Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 92 (1999)

Heft: 1

Artikel: Magnetostratigraphy and depositional history of the Upper Freshwater Molasse (OSM) of eastern Switzerland

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DOI: https://doi.org/10.5169/seals-168650

0012-9402/99/010097-7 $1.50 + 0.20/0
Birkhäuser Verlag, Basel, 1999

Eclogae geol. Helv. 92 (1999) 97–103

Magnetostratigraphy and depositional history of the Upper Freshwater Molasse (OSM) of eastern Switzerland

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Keywords: Magnetostratigraphy, Swiss Molasse basin, Upper Freshwater Molasse (OSM), alluvial deposition, sedimentation rates

ABSTRACT

Four magnetostratigraphic sections provide detailed insight into the depositional history of the Upper Freshwater Molasse (OSM) of eastern Switzerland between 17–13 Ma (Middle Miocene). The individual magnetostratigraphic sections are constrained by biostratigraphic data as well as radiometric ages of bentonites. A comparison of distal and proximal sections shows that sedimentation over the investigated time period is relatively uniform with an average rate of 0.25 mm/a. Before 15 Ma, however, the average sedimentation rates are significantly lower in both settings: < 0.1 mm/a in the distal area (ca. 16.5–15 Ma) and 0.15 mm/a in the proximal area (ca. 16–15 Ma). Our data suggest strongly varying sedimentation rates and erosional phases particularly in the distal area. The stratigraphic evolution of the eastern Swiss OSM is thus linked to a thrusting event at 15 Ma, following a phase of relative tectonic quiescence.

ZUSAMMENFASSUNG

Vier magnetostratigraphische Profile geben einen detaillierten Einblick in die Ablagerungsgeschichte der Oberen Süsswassermolasse (OSM) der Ostschweiz zwischen 17–13 Ma (Mittleres Miozän). Die einzelnen magnetostratigraphischen Profile sind zusätzlich durch biostratigraphische Daten sowie radiometrische Alter von Bentoniten abgestützt. Der Vergleich von distalen und proximalen Profilen zeigt eine recht einheitliche Sedimentationsrate von durchschnittlich 0,25 mm/a während des untersuchten Zeitraums. Vor 15 Ma sind diese Raten in beiden Ablagerungsräumen allerdings bedeutend geringer: < 0,1 mm/a in den distalen (ca. 16,5–15 Ma) und 0,15 mm/a in den proximalen Profilen (ca. 16–15 Ma). Unsere Resultate legen daher stark variierende Sedimentationsraten sowie erosive Phasen insbesondere im distalen Bereich nahe. Die stratigraphische Entwicklung der OSM in der Ostschweiz wird daher mit einer alpinen Überschiebungsphase um 15 Ma in Verbindung gebracht, die auf eine Phase relativer tektonischer Ruhe folgt.

Introduction

The Swiss Molasse basin is among the best understood foreland basins world-wide. The close relationship between the tectonic history of the Alpine orogen and the depositional processes within its adjacent northern foreland basin has been the focus of recent investigations of the Swiss Molasse basin (Schlunegger et al. 1997; Kempf et al. 1999 in press). These studies are based on detailed sedimentologic, biostratigraphic and magnetostratigraphic analyses (e. g. Keller 1989; Bolliger 1992; Schlunegger et al. 1996, 1997; Kempf et al. 1997). Thus, they provide a large data set of the temporal and spatial distribution of the marine and continental facies of the basin. Of great importance is the analysis of long continuous magnetostratigraphic sections that were formed under supposedly high sedimentation rates, and a sampling strategy in accordance to the expected duration of the section (Talling & Burbank 1993). This concept has successfully been applied to the Swiss Molasse basin and resulted in a very detailed Molasse chronology between 30 and 13 Ma (Burbank et al. 1992; Schlunegger et al. 1996; Kempf et al. 1997). However, in areas where sedimentation rates are low and/or erosional phases are likely to occur, magnetostratigraphic studies have to be done with special care. Additional independent data, such as radiometric ages or faunal successions, are needed for a well constrained correlation of local magnetostratigraphies with the geomagnetic polarity timescale (GPTS) of Cande & Kent (1992, 1995).

In eastern Switzerland, three well exposed magnetostratigraphic sections of the central Hörnli alluvial fan (20–13 Ma) were correlated to the GPTS on the basis of well-known micro-mammal faunas, leading to an excellent temporal resolution of these proximal deposits (Kempf et al. 1997). In the present paper, two new magnetostratigraphic sections located in a distal area at the western flank of the Hörnli alluvial fan were studied. Thus, the contemporaneous depositional processes from different fan areas can be compared.

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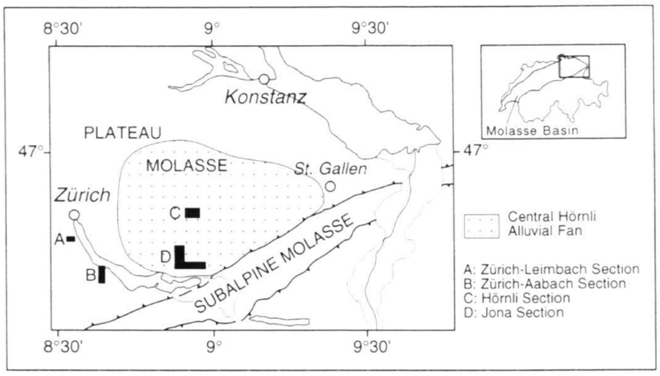

Fig. 1. Location of the Zürich (A, B), Hörnli (C) and Jona (D) sections in the Plateau Molasse of eastern Switzerland.

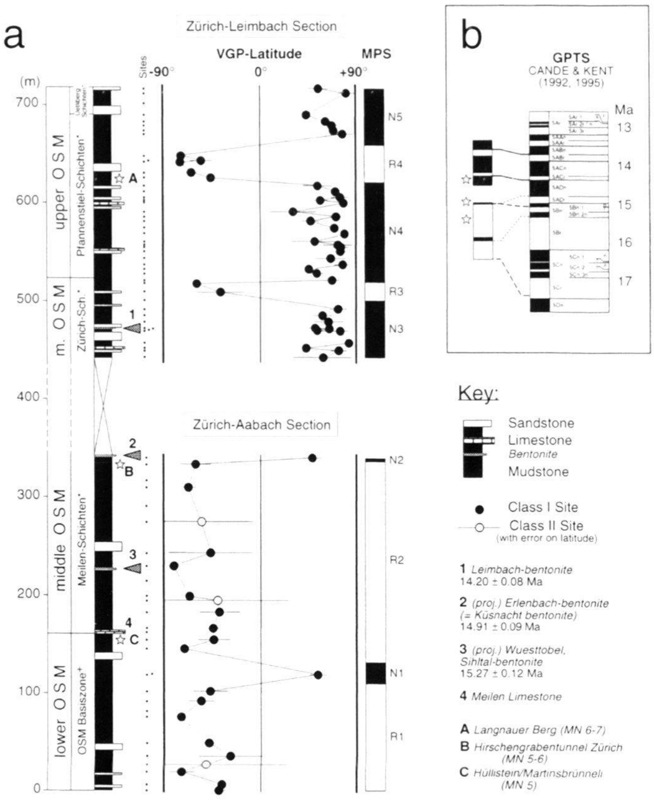

Fig. 2. (a) Local magnetostratigraphy (MPS) of the Zürich section including biostratigraphic (stars A–C) and chronostratigraphic (triangles 1–3) data and the Meilen limestone (4). Lithostratigraphy after Büchi (1957) (+) and Pavoni (1957, 1959) (*), radiometric ages of the bentonites from Gubler et al. (1992). (b) Well constrained magnetostratigraphic correlation of the Zürich-Leimbach MPS (bold lines), and uncertain correlation of the Zürich-Aabach MPS (dashed and dotted lines) to the GPTS. A detailed discussion is given in the text.

The stratigraphic sections presented in this paper give a close look into the youngest depositional history of the eastern Swiss Molasse basin between 17–13 Ma. In the following, we (i) discuss the correlation of two magnetostratigraphic sections of the lateral-distal fan-area to the GPTS and emphasize the importance of additional independent data for this correlation, (ii) compare the distal sections with two more or less contemporaneous magnetostratigraphic sections from the proximal Molasse and (iii) discuss a possible interaction between thrusting activity of the Alpine front and the stratigraphic evolution of the youngest Molasse in this area.

The eastern Swiss Molasse

The Oligo-Miocene Swiss Molasse basin is classically divided into four lithostratigraphic groups which form two shallowing-, coarsening- and thickening-upward megasequences (Matter et al. 1980; Keller 1989). The first megasequence consists of the Lower Marine Molasse (UMM) and Lower Freshwater Molasse (USM), the second comprises the Upper Marine Molasse (OMM) and Upper Freshwater Molasse (OSM). The marine deposits (UMM, OMM) formed in open marine to coastal environments, the continental 'freshwater' deposits (USM, OSM) consist of thick alluvial fan deposits (mostly conglomerates and sandstones) at the southern basin margin which interfinger with finer-grained clastics (mostly sand- and mudstones) towards the basin centre. Throughout the OMM, two large fan deltas (Hörnli, Napf) were deposited simultaneously at the southern basin border.

The time frame of the eastern part of the Swiss Molasse basin was established magnetostratigraphically by Kempf et al. (1997, 1999 in press): the UMM terminated between 31.5–30 Ma, the USM lasted from 31.5–30 to 19 Ma, the OMM from 19 to 17 Ma, and the OSM from 19 to 13 Ma. Towards the south, the generally flat-lying Plateau Molasse (upper USM to OSM) of the Swiss Molasse basin is bordered by the intensely thrusted and folded Subalpine Molasse (UMM to USM).

Lithostratigraphy and facies

The predominantly conglomeratic Hörnli and Jona sections (Fig. 1: sections C and D) are located in the proximal Hörnli alluvial fan, and have been discussed in detail by Kempf et al. (1997). The newly investigated Zürich sections (Fig. 1: sections A and B) are situated south of Zürich in the eastern Swiss Plateau Molasse and cover nearly the whole stratigraphic record of the distal OSM (Büchi 1957; Pavoni 1957). Both sections are made up of a thick mudstone sequence, interbedded with several sandstone beds derived from the Hörnli alluvial fan east of Lake Zürich (Fig. 2a). Lacustrine limestone beds are also present in these sections. Occasional influence of the Napf alluvial fan, located further west, is indicated petrographically by a lower dolomite content in the sandstones (pers. comm. Gubler 1995). The bedding of the Zürich-Leimbach section is horizontal, whereas the dip angle of the Zürich-Aabach section slightly increases up-section (towards S) from 0° to ~10° due to regional folding (Käpfnach-Roten-Anticline; Büchi 1958). A very important horizon within the Zürich-

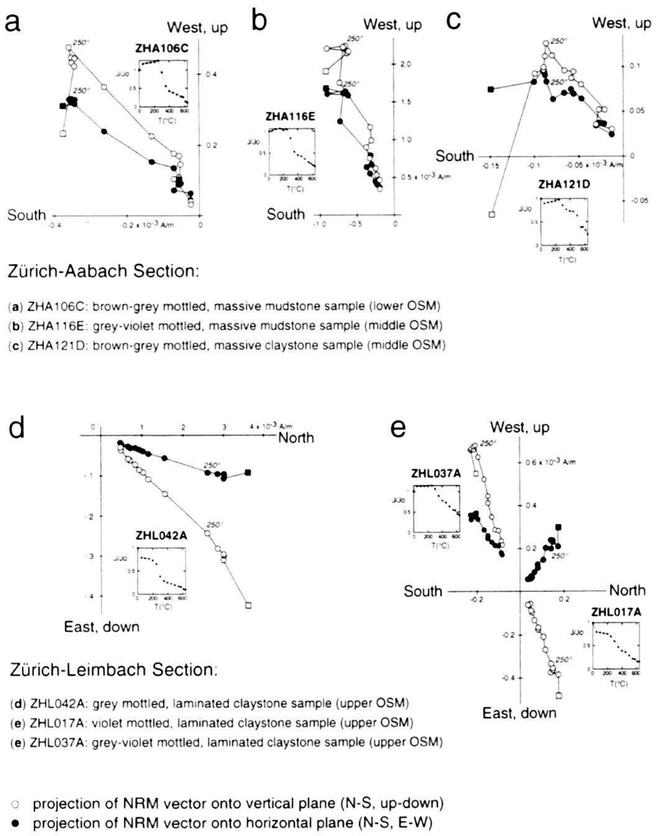

Fig. 3. Zijderveld diagrams of thermal demagnetization and intensity-loss of pilot samples from the Zürich sections. Open (full) symbols represent inclination (declination).

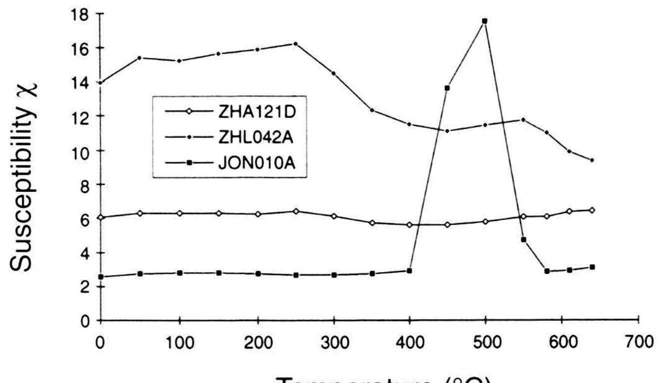

Fig. 4. Magnetic susceptibility during thermal demagnetization of pilot samples.

Aabach section is the *Meilen limestone*, a ca. 1 m thick limestone bed that represents the distal part of the *Hüllistein marker horizon* of the Hörnli alluvial fan (Pavoni 1955; Bürgisser 1980) (Fig. 2a). The Hüllistein marker horizon, usually present as a breccia or conglomerate, is interpreted to be caused by reworking of a landslide deposit at the former Alpine front, and is now exposed with a lateral extent of >65 km (Büchi & Welti 1950; Pavoni 1956; Bürgisser 1980, 1984). This horizon is of great importance for the regional correlation of the proximal and distal eastern Swiss OSM.

Biostratigraphy

Two biostratigraphically well constrained micro-mammal sites in the Zürich area (Bolliger 1992) were projected into the Zürich sections based on their stratigraphic position with reference to the Hüllistein marker horizon (Fig. 2a): the sites *Hirschengrabentunnel Zürich* (MN 5–6) ca. 130 m above Hüllistein and *Langnauer Berg* (MN 6–7) ca. 455 m above Hüllistein. The micro-mammal sites of *Hüllistein* and *Martinsbrünneli* (lower MN 5) are located directly below the Hüllistein marker horizon (Bürgisser et al. 1983; Bolliger 1992, 1997), and are therefore projected below the Meilen limestone (Fig. 2a).

Radiometric ages

The ages of three bentonite horizons reported by Gubler et al. (1992) are given in Figure 2a. One bentonite horizon crops out within the Zürich-Leimbach section (*Leimbach bentonite* at 470 m), the other two bentonites (*Erlenbach bentonite* at 340 m and *Wuesttobel bentonite* at 225 m) can be projected into the composite Zürich section relative to their stratigraphic positions with great confidence (Pavoni 1958; Pavoni & Schindler 1981; Gubler et al. 1992) (Fig. 2a).

Magnetostratigraphic methodology

Five oriented hand samples, predominantly laminated clay- and siltstones, were collected for magnetostratigraphy from each site. Samples were taken every 5–10 m in the Zürich-Leimbach section, every 10–15 m in the Zürich-Aabach section, and every 15–25 m in the proximal Hörnli and Jona sections (see Kempf et al. 1997), in order to document the expected reversals. Detailed site location maps are provided in Kempf (1998).

The demagnetization behaviour for seven pairs of representative samples of the analyzed sections was identified in a pilot study by stepwise thermal demagnetization (Fig. 3). The samples were taken from various stratigraphic levels and depositional systems (see Schlunegger et al. 1996 for justification). Thermal demagnetization was carried out in steps of 50°C from room temperature to 550°C, and in steps of 30°C from 550° to 640°C. The samples were analyzed using a cryogenic magnetometer with a noise level of 2–3 x 10^{-5} A/m. After each temperature step, the magnetic susceptibility χ was measured to identify any growth of magnetic minerals during sample processing (Fig. 4).

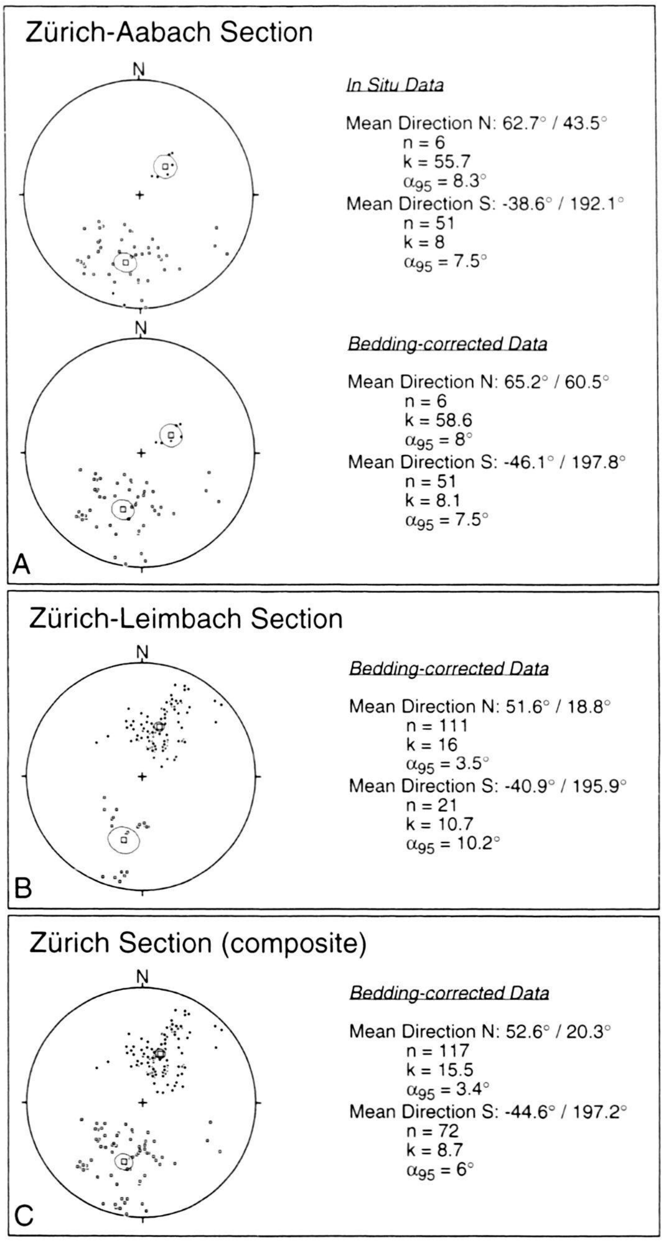

Fig. 5. Stereonet plots of class 1 normal (full symbols, lower hemisphere) and reversed (open symbols, upper hemisphere) magnetic directions for 'in situ' and 'bedding corrected' data of the Zürich-Aabach section and 'bedding-corrected' data of the Zürich-Leimbach section as well as the composite Zürich section. The mean directions and their α_{95} envelopes are shown.

Pilot study

Below 200–250°C most samples show a normal polarity that is interpreted as low-temperature overprint of the present-day earth's magnetic field (Fig. 3). Above 200–250°C a stable direction of the demagnetization vector is detected pointing towards the origin. No significant increase of the magnetic susceptibility, indicating the growth of new magnetic minerals during progressive heating, was observed in the Zürich sections. A slight decrease in magnetic susceptibility is observed in some samples (Fig. 4). However, a strong increase in magnetic susceptibility occurs above 350–400°C in samples from other sections of the Swiss Molasse basin (Fig. 4: JON010A), often in combination with unstable magnetic directions (Schlunegger et al. 1996; Kempf et al. 1997). We therefore demagnetized all samples from the Zürich sections at three heating steps between 200–350°C.

Fisher statistics (Fisher 1953) were used to test the coherence of the magnetic directions for each site. Groups of three samples were classified as 'class 1' if $k \geq 10$ and 'class 2' if $k < 10$ but the site showed an unambiguous polarity. Groups of two samples were also termed 'class 2' when the sites yielded an unambiguous polarity with $k \geq 10$. 'Class 3' sites revealed no coherent magnetic direction and were therefore discarded. We used class 1 and class 2 sites to calculate a virtual geomagnetic pole (VGP) (Fig. 2a). Additionally, an α_{95} envelope was calculated for each VGP latitude (Fisher 1953). To test each section for antipolarity we separated normal and reversed polarities only for the statistically coherent class 1 sites. The Zürich-Leimbach section passes the reversal test whereas the normal polarity values of the Zürich-Aabach section are strongly offset (Fig. 5a, b). Since only two normal sites are present in this section, however, the values are statistically not representative and their significance is doubtful. The composite Zürich section (Fig. 5c), though, clearly passes the reversal test according to McFadden & McElhinny (1990), as does the composite Hörnli/Jona section (see Kempf et al. 1997). The mean directions of the sections show a significant offset from the expected (N-S) direction of the declination (Fig. 5c). This was also observed in other sections throughout the Swiss Molasse basin, and has been related to a clockwise post-13-Ma tectonic rotation of the Swiss Alps (Kempf et al. 1998 and discussion therein). The inclination angles are also shallower than expected (Fig. 5c). In addition to a possible post-depositional flattening of the inclinations due to compaction, an overprint may have contributed to the particularly flattened inclination angle of the reversed samples. The samples of the southward dipping Zürich-Aabach section seem to be influenced by an incompletely removed high-temperature overprint since the demagnetization vectors do not point exactly to the origin on a straight line (Fig. 3a–c). Such a remaining overprint is probably due to the present-day earth's magnetic field, which affects both the inclination and declination. The effect on the declination, however, would result in a decrease of the rotation angle.

Results and discussion

Magnetostratigraphic correlation of the Zürich section

The Zürich-Leimbach section stratigraphically overlies the Zürich-Aabach section (Pavoni & Schindler 1981), and both have a composite thickness of ca. 700 m (Fig. 2a). A gap of

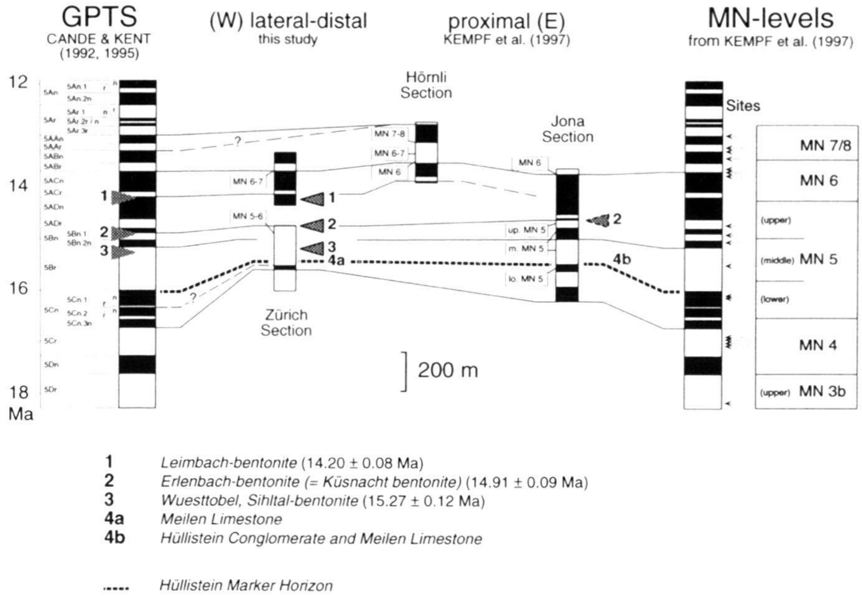

Fig. 6. Magnetostratigraphic correlation of the Zürich, Hörnli and Jona sections to the GPTS. Triangles indicate bentonite horizons (1–3). The Hüllistein marker horizon (4a, 4b) is marked with a bold dashed line. Absolute ages are taken from Gubler et al. (1992), biostratigraphy after Bolliger (1992, 1997). For discussion see text.

100 m is present between the sections due to poor exposures. The lithostratigraphic position of the composite Zürich section is lower to upper OSM (Büchi 1957; Pavoni 1957) (Fig. 2a).

The younger Zürich-Leimbach section totals 46 sites and only two sites (4%) had to be discarded because of incoherent magnetic directions (Fig. 2a). The remaining 44 sites were all classified as class 1, no class 2 site occurred. Five polarity zones are present (N3-N5), and all are composed of at least two class 1 sites. The Leimbach bentonite with an age of 14.2 ± 0.08 Ma is exposed near the base of this section (Fig. 2a, at 470 m) and provides a precise and unambiguous correlation of the upper part of the Zürich section with the GPTS (Cande & Kent 1992, 1995) (Fig. 2b). Thus, the polarity zones of the Zürich-Leimbach section (N3-N5) are correlated to the chrons 5ADn to 5ABn (Fig. 2b, bold lines).

From the total of 28 sites of the Zürich-Aabach section, 19 were classified as class 1 and three as class 2 (Fig. 2a). The remaining six sites (21%) showed very low intensities without coherent magnetic directions and had to be discarded. Most sites of the section revealed a reversed polarity (R1, R2) except two sites with normal polarity (N1, N2). The normal polarity of these two sites is defined by single class 1 sites. A reliable correlation of this lower part of the Zürich MPS to the GPTS is difficult by magnetostratigraphy alone. A reasonable magnetostratigraphic 'best-fit' correlation of the Zürich-Aabach MPS (R1-N2) ranges from 5Br to 5ADn with chron 5Bn.1n missing (Fig. 2b, dotted line), revealing a very smooth change in the sedimentation rate. Incorporation of the known absolute ages permits a more reliable correlation of the Zürich-Aabach MPS with the GPTS: R1-N2 correlate with 5Cr to 5Bn.1n (Fig. 2b, dashed line). This correlation shows a rather abrupt change in the sedimentation rate. Another limiting factor for the correlation of the Zürich MPS to the GPTS is the base of the OSM (resp. top of OMM). As indicated by magnetostratigraphic and biostratigraphic data, the top OMM/base OSM is placed on top of chron 5Dn or at the base of chron 5Cr (Schlunegger et al. 1997; Kempf et al. 1999 in press). Consequently, the composite Zürich section correlates to chrons 5Cr to 5ABn of the GPTS between ca. 17–13 Ma, however, with many reversals missing (Fig. 6). This correlation is also supported by the biostratigraphic data of the Zürich section when compared with the Hörnli/Jona data (Fig. 6).

Correlation of the distal and proximal OSM

Magnetostratigraphic studies in the central Hörnli alluvial fan of the eastern Swiss OSM were carried out on two sections that are biostratigraphically well constrained (Hörnli and Jona sections) (Fig. 1). The MPS's of both sections revealed ages of ca. 17–13 Ma (Fig. 6). Two markers are present in these sections: a bentonite horizon (projected) and the Hüllistein horizon (2 and 4b in Fig. 6). The bentonite matches the Küsnacht bentonite at ca. 14.9 Ma (Bolliger 1992; Gubler et al. 1992) whereas the Hüllistein horizon, situated between normal and reversed polarity (chrons 5Cn.1n and 5Br), revealed an age of ca. 16 Ma (Kempf et al. 1997) (Fig. 6). Assuming that the Hüllistein conglomerate and the Meilen limestone, which are part of the Hüllistein marker horizon, were deposited contemporaneously (Bürgisser 1980, 1984), we obtain a further age control for the distal Zürich section. However, since the Meilen limestone is located within a succession of reversed polarity sites (Fig. 2a, at 160 m), the assumption of synchronous deposition seems to be questionable. Yet, as mentioned, many polarity zones are missing from the Zürich section. This incomplete re-

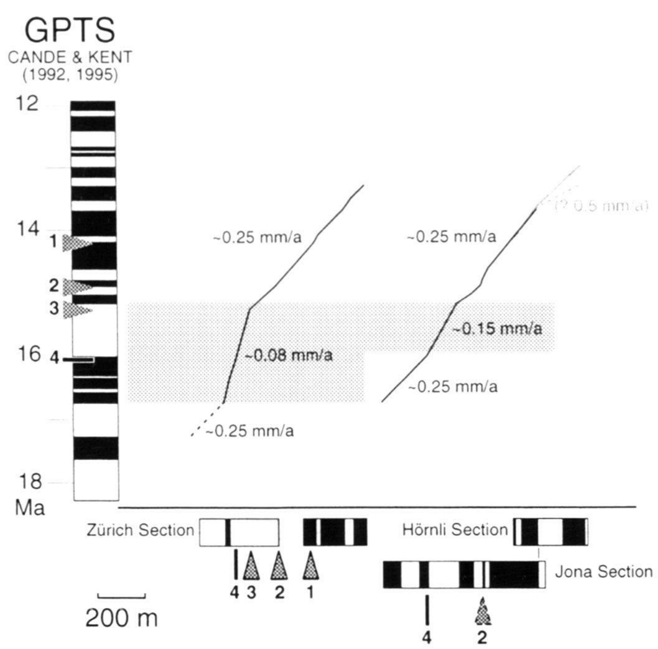

Fig. 7. Comparison of the sedimentation rates (compacted) of the Zürich and Hörnli/Jona sections. Position of absolute ages (1–3) and Hüllistein marker horizon (4) are given. Grey band shows time period of reduced sedimentation rate. For discussion see text.

versal record is most probably due to erosion and/or reduced sedimentation rates.

A first approach to estimate sedimentation rates in the Zürich area has been made by Gubler et al. (1992) on the basis of the ages of the three above mentioned bentonites. The upper limit of the OSM was estimated to 13 Ma which is in good agreement with our data. The OSM-base at 16.2 Ma (Gubler et al. 1992), however, is too young because their extrapolation did not consider variable sedimentation rates or erosion. Our data suggest that the overall sedimentation rate in the Hörnli, Jona and Zürich sections is ca. 0.25 mm/a (Fig. 7). Between 16.5–15 Ma, the rates are strongly reduced to < 0.1 mm/a on average in the Zürich section, in combination with erosion, and to 0.15 mm/a between 16–15 Ma in the more proximal Jona section (Fig. 7).

Orogenic activity and basin sedimentation

The time span of our investigated sections is 17–13 Ma. During this time, most of the active drainage of the Swiss Alps was provided by the Hörnli alluvial fan in the east (20–13 Ma), and the Napf alluvial fan some 70 km further to the west (21.5–14 Ma) (Kempf et al. 1997; Schlunegger et al. 1997). Our magnetostratigraphic results suggest decreasing sedimentation rates within the OSM succession of eastern Switzerland between 16.5–15 Ma. The decrease is very prominent in the distal area (Zürich section) and less so in the proximal area (Jona section). This drop implies either decreased sediment supply from the Alps or a widening of the depositional area. The coarse conglomerates of the Hörnli alluvial fan until ca. 15 Ma (Kempf et al. 1997) were succeeded by marls with almost no conglomerate deposition (Öhningerzone of Büchi 1957). This zone extends from the distal basin (N) into the proximal fan area (S) and even includes lake deposits (Habicht 1987). Subsequently, thick, coarse conglomerates prograded northwards far into the basin (Bürgisser 1984; Habicht 1987). Following the stratigraphic models of Flemings & Jordan (1990), facies progradation away from the thrust front is interpreted to be linked with continued thrusting or even tectonic quiescence, whereas an abrupt facies change from coarse to fine within a proximal setting seems to record the onset of a thrusting event (see also Blair & Bilodeau 1988). The stratigraphic evolution of the youngest eastern Swiss OSM can thus be interpreted to have been controlled by the begin of a late Alpine thrusting event at ca. 15 Ma which led to a final, strong progradation of the Hörnli alluvial fan into the Molasse basin lasting until at least 13 Ma. Before 15 Ma, relative tectonic quiescence caused decreasing sedimentation rates and erosion in the area of the southern Molasse basin (16.5-15 Ma; Fig. 7).

This late Alpine thrusting event probably caused the formation of the triangle zone between the Plateau and Subalpine Molasse, which led to the backthrust of the southern margin of the Plateau Molasse (see also detailed discussion in Kempf et al. 1999 in press).

Conclusions

The radiometrically and biostratigraphically constrained magnetostratigraphic study of distal and proximal alluvial fan deposits allows detailed insight into the stratigraphic evolution of the Upper Freshwater Molasse (OSM) of eastern Switzerland. The correlation of the magnetostratigraphic sections, which consist of conglomerates of the Hörnli alluvial fan (Hörnli and Jona section) as well as sand- and mudstones from the western flank of this fan (Zürich section), revealed an age of 17–13 Ma of these deposits. This correlation is supported by micro-mammal faunas, absolute ages of bentonites, and a regional marker horizon (Hüllistein). These independent data are particularly important in the distal area, where erosion and strongly reduced sedimentation rates occur.

The comparison of the proximal and distal sections revealed similar overall sedimentation rates of ca. 0.25 mm/a. A significant decrease to values of < 0.1 mm/a (16.5–15 Ma) in the distal and to ca. 0.15 mm/a (16–15 Ma) in the proximal area is indicated by our data. The decrease of the sedimentation rate is interpreted to have coincided with a time period of relative tectonic quiescence. The following increase of the sedimentation rate, more or less contemporaneous in both settings, can be linked to a new thrusting event at ca. 15 Ma. The stratigraphic expression of the begin of this thrusting event is initially a sharp transition from conglomerates to marls, even in the proximal area. This retrogradation of the conglomeratic facies seems to be due to enhanced subsidence in the proximal basin. During continued thrusting, alluvial fan conglomerates prograded again towards the basin.

Our study establishes a detailed picture of the youngest stratigraphic evolution of the eastern Swiss Molasse basin between 17–13 Ma and links sedimentary processes with a thrusting event of the Alpine orogen at 15 Ma. This thrusting event is probably related to the formation of the triangle zone and backthrusting of the southern margin of the Plateau Molasse.

Acknowledgements

Special thanks go to T. Gubler for his introduction to the Zürich-Leimbach section during a field trip in 1995. Discussions with T. Bolliger about the isochrony of the marker horizon and the regional stratigraphy are kindly acknowledged. Thanks go also to F. Schlunegger and P. Strunck for many fruitful discussions and to S. J. Burns for the help with the English. S. Lund and S. Henyey (University of Southern California) provided much appreciated technical assistance and advice with the paleomagnetic sample processing. The help of B. Hartmann during sample collection in the steep slopes of the 'Falätsche' is appreciated. The critical reviews of F. Heller and R. Arlitt are kindly acknowledged. This study was supported by the Swiss National Science Foundation (Grant No. 20-42890.95 and 20–50495.97).

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Manuscript received August 25, 1998
Revision accepted March 12, 1999