Wellen und Gezeiten bei der Ablagerung der Oberen Meeresmolasse. *Mitt Naturf Ges Luzern* 31:245–271
- Kempf O, Matter A (1999) Magnetostratigraphy and depositional history of the Upper Fresh Water Molasse (OSM) of eastern Switzerland. *Eclogae Geol Helv* 92:97–103
- Kempf O, Pross J (2005) The lower marine to lower freshwater Molasse transition in the northern Alpine foreland basin (Oligocene; central Switzerland–south Germany): age and geodynamic implications. *Int J Earth Sci* 94:160–171

- Kempf O, Bolliger T, Kälin D, Engesser B, Matter A (1997) New magnetostratigraphic calibration of early to middle Miocene mammal biozones of the North Alpine Foreland Basin. In: Aguilar JP, Legendre S, Michaux J (eds) Actes du congrès Biochrom'97. Mém Trav EPHE Inst Montpellier 21:547–561
- Kempf O, Matter A, Burbank DW, Mange M (1999) Depositional and structural evolution of a foreland basin margin in a magnetostratigraphic framework: the eastern Swiss Molasse Basin. *Int J Earth Sci* 88:253–275
- Kiderlen H (1931) Beiträge zur Stratigraphie und Paläogeographie des süddeutschen Tertiärs. *N Jb Mineral Beil Bd B* 66:215–384
- Kuhlemann J (2000) Postcollisional sediment budget of circum-Alpine basins. *Mem Sci Geol* 52:1–91
- Kuhlemann J, Kempf O (2002) Post-Eocene evolution of the North Alpine Foreland Basin and its response to Alpine tectonics. *Sediment Geol* 152:45–78
- Lemcke K (1972) Die Lagerung der jüngsten Molasse im Alpenvorland. *Bull Ver Schweiz Petrol Geol Ing* 39:29–41
- Lemcke K (1985) Flußfracht von Ur-Main und Ur-Naab in der Schweiz und im deutschen Molassebecken. *Bull Ver Schweiz Petrol Geol Ing* 51:13–21
- Lemcke K (1988) Geologie von Bayern I. Das bayerische Alpenvorland vor der Eiszeit. Schweizerbart, Stuttgart, 175 pp
- Lemcke K, Engelhardt V, Fichtbauer H (1953) Geologische und sedimentpetrographische Untersuchungen im Westteil der ungefalteten Molasse des süddeutschen Alpenvorlandes. *Beih Geol Jb* 11:1–64
- Luterbacher H, Koehler J, Winder H (1992) The northern margin of the Molasse Basin in SW Germany. *Eclogae Geol Helv* 85:787–788
- Mein P (1975) Résultats du groupe de travail des vertébrés: biozonation du Néogène méditerranéen à partir des mammifères. In: Report on activity of RCMN working groups (1971–1975), pp 78–81
- Mein P (1989) Updating of MN zones. In: Lindsay EH, Fahlbusch V, Mein P (eds) European neogene mammal chronology, vol 180. Plenum Press, New York, NATO ASI Ser A, pp 73–90
- Mödden C, Schäfer P, Reichenbacher B, Schwarz J, Kadolsky D (2000) Säugetiere, Fisch-Otolithen, Ostracoden, Mollusken und Charophyten aus den Süßwasser-Schichten (Oligozän) von Wolfshelm im Mainzer Becken. *Paläont Z* 74:343–361
- Mutti M, Hallock P (2003) Carbonate systems along nutrient and temperature gradients: some sedimentological and geochemical constraints. *Int J Earth Sci* 92:465–475
- Nägele E (1962) Zur Petrographie und Entstehung des Albsteins. *N Jb Geol Paläont Abh* 189:255–274
- Patterson WP, Smith GR, Lohmann KC (1993) Continental paleothermometry and seasonality using the isotopic composition of aragonite otoliths of freshwater fishes. In: Swart PK, Lohmann KC, McKenzie J, Swart S (eds) Climate change in continental isotopic records. American Geophysics Union, pp 191–202
- Reichenbacher B (1989) Feinstratigraphische Gliederung der Kirchberger Schichten (Unter-Miozän) an der Typuslokalität Illerkirchberg bei Ulm. *Geol Bavar* 94:135–177
- Reichenbacher B (1993) Mikrofaunen, Paläogeographie und Biostratigraphie der miozänen Brack- und Süßwassermolasse in der westlichen Paratethys unter besonderer Berücksichtigung der Fisch-Otolithen. *Senckenbergiana Lethaea* 73:277–374
- Reichenbacher B (1999) Preliminary otolith-zonation in continental Tertiary deposits of the Paratethys and adjacent areas. *N Jb Geol Paläont Abh* 214:375–390
- Reichenbacher B, Weidmann M (1992) Fisch-Otolithen aus der oligo-/ miozänen Molasse der West-Schweiz und der Haute-Savoie (Frankreich). *Stutt Beitr Naturkd B* 184:1–83
- Reichenbacher B, Böttcher R, Bracher H, Doppler G, von Engelhardt W, Gregor HJ, Heissig K, Heizmann EPJ, Hofmann F, Kälin D, Lemcke K, Luterbacher H, Martini E, Pfeil F, Reiff W, Schreiner A, Steininger FF (1998) Graupensandrinne – Ries-Impakt: Zur Stratigraphie der Grimmelfinger Schichten, Kirchberger Schichten und Oberen Süßwassermolasse. *Z Dt Geol Ges* 149:127–161
- Reichenbacher B, Böhme M, Heissig K, Prieto J, Kossler A (2004a) New approach to assess biostratigraphy, palaeoecology and past climate in the South German Molasse Basin during the Early Miocene (Ottangian, Karpatian). *Courier Forschungsinst Senckenberg* 249:71–89
- Reichenbacher B, Uhlrig U, Kowalke T, Bassler B, Matzke-Karasz R, Schenk B (2004b) Biota, palaeoenvironments and biostratigraphy of continental Oligocene deposits from the south German Molasse basin (Penzberg Syncline). *Palaeontology* 47:639–677
- Remane A (1958) Die Biologie des Brackwassers. In: Thienemann A (ed) Die Binnengewässer 22. Schweizerbart, Stuttgart, 216 pp
- Rögl F (1998) Palaeogeographic considerations for Mediterranean and Paratethys seaways (Oligocene to Miocene). *Ann Naturhist Mus Wien* 99A:279–310
- Sach V, Gaudant J, Reichenbacher B, Böhme M (2003) Die Fischfaunen der Fundstellen Edelbeuren-Maurerkopf und Wannwaldtobel 2 (Miozän, Obere Süßwassermolasse, Süddeutschland). *Stutt Beitr Naturkd B* 334:1–25
- Schlickum WR (1963) Die Molluskenfauna der Süßbrackwassermolasse von Ober- und Unterkirchberg. *Archiv Molluskenkd* 92:1–10
- Schlunegger F, Burbank DW, Matter A, Engesser B, Mödden C (1996) Magnetostratigraphic calibration of the Oligocene to Middle Miocene (30–15 Ma) mammal biozones and depositional sequences of the Swiss Molasse Basin. *Eclogae Geol Helv* 89:753–788
- Schlunegger F, Matter A, Burbank DW, Klaper EM (1997a) Magnetostratigraphic constraints on relationships between evolution of the central Swiss Molasse basin and Alpine orogenic events. *GSA Bull* 109:225–241
- Schlunegger F, Jordan TE, Klaper EM (1997b) Controls of erosional denudation in the orogen on foreland basin evolution: the Oligocene central Swiss Molasse Basin as an example. *Tectonics* 16:823–840
- Schlunegger F, Melzer J, Tucker G (2001) Climate, exposed source rock lithologies, crustal uplift and surface erosion: a theoretical analysis calibrated with data from the Alps/North Alpine Foreland Basin system. *Int J Earth Sci* 90:484–499
- Schreiner A (1966) Zur Stratigraphie der Oberen Meeresmolasse zwischen der Oberen Donau und dem Überlinger See (Baden-Württemberg). *Jber Mitt Oberrhein Geol Ver NF* 48:91–104
- Schreiner A (1976) Hegau und westlicher Bodensee. *Samml Geol Führer* 62:1–93
- Schwerd K, Doppler G, Unger HJ (1996) Gesteinsfolge des Molassebeckens und der inneralpinen Tertiärbecken—Allgemeiner Überblick. In: Bayerisches Geologisches Landesamt (ed) Erläuterungen zur Geologischen Karte von Bayern 1:500 000, pp 141–149
- Sissingh W (1997) Tectonostratigraphy of the North Alpine Foreland Basin: correlation of tertiary depositional cycles and orogenic phases. *Tectonophysics* 282:223–256
- Sissingh W (1998) Comparative tertiary stratigraphy of the Rhine Graben, Bresse Graben and Molasse Basin: correlation of Alpine foreland events. *Tectonophysics* 300:249–284
- Sissingh W (2001) Tectonostratigraphy of the West Alpine Foreland: correlation of Tertiary sedimentary sequences, changes in eustatic sea-level and stress regimes. *Tectonophysics* 333:361–400
- Steininger FF (1999) Chronostratigraphy, geochronology and biochronology of the Miocene “European Land Mammal Mega-Zones” (ELMMZ) and the Miocene “Mammal-Zones (MN-Zones)”. In: Rössner GE, Heissig K (eds) The Miocene Land mammals of Europe. Pfeil, Munich, pp 9–24
- Strunck P (2001) The Molasse of Western Switzerland. Dissertation, Phil-Naturwiss Fak Univ, Bern, 246 pp
- Strunck P, Matter A (2002) Depositional evolution of the western Swiss Molasse. *Eclogae Geol Helv* 95:197–222
- Thorrold SR, Campana SE, Jones CM, Swart PK (1997) Factors determining $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ fractionation in aragonitic otoliths of marine fish. *Geochim Cosmochim Acta* 61:2909–2919

- Tipper JC, Sach VJ, Heizmann EPJ (2003) Loading fractures and Liesegang laminae: new sedimentary structures found in the north-western North Alpine Foreland Basin (Oligocene–Miocene, south-west Germany). *Sedimentology* 50:791–813
- Uhlig U, Reichenbacher B, Bassler B (2000) Säugetiere, Fisch-Otolithen und Charophyten aus den Unteren Cyrenen-Schichten (Oligozän) der bayerischen Faltenmolasse (Murnauer Mulde). *Eclogae Geol Helv* 93:503–516
- Wenger WF (1987) Die Basis der Oberen Meeresmolasse im westlichen Oberbayern, am Überlinger See, in Vorarlberg und St. Gallen. *Mitt Bayer Staatssamml Paläont Hist Geol* 27:159–174
- Werner J (1975) Erläuterungen zu Blatt 8020 Meßkirch. *Geol Kt Baden-Württemb* 1:25000, 209 pp
- Woydack A, Morales-Nin B (2001) Growth patterns and biological information in fossil fish otoliths. *Paleobiology* 27:369–378
- Wurster CM, Patterson WP (2001) Late Holocene climate change for the eastern interior United States: evidence from high-resolution $\delta^{18}\text{O}$ values of sagittal otoliths. *Palaeogeogr Palaeoclimatol Palaeoecol* 170:81–100
- Zöbelein KH (1985) Stratigraphie der nördlichen und teils mittleren Vorlandmolasse zwischen Hegau und Isar anhand von 11 Profilen. *Mitt Bayer Staatssamml Paläont Hist Geol* 25:209–273
- Zweigel J, Aigner T, Luterbacher H (1998) Eustatic *versus* tectonic controls on Alpine foreland basin fill: sequence stratigraphy and subsidence analysis in the SE German Molasse). In: Mascle A, Puigdefàbregas C, Luterbacher HP, Fernández M (eds) *Cenozoic Foreland Basins of Western Europe*. *Geol Soc London Spec Publ* 134:299–323