Int J Earth Sci (Geol Rundsch) (2005) 94: 160–171
DOI 10.1007/s00531-004-0437-0

ORIGINAL PAPER

Oliver Kempf · Jörg Pross

The lower marine to lower freshwater Molasse transition in the northern Alpine foreland basin (Oligocene; central Switzerland–south Germany): age and geodynamic implications

Received: 10 November 2003 / Accepted: 28 July 2004 / Published online: 6 October 2004

Abstract The Wilhelmine Alpe section near Immenstadt (Allgäu, south Germany), which represents one of the best continuously exposed outcrops within the northern Alpine foreland basin, has been analyzed for magnetostratigraphic and palynostratigraphic signals. The section comprises the marine-to-terrestrial transition from Lower Marine (UMM) to Lower Freshwater Molasse (USM) sediments. Based on the correlation of the local magnetic pattern with the geomagnetic polarity timescale (GPTS) and palynostratigraphic data, an age of about 31 Ma is suggested for the UMM–USM transition in the Wilhelmine Alpe section. A comparison with coeval magnetostratigraphic sections from central and eastern Switzerland indicates that the regression of the UMM sea along the southern margin of the Molasse basin occurred strongly heterochronously between 31.5 and 30 Ma. The heterochroneity is attributed to the deposition of fan-delta and alluvial fan sediments which document that the overall marine conditions during the UMM were accompanied by strong clastic input derived from the rising Alps. This clastic contribution had a much stronger influence on the depositional pattern than previously thought.

O. Kempf (✉)
Institut für Umweltgeologie,
Technische Universität Braunschweig,
Pockelsstr. 3, 38106 Braunschweig, Germany
E-mail: oliver.kempf@tu-bs.de
Tel.: +49-531-3917245
Fax: +49-531-3918130

J. Pross
Institut für Geowissenschaften,
Universität Tübingen, Sigwartstrasse 10,
72076 Tübingen, Germany

Present address: J. Pross
Laboratory of Palaeobotany and Palynology,
Department Geobiology, Universiteit Utrecht,
Budapestlaan 4, 3584 Utrecht, The Netherlands
E-mail: joerg.pross@uni-tuebingen.de

Keywords North Alpine foreland basin · Oligocene · Stratigraphic control · Magnetostratigraphy · Palynology

Introduction

The northern Alpine foreland basin ranges among the best-investigated foreland basins worldwide. Its depositional history begins with deep-marine Flysch sediments of Early Tertiary (Paleocene to Early Oligocene) age, followed by Mid-Oligocene to Miocene shallow-marine and continental Molasse deposits (Matter et al. 1980; Herb 1988; Sinclair et al. 1991).

For a long time, geological research has focussed on their potential for hydrocarbon production (e.g. Lemcke 1967; Bachmann et al. 1982), but also on their relevance for groundwater management in a relatively densely populated area (Keller 1992). During the last decade, northern Alpine foreland basin studies have increasingly concentrated on elucidating the interaction of orogenic processes with coeval stratigraphic foreland basin evolution (Sinclair et al. 1991; Sinclair and Allen 1992). As a prerequisite, these studies depend critically on a well-established stratigraphic framework.

Radiometric data are scarce for the basin sediments from the northern Alpine foreland. Radiometric ages, derived from U–Pb dating of zircons, are only available for three bentonite horizons in the youngest Molasse deposits of the Zurich area (eastern Switzerland), ranging between 15.3 and 14.2 Ma (Gubler et al. 1992). Biostratigraphy, on the other hand, has been intensely applied for regional correlation within the Molasse basin, and resulted in a regional biostratigraphic zonation based on micro-mammal faunas (Engesser and Mayo 1987; Engesser 1990), on charophytes (Riveline et al. 1996; Berger 1999) and on otoliths (Reichenbacher 1999). However, especially for the Oligocene deposits, these data are scattered throughout the basin and a reliable correlation is often hindered by the poor preservation of these fossil remains in high-energy environments of alluvial fans and river systems or deltaic and coastal facies zones.

Palynological analyses using organic-walled dinoflagellate cysts (dinocysts), which have a high potential to provide biostratigraphic control and palaeoenvironmental information on marginal marine settings from the Late Triassic onwards (e.g. Stover et al. 1996; Pross et al. 2004; Sluijs et al. 2004) have yet only scarcely been carried out on sediments from the northern Alpine foreland basin (Hochuli 1978; Köhler 1991; J. Pross, unpublished data).

Similarly, it is only recently that palaeomagnetic techniques have yielded a very refined temporal correlation of different sections from that region (Burbank et al. 1992; Schlunegger et al. 1996; Kempf et al. 1997, 1999; Kempf and Matter 1999; Strunck and Matter 2002). This led to a better understanding of the dynamic stratigraphic evolution and the coupling of depositional and tectonic processes during the Oligocene and Middle Miocene (ca. 32–13 Ma; Schlunegger et al. 1997, 1998; Kempf et al. 1999).

Of particular relevance for palaeogeographic reconstructions is the evolution of the depositional pattern in the Molasse basin in response to eustatic sea level fluctuations and sediment supply. In the Molasse basin, two shallowing-upward megasequences of marine to terrestrial sedimentary environments are present. These marine-to-terrestrial environmental changes were classically interpreted to have resulted from sea level fluctuations (Lemcke 1984; Bachmann and Müller 1991, 1992).

Alternatively, focussing on the sediment supply from the Alps into the northern foreland, quantitative attempts were carried out by Kuhlemann (2000), Schlunegger and Hinderer (2001), Schlunegger et al. (2001) to better understand the changing sediment transfer over time. According to these papers, terrestrial sedimentation corresponds to strongly increased sediment input, whereas marine sedimentation occurred when terrigenous input was low (Kuhlemann 2000). Thus, sediment budget estimates favour sediment supply as preferred control for the depositional pattern (Kuhlemann and Kempf 2002). Hence, to provide valuable information on the controls on sedimentation, high-resolution chronostratigraphy is required for the marine-to-terrestrial transition.

Based on data resulting from an integrated magnetostratigraphic and palynostratigraphic approach, this paper aims to provide new insights into the age and nature of the transition from marine to terrestrial conditions in the older megasequence [Lower Marine and Lower Freshwater Molasse (UMM, USM)] of the northern Alpine foreland.

Geological framework and age control

The largely undeformed part of the north Alpine foreland basin, the Molasse basin (Oligocene to Miocene), stretches along the northern front of the Alpine orogen from Geneva (Switzerland) in the southwest across Switzerland and southern Germany to Vienna (Austria) in the northeast over about 700 km. The wedge-shaped basin fill is >4 km thick at the southern basin margin and feathers out towards the north. A narrow zone of deformed thrust sheets along the southern basin margin formed partially during Molasse deposition in the course of late Alpine convergence during Late Oligocene to Middle Miocene times (Matter et al. 1980).

In the western part of the Molasse basin, sediments can be attributed to two shallowing-upward megasequences that are composed of four lithostratigraphic groups (Fig. 1; Matter et al. 1980; Lemcke 1988). These are the UMM and USM at the base and, following a transgression, the Upper Marine and Upper Freshwater Molasse (OMM, OSM). In the exclusively terrestrial (“freshwater”) environments, alluvial fan deposits formed along the southern basin margin, whereas fluvial and lacustrine sediments were deposited in the more central and external parts of the Molasse basin. The marine units consist of mostly shallow marine siliciclastics deposited in tidal and storm-influenced environments. Near the Alpine front, alluvial fan and fan delta deposits interfinger with the marine sediments. South of Munich, a deltaic complex formed in the transitional zone between the terrestrial USM in the west and the marine deposits in the east during the Late Oligocene to earliest Miocene, the Lower Brackish Molasse or Cyrena-Beds (Geissler 1975; Barthelt 1989). In the following, we focus on the UMM of the western part of the basin with emphasis on its transition to the USM.

A Rupelian age is generally assumed for the middle and upper (younger) parts of the UMM (Frei 1979; Habicht 1987), although a Chattian age cannot be excluded (Lemcke 1988). However, as lithostratigraphic units are obviously facies-dependent, temporal variations in the age of the UMM/USM boundary due to facies migration are very probable (Diem 1986a).

Biostratigraphic information derived from mammals, charophytes and otoliths indicates a Chattian age for the brackish Cyrena-Beds of the Bavarian Molasse basin (Mammal Paleogene Zone MP 24; Uhlig et al. 2000) corresponding to the UMM–USM transition in this part of the Molasse basin. Only recently, the UMM–USM transition in the Bavarian Molasse (Penzberg Syncline) has been dated biostratigraphically to 28–29 Ma (Reichenbacher et al. 2004).

Chronostratigraphic methods, in contrast, provide facies-independent age information. For the Swiss Molasse basin, this has been demonstrated by magnetostratigraphic studies (Schlunegger et al. 1996; Kempf and Matter 1999). Ages derived from the correlation of magnetic sections with the global polarity time scale (Cande and Kent 1992, 1995) were constrained by well-defined micro-mammal faunas within the sections. This resulted in a basin-wide applicable calibration chart (Schlunegger et al. 1996; Kempf et al. 1997; Strunck and Matter 2002). However, the calibration of mammal data

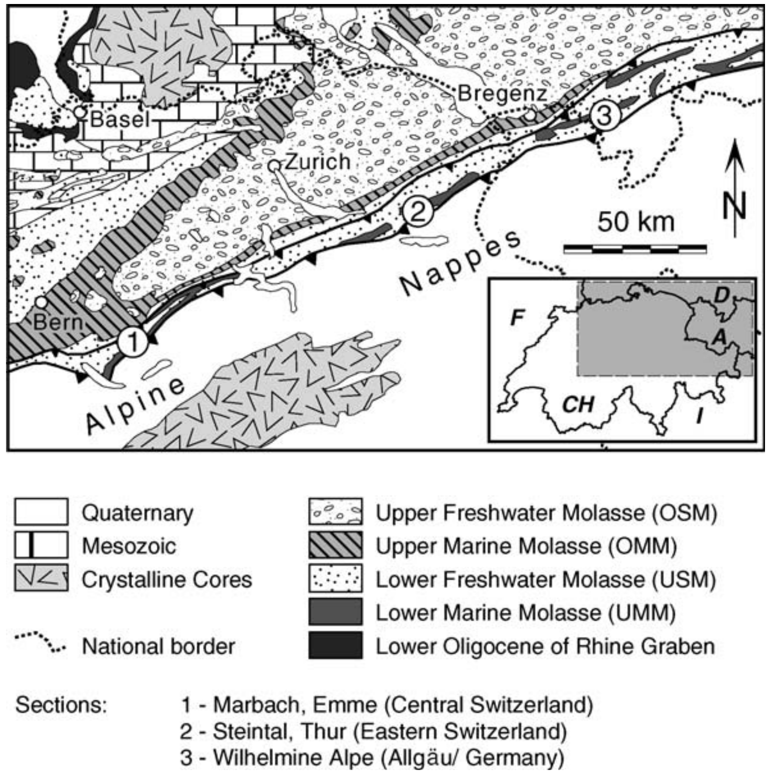

Fig. 1 Geological overview of the western part of the Molasse basin and location of investigated and discussed sections. Modified after Keller et al. (1990)

is only available from ca. 28–13 Ma (USM–OSM). Hence, older strata, such as those comprising the UMM–USM transition, largely lack direct biostratigraphic constraints.

A global sea level drop at the onset of the Chattian causing an UMM regression towards the east has been suggested by many authors (Lemcke 1988; Bachmann and Müller 1992; Zweigel et al. 1998). This sea level drop around 28.5 Ma (Haq et al. 1987; Abreu and Anderson 1998) is interpreted as one of the most drastic eustatic events in earth history (Lemcke 1988; Harland et al. 1990).

The Wilhelmine Alpe section

The studied Wilhelmine Alpe section is located in the folded Molasse (“Faltenmolasse”) of south Germany (Allgäu). There, the UMM is subdivided into three units indicating a shallowing-upward trend in the depositional realm (Fig. 2; Lemcke and Vollmayr 1971; Diem 1986b; Scholz 1999, 2000). The basal Deutenhausener beds, composed of turbiditic flysch-like mud-, silt- and sandstones, grade upwards into shelfal mud- and siltstones of the Tonmergel beds (Switzerland: Grisigen marls). The marine series terminates with the Baustein beds, a regressive coastal sequence that mostly consists of silt- and sandstones (Switzerland: Horw sandstones). On top, terrestrial conglomerates and marls (USM) follow.

The investigated section is located near the Lower Wilhelmine Alpe, a mountain hut ca. 12 km SW of Immenstadt/Allgäu (Sect. 3 on Fig. 1). The section is located at the southern margin of the southernmost thrust sheet (“Steiglenbach Mulde”) of the deformed Molasse (“Faltenmolasse”) in the Allgäu region. To the south, the deformed Molasse is bordered by Flysch and Helvetic nappes (up to Eocene/earliest Oligocene in age; Bayerisches Geologisches Landesamt 1996). The Molasse beds are tilted, dipping ca. 60–90° north or, if slightly overturned, south. A detailed description of the Wilhelmine Alpe section has been provided by Lemcke and Vollmayr (1971).

The lithostratigraphic log (after Diem 1986b) comprises most of the UMM (base is tectonically confined) and the lowermost USM (Fig. 2). An overall shallowing trend towards the top of the succession is indicated by an increase in grain size. The entire section is about 270 m thick, but due to outcrop conditions, only the upper 200 m (including the Tonmergel and Baustein beds of the UMM and the basal USM) were sampled for magneto- and palynostratigraphy.

Materials and methods

Magnetostratigraphy

A total of 26 sites were sampled along a continuously exposed section for palaeomagnetic analysis; 25 within the UMM and one in the USM (Fig. 2). Samples are predominantly from grey, laminated and massive claystones and rarely from siltstones. Five individual

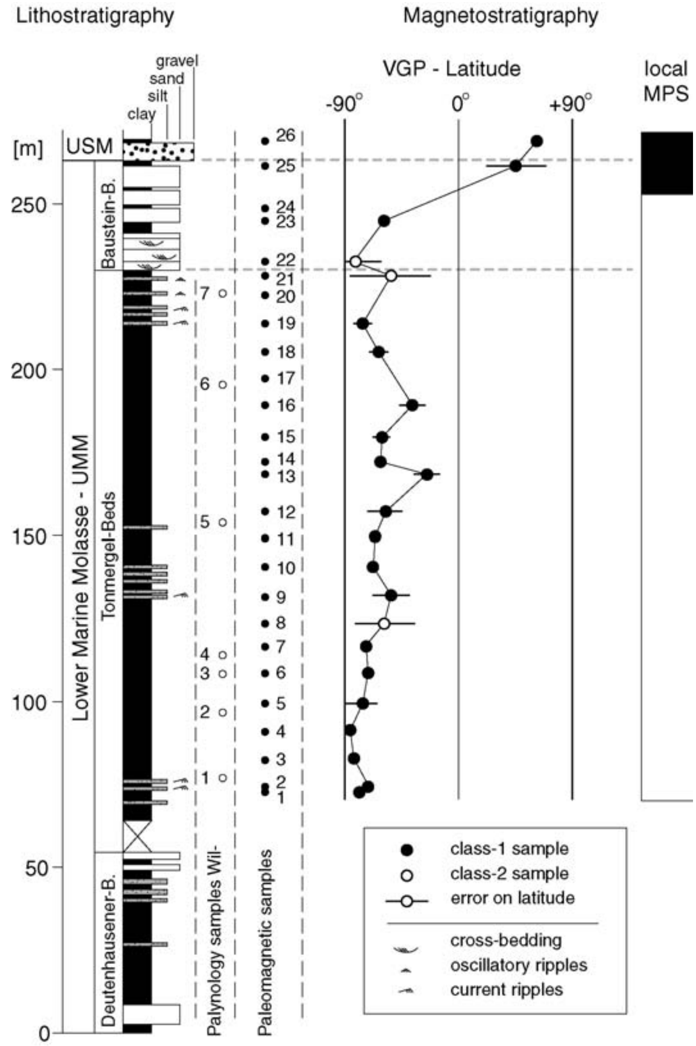

Fig. 2 Lithostratigraphic log, sample positions, and magnetostratigraphic results from the Wilhelmine Alpe section. Lithostratigraphy after Diem (1986b)

specimens were sampled at each site and oriented in the field. Bedding was measured at each site. In a pilot study, representative samples from different stratigraphic levels were thermally demagnetised (Fig. 3). Temperature steps were 50° until 550°C and 30° until 640°C. The samples were analysed using a cryogenic magnetometer with a noise level of 3×10^{-5} A/m for $\sim$3 cm^3 samples. After each temperature step, the magnetic low-field susceptibility was measured to identify any change of magnetic minerals during sample processing (Fig. 3a).

Measurements of the magnetic susceptibility revealed a strong increase at 300–400°C for some specimens (Fig. 3a). This indicates newly formed magnetic minerals probably due to oxidation of sulfides (Butler 1992), which may have formed under reducing depositional conditions (see also Schlunegger et al. 1996). All magnetic directions measured above 300°C were therefore excluded from our reconstruction of the local magnetic polarity stratigraphy (MPS). Most specimens showed a slight, unstable overprint below 200°C (Fig. 3b), which may be interpreted as caused by the present-day earth magnetic field. Demagnetisation above 200°C (Fig. 3b) shows an intensity decrease and a stable demagnetisation path towards the origin, with the associated magnetic direction remaining stable until at least 400°C, suggesting a characteristic remanent magnetisation. However, because of the susceptibility increase beginning around 300°C, as discussed above, the temperature window for the thermal demagnetisation of the remaining samples (i.e. not demagnetised during the pilot study) was between 200 and 300°C. Directions were determined for each site using three specimens for a site mean direction for all temperature steps between 200 and 300°C; the site mean directions chosen in Fig. 4 yielded the best statistical parameters within the temperature window for each site.

Palynology

The seven samples that were taken near sites sampled for palaeomagnetics were subjected to palynological analysis. All samples are from grey, laminated, partially silty UMM claystones. Between 10 and 20 g of sample

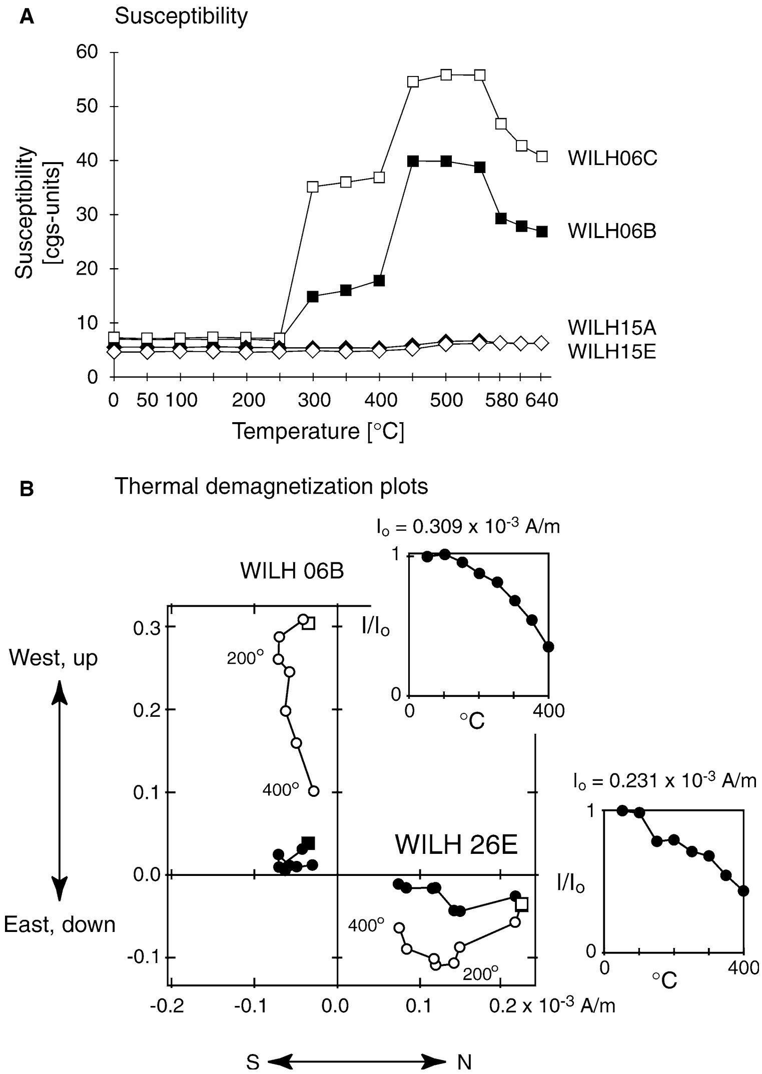

Fig. 3 Magnetic properties of pilot samples during thermal demagnetisation: **a** magnetic susceptibility, **b** natural remanent magnetisation (NRM) after tilt-correction

material was processed following standard palynological techniques (e.g. Pross 2001a). Briefly, the processing procedure included carbonate and silica digestion through hydrochloric (HCl) and hydrofluoric (HF) acids, respectively, with rinsing through a 10-μm nylon mesh after each step. If necessary, the recovered residue was then treated with nitric acid (HNO_3) to partially oxidise the organic matter and with potassium hydroxide (KOH) solution to remove humic acids. A short ultrasonic treatment (5–10 s) helped to disperse the residue. After thorough mixing to obtain homogeneity, the residues were mounted on glass slides using glycerine jelly as a mounting medium. A minimum of two slides was prepared and semiquantitatively evaluated with regard to their content of dinocysts using the following categories: A = abundant, C = common, F = few, and R = rare. To facilitate a broad overall characterisation of environmental conditions, other accompanying marine (i.e. acritarchs, prasinophytes) and terrestrial palynomorphs (i.e. pollen and spores, freshwater algae) were also registered.

Absolute ages for first occurrence datums (FOs) and last occurrence datums (LOs) of dinocyst taxa are after Williams et al. 2004) and are based on interpolations between age control points in sections with magnetostratigraphic and/or radiometric age control. Dinocyst taxonomy is in accordance with that cited in Williams et al. (1998). Slides are stored in the collection of the Institute of Geosciences, Tübingen University, Germany.

Results and interpretation

Magnetostratigraphy

Of the 26 sites analysed, 23 resulted in well-defined magnetic directions, three sites gave no interpretable magnetic signals (either due to ambiguous directions or too-weak magnetic intensities); site spacing was less than 10 m on average (Fig. 2). The resulting magnetic directions (in situ) were corrected for bedding (*tilt-corrected*).

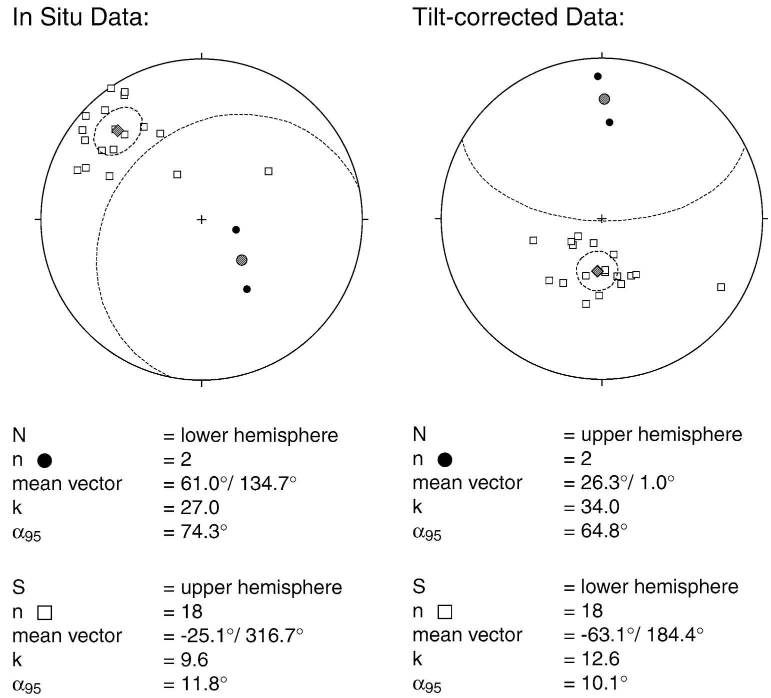

Fig. 4 NRM statistical parameters before (in situ) and after correction for post-depositional tilting (*horizontal fold axes*)

A polarity was defined using three individual specimens at each site. Class-1 sites were defined by k≥10, class-2 were defined by k < 10 or by two specimens with k≥10 and unambiguous polarity (Fig. 2). In addition, an α_{95} error envelope was calculated for each of the virtual geomagnetic poles (VGP) (Fisher 1953).

Twenty sites were classified "class-1" (87%) and three sites were classified "class-2" (13%). The resulting VGPs were reversed except for the uppermost two sites, which revealed normal polarity (Fig. 2). Statistical parameters (Fisher 1953) deduced from the VGPs (only "class-1") showed an improvement from in situ to *tilt-corrected* data, despite the limited statistical significance for only two normal polarity sites (Fig. 4). According to the geocentric axial dipole model, reverse and normal polarity directions should be antipodal, and their inclinations should be in agreement with the latitude during the time of magnetisation. Our data show that declinations of averaged reverse and normal site mean directions are nearly antipodal after correction for tilt (1.0 and 184.4°; Fig. 4). However, the inclinations differ significantly (26.3 and −63.1°; Fig. 4). While the inclination of the reverse site mean direction revealed a reasonable value for the given paleo-latitude (Oligocene, e.g. Besse and Courtillot 1991), the inclination of the normal site mean direction is obviously too shallow. One possible explanation may be the small amount of data (only two normal sites). Another likely reason may be an overprint caused by the present-day earth's magnetic field. At present, because of the ca. 90° tilt of the UMM beds, the earth's magnetic field adds a normal component, which is ca. 90° rotated in comparison with the sample directions. The resulting magnetic vector (present-day plus Oligocene component) would result in a decrease of the inclination angle. Hence, the observed deviation from the expected inclination angle of the normal polarity sites are likely to be caused by the present-day earth's magnetic field, suggesting that this overprint was not fully removed during thermal demagnetisation. This overprint apparently did not affect (or was removed from) the reverse polarity sites. Hence, due to the presence of two clearly distinct normal and reverse polarities and the statistical improvement of the data after tilt correction, we infer that the resulting polarities are significant and represent the characteristic magnetic signal of the sampled sites.

In conclusion, a reversed polarity can be seen in the fine-grained deposits of the Tonmergel and most of the Baustein beds (Fig. 2). The polarity change from reversed to normal occurs within the upper part of the Baustein beds. The following terrestrial deposits show normal polarity. The polarity change from reversed to normal occurs therefore at the end of (but still within) the UMM, shortly before the turn from marine (UMM) to terrestrial (USM) sedimentation.

A robust correlation of the Wilhelmine Alpe section with the GPTS based solely on magnetostratigraphic data is problematic due to the occurrence of only one polarity change and the section's relatively short thickness of about 200 m. Hence, a correlation based on the reversal only is impossible. However, assuming reasonable sedimentation rates for the UMM depositional environment, and considering plausible age brackets for the UMM deposits between the underlying Flysch and overlying USM, three plausible correlations can be deduced for the investigated magnetic polarity stratigraphy of the Wilhelmine Alpe section (Fig. 5). The correlation of the reversed-to-normal polarity change is possible

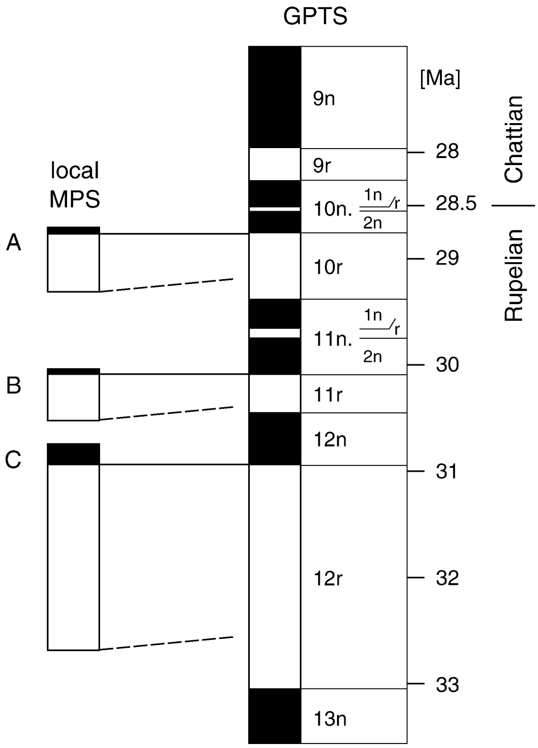

Fig. 5 Possible correlations of the magnetostratigraphic data from the Wilhelmine Alpe section to the geomagnetic polarity timescale. (Cande and Kent 1992, 1995). See text for discussion

around 31 Ma (chrons 12r-12n), around 30 Ma (chrons 11r-11n.2n) and around 28.75 Ma (chrons 10r-10n.2n; close to the early Chattian global sea level drop) (Cande and Kent 1992, 1995; Berggren et al. 1995).

Palynologically deduced palaeoenvironmental signals and palynostratigraphy

All processed samples contain both marine and terrestrial palynomorphs in good to moderate preservation (see Table 1 for an overview of results). The high amount of palynoclasts (predominantly dark brown and black wood particles) and the abundant to common occurrence of sporomorphs (predominantly bisaccate pollen and trilete spores) in all samples indicate a strong terrestrial influence on the depositional environment throughout the section. The abundance of terrigenous components in the palynological assemblages increases upsection, thus supporting the sedimentologically derived observation of increasing proximity of the depositional environment at Wilhelmine Alpe (cf. Chap. 3).

Dinocysts are present in all samples investigated (Table 1). The number of taxa is highest in the samples from the lowest part of the section. Its decrease upsection indicates a trend towards more marginal marine conditions (if representing a primary signal), and/or increasingly unfavourable depositional conditions for organic-walled microfossils (if representing a secondary signal). However, the presence of *Impagidinium* spp., a genus indicative of open-marine environments (e.g. Brinkhuis 1994) in samples Wil-1 and Wil-2 in combination with its absence in samples upsection supports the view of increasingly marginal marine conditions upsection.

Biostratigraphically, the samples investigated contain dinocyst associations indicating an Early Oligocene (Rupelian) age. A list of identified dinocyst taxa is given in Table 1.

Based on the presence of *Enneadocysta pectiniformis*, samples Wil-1, Wil-4, and Wil-7 are assigned an age of 36.5–29.3 Ma following the absolute ages given by Williams et al. 2004. Additional age information is available for Sample Wil-2; based on the FO of *Reticulatosphaera actinocoronata* and the LO of *E. pectiniformis* as given by Williams et al. 2004, this sample can be dated at 35.1–29.3 Ma. Sample Wil-3 yields the most detailed age data of all samples investigated based on the presence of *Areoligera semicirculata*, which has a FO at 33.7 Ma and a LO at 30.2 Ma according to Williams et al. 2004. Sample Wil-5 contains only long-ranging dinocysts of little age-diagnostic value. Besides *E. pectiniformis*, Sample Wil-6 has yielded findings of *Wetzeliella gochtii*. This taxon is widely considered as one of the biostratigraphically most significant members of Oligocene dinocyst assemblages, with an FO of 32.8 and an LO of 26.6 Ma in mid-northern latitudes (see Pross 2001b, for a more detailed discussion and additional references). Utilizing these data, sample Wil-6 can be assigned an age between 32.8 and 29.3 Ma. However, the LOs of *W. gochtii* in Europe are latitudinally strongly diachronous, with earlier LOs in more southern localities of Central and Western Europe and later LOs in more northern localities. This extinction pattern can possibly be explained by northward-directed palaeoceanographic changes in the gateway connecting the Northwest European Tertiary Basin and the Tethyan realm via the Rhône and Rhine grabens (Pross 2001b). For the southern Rhine Graben, which is located ca. 200 km west of the Wilhelmine Alpe section and was directly connected with the UMM sea (Kuhlemann et al. 1999), the LO of *W. gochtii* is estimated at around 31.2 Ma (Pross 2001b). This datum is based on a calibration of the dinocyst data of Rauscher & Weiler (1988) and Schuler (1990) to the nannoplankton zonation age control available for the respective sections. Based on the close vicinity of the Wilhelmine Alpe section to the southern Rhine Graben, it seems reasonable to assume a very similar LO of *W. gochtii* at both sections. This would suggest an age of around 32.8–31.2 Ma for sample Wil-6.

Summarizing, the biostratigraphic results from samples Wil-1–Wil-7 are internally consistent and suggest an age between 36.5 and 29.3 Ma. Samples Wil-3 and Wil-6 allow to further narrow down the time of deposition, with Sample Wil-3 yielding 33.7–30.2 Ma and sample Wil-6 (tentatively) yielding 32.8–31.2 Ma.

Timing of the UMM–USM transition in the Molasse basin: a discussion

UMM–USM transition in the Wilhelmine Alpe section (central Molasse basin)

The combination of magneto- and palynostratigraphic data from the Wilhelmine Alpe section of the central Molasse basin allows correlating the magnetic reversal to the GPTS with great confidence. This, in turn, allows dating the UMM–USM transition in this part of the Molasse basin.

The palynomorphs of the samples Wil-1–Wil-7 consistently indicate a Rupelian age. Based on the age assignment for sample Wil-3 (33.7–30.2 Ma), we can exclude solution "A" (polarity change at ca. 29 Ma; see Fig. 5) because this correlation is too young. Solution "B" (polarity change at ca. 30 Ma) is possible, however unlikely, since the biostratigraphic results for sample Wil-6 suggest an older age. The most likely correlation is therefore given by solution "C" (polarity change at 31 Ma) matching the chrons 12r and 12n (Fig. 5). Thus, we suggest that the UMM–USM transition of the Wilhelmine Alpe section occurred around 31 Ma.

UMM–USM transition in the western Molasse basin (Switzerland)

At present, four magnetostratigraphic sections have yielded the UMM–USM transition in the Swiss (i.e. western) part of the Molasse basin (Fig. 1; Fig. 6). As all these sections are part of the Subalpine Molasse, they document the situation at the southern basin margin. Two of the sections are located in central Switzerland (Marbach and Emme sections; Schlunegger et al. 1996; Mägert 1998) and two of them in eastern Switzerland (Steintal and Thur sections; Kempf et al. 1999). All sections were analysed magnetostratigraphically according to the protocol outlined above and they revealed magnetic signals at similar temperature windows as the material from the Wilhelmine Alpe section (for details see Schlunegger et al. 1996; Kempf et al. 1999).

Marbach and Emme sections (central Switzerland)

The Marbach and Emme sections are part of the same tectonic unit (Beichlen-Farneren thrust sheet; Gasser 1966) and laterally ca. 12 km apart. The UMM–USM transition in the Marbach section occurs during normal polarity correlated to chron 11n.2n of Cande and Kent (1992, 1995); it has thus an age of ca. 30 Ma (Schlunegger et al. 1996). Alternative correlations can be ruled out based on micro-mammal data from two sites in a nearby section (Schlunegger et al. 1996).

In the Emme section, the UMM–USM transition is present as a fan delta complex and not as a regressive coastal sequence as in the Marbach section. The transition is correlated to chron 12r (reverse polarity) around 31.5–31 Ma (Mägert 1998). Alternative correlations are unlikely since they would have to explain strongly fluctuating sedimentation rates. Moreover, a diachroneity of the UMM–USM transition is also evident from tracing lithostratigraphic marker beds in the field (Mägert 1998).

Thur and Steintal sections (eastern Switzerland)

An reverse polarity marks the UMM–USM transition in the Thur section, which is correlated to chron 12r representing an age of around 31.5 Ma (Kempf et al. 1999). There is no plausible alternative correlation due to a regional correlation of three different magnetostratigraphic sections that are additionally based on petrographic data (Kempf et al. 1999).

In contrast, the UMM–USM transition at the Steintal section matches the polarity change from reverse to normal of chrons 12r and 12n (Kempf et al. 1999) and hence occurs at around 31 Ma.

The eastern Swiss sections are part of the same depositional system and laterally only 5 km apart (Kempf et al. 1999). They are, however, located in different thrust sheets (Habicht 1945). The structurally higher Speer thrust sheet (including the Thur section) was originally located somewhat further south than the Schorhüttenbach thrust sheet (containing the Steintal section). Both sections exhibit a similar facies for the UMM–USM transition, i.e. regressive coastal sequences. Hence, the combined data from the Thur and Steintal sections notify a seaward (i.e. northward) prograding coastline from south to north between 31.5 and 31 Ma (Kempf et al. 1999).

UMM–USM transition in the eastern Molasse basin (Bavaria)

Uhlig et al. (2000) and Reichenbacher and Uhlig (2002) correlated two sites of a brackish unit above the UMM ("Untere Cyrenen-Schichten") to a Chattian age (the Murnau syncline comprises MP 24 and the Marienstein-Hausham syncline, ca. 20 km further East, MP 25) based on micro-mammal and fish faunas. Both sites are situated in the folded Molasse at the southern basin margin ca. 100–120 km east of the Wilhelmine Alpe section. There, the terrestrial deposits of the USM merge into brackish and marine deposits to the east. The Rupelian-Chattian boundary is located below the brackish unit within the upper part of the Baustein beds of the UMM (Reichenbacher and Uhlig 2002). These biostratigraphic data indicating earliest Chattian ages are in favour of an assumed UMM-regression around 28.5 Ma (Haq et al. 1987; Abreu and Anderson 1998). Moreover, they are consistent with an eastward-directed regression.

Table 1 Dinoflagellate cysts identified in the investigated samples. A = abundant, C = common, F = few, R = rare. For stratigraphic positions of samples

Sample no.	Strat. pos. (m)	Dinoflagellate cysts												
		Cleistosphaeridium diversispinosum	*Lejeunecysta hyalina*	*Pentadinium laticinctum*	*Hystrichokolpoma rigaudiae*	*Impagidinium* spp.	*Achomosphaera alcicornu*	*Areoligera* spp.	*Deflandrea phosphoritica*	*Enneadocysta pectiniformis*	*Homotryblium floripes*	*H. tenuispinosum*	*Spiniferites ramosus*	*Reticulatosphaera actinocoronata*
Wil-7	224							R	R	R	F	F	C	
Wil-6	196						F	R	R	R			A	
Wil-5	154						F		R			R	C	
Wil-4	114						F		R	F	R	R	A	
Wil-3	108							F	R	F		R	A	
Wil-2	97				F	F		R	F	F	R	R	A	R
Wil-1	77	R	R	F	R	F	F	R	F	R	R	R	A	

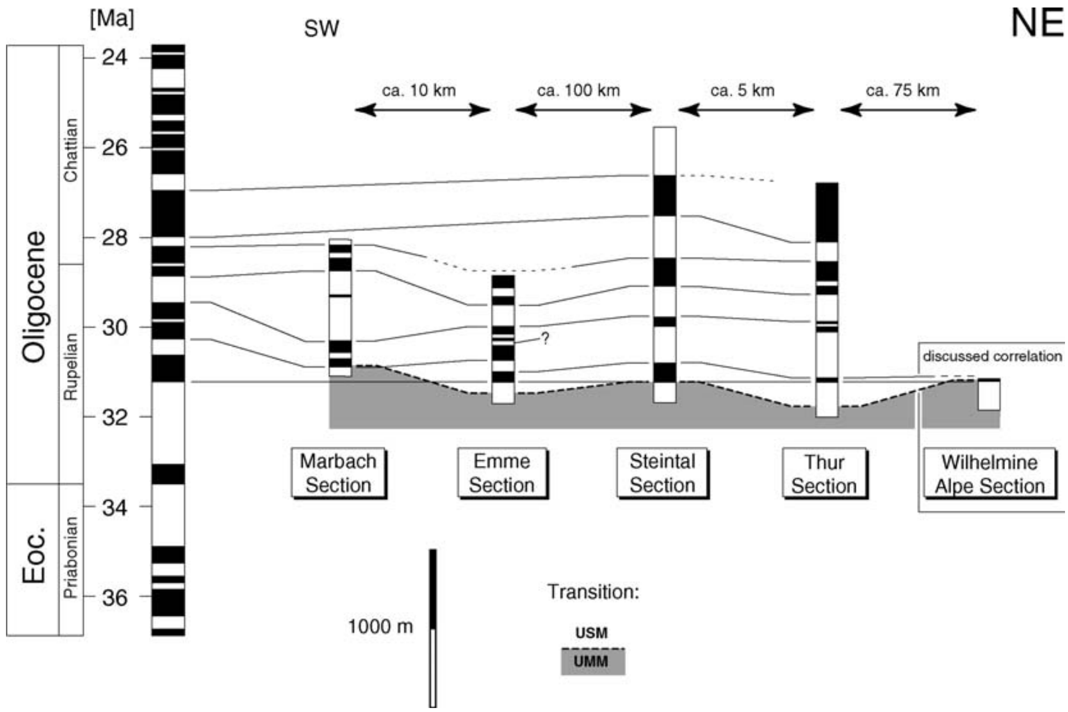

Fig. 6 Regional magnetostratigraphic setting of the UMM–USM transition from central Switzerland to southern Germany. Stratigraphic chart is from Cande and Kent (1992, 1995) and Berggren et al. (1995). See text for discussion

The data from the Wilhelmine Alpe section and from sections located further west show that the UMM–USM transition occurred strongly diachronously between 31.5–30 Ma along the southern basin margin (Fig. 6). Thus, the transition took place well before the Rupelian-Chattian boundary at 28.5 Ma. Indications for a regression, which conforms with the global sea level drop at 28.5 Ma, are only inferred from the eastern Molasse basin.

The consistency of the age determination derived from combined bio- and magnetostratigraphy can also be seen in the sedimentation rate estimates deduced from the sections mentioned above. The calculation of minimum sedimentation rates, i.e. the compacted stratigraphic thickness divided by the available time derived from the GPTS and the reversal pattern of each section, reveals similar values for all sections. Minimum sedimentation rates for the UMM (Tonmergel beds/ Grisigen marls and Baustein beds/Horw sandstones) are 30 mm/ka (60 m/2.1 Ma) for the Emme and Thur sections, 50 mm/ka (110 m/2.1 Ma) for the Steintal section, and 150 mm/ka (50 m/0.33 Ma) for the Marbach section. The Wilhelmine Alpe section yields 85 mm/ka (180 m/2.1 Ma). Hence, calculated minimum sedimentation rates in that part of the basin are consistently 150 mm/ka or less.

In contrast, the calculation of sedimentation rates based on magnetostratigraphic correlations according to solutions “A” and “B” (Fig. 5) reveal strongly increased values. Minimum sedimentation rates for the UMM of the Wilhelmine Alpe section would be 530 mm/ka (given see also Fig. 2

Thalassiphora pelagica	*Systematophora placacantha*	*Spiniferites mirabilis*	*Operculodinium centrocarpum*	*A. semicirculata*	*Palaeocystodinium golzowense*	*Phthanoperidinium* sp.	*Cordosphaeridium cantharellum*	*Dapsilidinium pseudocolligerum*	*Wetzeliella gochtii*	*W. symmetrica*	Terrigenous palynoclasts
			F								A
		R	C						R	F	A
			C					R			A
	R		C				R	R			C
R			C	R	R	R					C
R	R	R	C								C
											C

a correlation of the reversal at 30 Ma), and 300 mm/ka (if a correlation of the reversal is assumed at 29 Ma). However, sedimentation rates of 300 or even > 500 mm/ka were recognised only in alluvial fans and proximal fluvial facies during USM and OSM deposition (Kempf et al. 1999).

At present, no conclusions can be drawn for the UMM–USM transition in the seaward part of the Molasse basin, away from the basin margin, due to the lack of stratigraphic data.

Conclusions

In this study we present a unique combination of magnetostratigraphic and palynostratigraphic analyses to achieve a reliable age determination for foreland basin deposits. Our approach yielded unequivocal results in a marginal marine depositional environment where classical biostratigraphic methods, such as micropalaeontology or mammal biostratigraphy, are deficient. The presented methodological combination of magnetostratigraphy and palynostratigraphy bears a great potential for age determination of other sections in the circum-alpine region.

Our integrated magneto- and palynostratigraphic approach has yielded the first chronostratigraphic calibration of the UMM–USM transition in the German part of the northern Alpine foreland basin. At the Wilhelmine Alpe section, this transition occurred during the middle Rupelian (middle Early Oligocene) at ca. 31 Ma.

The comparison with other chronostratigraphically calibrated sections from Switzerland shows that the onset of terrestrial sedimentation in the central and western part of Molasse basin occurred (1) before the major global regression presumably at 28.5 Ma, at the turn of the Early/Late Oligocene (Haq et al. 1987; Abreu and Anderson 1998) and (2) strongly diachronously during ca. 31.5–30 Ma.

Data indicating that the UMM regression took place during the major global regression at 28.5 Ma only exist for the eastern part of the basin, south of Munich.

Furthermore, the chronostratigraphic data clearly show that the UMM–USM transition at the southern basin margin neither followed any spatial trend, e.g. from west to east, nor any temporal tendency, e.g. earlier in the west, later in the east, but took place individually at each of the locations studied in the central and western Molasse basin. Hence, the onset of terrestrial deposition occurred within 1.5 Myr and over a lateral distance of about 200 km at the southern Molasse basin margin.

The UMM–USM transition occurred earlier at places where sediment supply from the Alps was provided. It is therefore very likely that the UMM–USM transition was rather the result of (locally different) increased sediment supply due to enhanced uplift of the Alpine orogen than a consequence of eustatic sea level-fall.

The results of our study support the outcome of quantitative sediment budget studies (Kuhlemann 2000; Schlunegger and Hinderer 2001; Schlunegger et al. 2001), which emphasises the major role of sediment supply for the transition of marine to terrestrial sedimentation in the northern Alpine foreland basin.

Acknowledgements The authors would like to thank Douglas W. Burbank (UC Santa Barbara, USA) and Albert Matter (Universität Bern, Switzerland) who sampled the magnetic specimens from the Wilhelmine Alpe section and provided the opportunity to analyse and utilise the samples in this paper. We would also like to thank Steve Lund and Salley Henyey (both USC Los Angeles, USA) for introducing Oliver Kempf to magnetic laboratory work. Special thanks go to Birgit Schimpf (Ludwigsburg) for logistic support. Bettina Reichenbacher (München) and Matthias Hinderer (Darmstadt) gratefully provided constructive reviews of an earlier version of the manuscript. The constructive critics of Friedrich Heller (ETH Zürich) and an anonymous reviewer are kindly appreciated, and significantly improved the scientific quality of this paper. The work of Jörg Pross was partly supported by the German Research Foundation (DFG; grant PR 651/1-1).

References

Abreu VS, Anderson JB (1998) Glacial eustasy during the Cenozoic: sequence stratigraphic implications. Am Assoc Petrol Geol Bull 82:1385–1400

Bachmann GH, Dohr G, Müller M (1982) Exploration in a classic thrust belt and its foreland, Bavarian Alps, Germany. Am Assoc Petrol Geol Bull 66:2529–2542
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. European Association of Petrology and Geoscience, Special Publication, vol 1. University Press, Oxford, pp 263–276
Bachmann GH, Müller M (1992) Sedimentary and structural evolution of the German Molasse Basin. Eclogae Geol Helv 85:519–530
Barthelt D (1989) Faziesanalyse und Untersuchung der Sedimentationsmechanismen in der Unteren Brackwasser-Molasse Oberbayerns. Münchner Geowiss Abh A 17:1–118
Bayerisches Geologisches Landesamt (1996) Erläuterungen zur Geologischen Karte von Bayern 1:500000, 4th edn. München, p 329
Berger J-P (1999) Redefinition of European Oligo-Miocene charophyte biozonation. Aust J Botany 47:283–296
Berggren WA, Kent DV, Swisher CC, Aubry M-P (1995) A revised Cenozoic geochronology and chronostratigraphy. In: Berggren WA, Kent DV, Aubry MP, Hardenbol J (eds) Geochronology, time scales and global stratigraphic correlations. SEPM Spec Publ 54:17–28
Besse J, Courtillot V (1991) Revised and synthetic apparent polar wander paths of the African, Eurasian, North American and Indian plates, and true polar wander since 200 Ma. J Geophys Res 96:4029–4050
Brinkhuis H (1994) Late Eocene to Oligocene dinoflagellate cysts from the Priabonian type-area (northeast Italy): biostratigraphy and paleoenvironmental interpretation. Palaeogeogr Palaeoclimatol Palaeoecol 107:121–163
Burbank DW, Engesser B, Matter A, Weidmann M (1992) Magnetostratigraphic chronology, mammalian faunas, and stratigraphic evolution of the Lower Freshwater Molasse, Haute-Savoie, France. Eclogae Geol Helv 85:399–431
Butler RF (1992) Paleomagnetism. Blackwell, Boston, p 319
Cande SC, Kent DV (1992) A new geomagnetic polarity timescale for the late Cretaceous and Cenozoic. J Geophys Res 97:13917–13951
Cande SC, Kent DV (1995) Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. J Geophys Res 100:6093–6095
Diem B (1986a) Die Untere Meeresmolasse zwischen der Saane (Westschweiz) und der Ammer (Oberbayern). Eclogae Geol Helv 79:493–559
Diem B (1986b) Die Untere Meeresmolasse zwischen der Saane (Westschweiz) und der Ammer (Oberbayern). Unpublished PhD Thesis, Universität Bern
Engesser B (1990) Die Eomyidae (Rodentia, Mammalia) der Molasse der Schweiz und Savoyens. Systematik und Biostratigraphie. Schweiz Paläont Abh 112:1–144
Engesser B, Mayo NA (1987) A biozonation of the lower freshwater Molasse (Oligocene and Agenian) of Switzerland and Savoy on the basis of fossil mammals. Münchner Geowiss Abh A 10:67–84
Fisher RA (1953) Dispersion on a sphere. Proc R Soc Lond A 217:295–305
Frei H-P (1979) Stratigraphische Untersuchungen in der subalpinen Molasse der Nordost-Schweiz zwischen Wägitaler Aa und Urnäsch. Mitt Geol Inst ETH Univ Zürich NF 233:1–207
Gasser U (1966) Sedimentologische Untersuchungen in der äusseren Zone der subalpinen Molasse des Entlebuchs (Kt. Luzern). Eclogae Geol Helv 59:723–772
Geissler P (1975) Räumliche Veränderung und Zusammensetzung der Flöze in den Kohlebergwerken Hausham und Penzberg. Geol Bavarica 73:61–106
Gubler T, Meier M, Oberli F (1992) Bentonites as time markers for sedimentation of the upper freshwater Molasse: geological observations corroborated by high-resolution single-Zircon U–Pb ages. 172. Jahresversammlung SANW, Abstracts, pp 12–13
Habicht K (1945) Geologische Untersuchungen im südlichen sanktgallisch-appenzellischen Molassegebiet. Beitr Geol Karte Schweiz NF 83, Kümmerly & Frey, Bern, p 166
Habicht K (1987) Internationales stratigraphisches Lexikon. Band I Europa Fasz 7 Schweiz 7b Schweizerisches Mittelland (Molasse). Schweiz Geol Komm, Basel, p 528
Haq BU, Hardenbol J, Vail PR (1987) Chronology of fluctuating sea levels since the Triassic. Science 235:1156–1167
Harland WB, Armstrong RL, Cox AV, Craig LE, Smith AG, Smith DG (1990) A geologic time scale 1989, 2nd edn. University Press, Cambridge, p 263
Herb R (1988) Eocaene Paläogeographie und Paläotektonik des Helvetikums. Eclogae Geol Helv 81:611–657
Hochuli PA (1978) Palynologische Untersuchungen im Oligozän und Untermiozän der zentralen und westlichen Paratethys. Beitr Paläont Österreich 4:1–132
Keller B (1992) Hydrogeologie des schweizerischen Molasse-Beckens: Aktueller Wissensstand und weiterführende Betrachtungen. Eclogae Geol Helv 85:611–651
Keller B, Bläsi H, Platt NH, Mozley PS, Matter A (1990) Sedimentäre Architektur der distalen Unteren Süsswassermolasse und ihre Beziehung zur Diagenese und den petrophysikalischen Eigenschaften am Beispiel der Bohrungen Langenthal. Geol Ber Landeshydrol Geol 13:1–100
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 J-P, Legendre S, Michaux J (eds) Actes du Congrès BiochroM'97. Mém Trav EPHE Inst Montpellier 21:547–561
Kempf O, Matter A (1999) Magnetostratigraphy and depositional history of the Upper Freshwater Molasse (OSM) of eastern Switzerland. Eclogae Geol Helv 92:97–103
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
Köhler J (1991) Untersuchung einer Mikroflora aus dem Untermiozän der westlichen Paratethys (Obere Meeresmolasse, Überlingen a. Bodensee) und deren Vergleich mit einer zeitgleichen Mikroflora aus der zentralen Paratethys (OMM, Eggenburg). Unpublished Diploma Thesis, Universität Tübingen
Kuhlemann J (2000) Post-collisional sediment budget of circum-Alpine basins (Central Europe). Mem Sci Geol Padova 52:1–91
Kuhlemann J, Kempf O (2002) Post-Eocene evolution of the North Alpine Foreland Basin and its response Alpine tectonics. Sediment Geol 152:45–78
Kuhlemann J, Spiegel C, Dunkl I, Frisch W (1999) A contribution to the middle Oligocene paleogeography of central Europe: new evidence from fission track ages of the southern Rhine-Graben. Neues Jahrb Geol Paläont Abh 214:415–432
Lemcke K (1967) Zwölf Jahre Öl- und Gasförderung im süddeutschen Alpenvorland: ein Überblick. Bull Ver Schweiz Petrol-Geol -Ing 33:23–31
Lemcke K (1984) Geologische Vorgänge in den Alpen ab Obereozän im Spiegel vor allem der deutschen Molasse. Geol Rdsch 73:371–397
Lemcke K (1988) Geologie von Bayern.—I. Teil: Das bayerische Alpenvorland vor der Eiszeit. E Schweizerbart, Stuttgart, p 175
Lemcke K, Vollmayr T (1971) Führer zur Exkursion in die Allgäuer Faltenmolasse am, 21 Juni 1970. Bull Ver Schweiz Petrol-Geol -Ing 37:18–24
Mägert M (1998) Sedimentation und Entwicklung des Beichlen—Schuttfächers (Untere Süsswassermolasse—Entlebuch). Unpublished MSc Thesis, Universität Bern, p 176
Matter A, Homewood PW, Caron C, Rigassi D, van Stuijvenberg J, Weidmann M, Winkler W (1980) Flysch and Molasse of western and central Switzerland (Excursion No. 5). In: Trümpy R (ed) Geology of Switzerland, a guide-book, part B, excursions. Schweiz Geol Komm, Basel, pp 261–293
Pross J (2001a) Paleo-oxygenation of Tertiary epeiric seas: evidence from dinoflagellate cysts. Palaeogeogr Palaeoclimatol Palaeoecol 166:369–381

Pross J (2001b) Dinoflagellate cyst biogeography and biostratigraphy as a tool for palaeoceanographic reconstructions: an example from the Oligocene of western and northwestern Europe. Neues Jahrb Geol Paläont Abh 219:207–219

Pross J, Kotthoff U, Zonneveld KAF (2004) Die Anwendung organischwandiger Dinoflagellatenzysten zur Rekonstruktion von Paläoumwelt, Paläoklima und Paläozeanographie: Möglichkeiten und Grenzen. Paläont Zeitschr 78:5–39

Rauscher R, Weiler H (1988) Dinoflagellate cysts: France, the Federal Republic of Germany, the Rhine Graben. In: Vinken R (ed) The Northwest European Tertiary Basin. Results of the international geological correlation programme no. 124. Geol Jahrb A 100, p 335

Reichenbacher B (1999) Preliminary otolith-zonation in continental Tertiary deposits of the Paratethys and adjacent areas. Neues Jahrb Geol Paläont Abh 214:375–390

Reichenbacher B, Uhlig U (2002) Die Fischfauna der chattischen Unteren Cyrenen-Schichten in der Murnauer Mulde (süddeutsche Faltenmolasse). Cour Forsch Senckenberg 237:175–191

Reichenbacher B, Uhlig U, Kowalke T, Bassler B, Matzke-Karasz R, Schenk B (2004) Biota, palaeoenvironments and biostratigraphy of continental Oligocene deposits from the south German Molasse basin (Penzberg Syncline). Palaeontol 47

Riveline J, Berger J-P, Feist M, Martin-Closas C, Schudack M, Soulié-Märsche I (1996) European Mesozoic-Cenozoic charophyte biozonation. Bull Soc Géol Fr 167:453–468

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, Hinderer M (2001) Crustal uplift in the Alps: why the drainage pattern matters. Terra Nova 13:425–432

Schlunegger F, Jordan TE, Klaper EM (1997) 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

Schlunegger F, Slingerland R, Matter A (1998) Crustal thickening and crustal extension as controls on the evolution of the drainage network of the central Swiss Alps between 30 Ma and the present: constraints from the stratigraphy of the North Alpine Foreland Basin and the structural evolution of the Alps. Basin Res 10:197–212

Scholz H (1999) Die "klassische" Molasse-Gliederung vom Südrand des Molassebeckens in Südwestbayern—bewährt oder problematisch? Neues Jahrb Geol Paläont Abh 214:391–413

Scholz H (2000) Die tertiären Grobschüttungen am Südrande des Molassebeckens im Allgäu (Südwestbayern)—eine Synopsis. Neues Jahrb Geol Paläont Abh 218:61–84

Schuler M (1990) Environments et Paléoclimats paléogènes. Palynologie et biostratigraphie de l'Eocène et de l'Oligocène infèrieur dans les fossès rhènan, rhodanien et de Hesse. Documents BRGM 190:1–503

Sinclair HD, Allen PA (1992) Vertical versus horizontal motions in the Alpine orogenic wedge: stratigraphic response in the foreland basin. Basin Res 4:215–232

Sinclair HD, Coakley BJ, Allen PA, Watts AB (1991) Simulation of foreland basin stratigraphy using a diffusion model of mountain belt uplift and erosion: an example from the central Alps, Switzerland. Tectonics 10:599–620

Sluijs A, Pross J, Brinkhuis H (2004) From greenhouse to icehouse; organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene. Earth Sci Rev (in press)

Stover LE, Brinkhuis H, Damassa SP, de Verteuil L, Helby RJ, Monteil E, Partridge AD, Powell AJ, Riding JB, Smelror M, Williams GL (1996) Mesozoic-Tertiary dinoflagellates, acritarchs and prasinophytes. In: Jansonius J, McGregor DC (eds) Palynology: proncipl es and applications, vol. 2. Am Assoc Stratigr Palynologists Foundation, Dallas, pp 641–750

Strunck P, Matter A (2002) Depositional evolution of the western Swiss Molasse. Eclogae geol Helv 95:197–222

Uhlig U, Reichenbacher B, Bassler B (2000) Säugetiere, Fisch-Otolithen und Charophyten ans den Unteren Cyrenen-Schichten (Oligozän) der bayerischen Faltenmolasse (Murnauer Mulde). Eclogae geol Helv 93:503–516

Williams GL, Brinkhuis H, Pearce MA, Fensome RA, Weegink JW (2004) Southern ocean and global dinoflagellate cyst events compared: index events for the late Cretaceous–Neogene. Proc ODP Sc Res 189

Williams GL, Lentin JK, Fensome RA (1998) The Lentin and Williams index of fossil dinoflagellates, 1998 edn. Am Assoc Stratigr Palynologists, Dallas, Contrib Ser 34, p 817

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 H, Fernàndez M (eds) Cenozoic foreland basins of Western Europe. Geol Soc Lond Spec Publ vol. 134, pp 299–323