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Depositional evolution of the western Swiss Molasse

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Key words: Swiss Molasse basin, magnetostratigraphy, biostratigraphy, heavy mineral analysis, seismic lines, sedimentology, alluvial deposition

ZUSAMMENFASSUNG

Zur Rekonstruktion der Entwicklung des westschweizer Molassebeckens (zwischen Genfer See und Bern) wurde eine detaillierte sedimentologische Analyse von elf magneto- und biostratigraphisch datierten Profilen mit lithologischen und petrographischen Daten aus 15 Bohrungen und 21 interpretierten seismischen Linien kombiniert.

Im Laufe von 20 Mio. Jahren (zwischen Rupelium und Langhian) transportierten Flüsse den Erosionsschutt der Alpen nach Norden in das Molassebecken. Während des Rupeliums existierte ein schmales marines Becken im südlichen Teil des Arbeitsgebietes. Im späten Rupelium weitete sich dann das Molassebecken beträchtlich nach Norden aus und ein mäandrierendes Flußsystem etablierte sich im distalen Teil des Beckens parallel zur Beckenachse. Der Ablagerungsraum blieb über die gesamte Zeit der Sedimentation der USM (Chatt und Aquitan) eine Peneplain mit sehr geringem Gradienten, nahe der Erosionsbasis. Während verschiedener Stadien der USM zeigen palustrine Verhältnisse reduzierte Abflußraten an. Dies wurde möglicherweise durch Schwankungen des Meeresspiegels und/oder durch progradierende alluviale Fächer im mittleren oder östlichen Molassebecken ausgelöst. Während der darauffolgenden Sedimentation der OMM (Burdigal) herrschten flachmarine Verhältnisse im Molassebecken. Die völlige Überflutung in den distalen Beckenbereichen erfolgte in einem relativ kurzen Zeitraum um 20.2 Ma. Im südlichen (proximalen) Teil des Beckens erfolgte die Transgression verzögert und heterochron. Dies wurde durch den Einfluß der aus den Alpen kommenden, radial in das Becken einmündenden Flußsysteme bedingt, die durch die Ausbildung von Schuttfächern am Beckenrand kontinentale Ablagerungsbedingungen aufrechterhielten.

ABSTRACT

To reconstruct the development of the western Swiss Molasse Basin, a detailed sedimentological analysis of 11 magnetostraphically and biostratigraphically dated sections was combined with lithologic and petrographic data from 15 wells and interpretation of 21 seismic lines.

Orogenic detritus was transported by rivers into the Molasse Basin from Rupelian to Langhian times (i.e., during 20 my). During the Rupelian a narrow marine basin existed in the southern part of the study area. In the late Rupelian, the Molasse Basin widened significantly towards the north and a meandering river system established in its distal part parallel to the basin axis. The paleoenvironment remained a very low gradient plain close to base level during deposition of the USM in the Chattian and Aquitanian time. Palustrine conditions indicate a reduced drainage at some stages during USM, possibly triggered by sea level changes and/or prograding alluvial fans in the central or eastern Molasse Basin. Shallow marine conditions were established again during the following OMM stage (Burdigalian). The complete flooding and opening of the E-W OMM seaway occurred at about 20.2 Ma within a relatively short time interval. At the southern basin margin the marine transgression was diachronous because of the interaction with the radial dispersal systems draining the Alpine orogen. Deposition of continental sediments persisted while the distal parts were already flooded by the Burdigalian sea.

1 Introduction

The sediment record of the North Alpine Molasse Basin provides an important source of information about the last 30 million years of Alpine evolution. The Swiss Molasse Basin has been studied for several decades and as a result the lithostratigraphy, biostratigraphy and sedimentary environments have been established in considerable detail (e.g. BERGER 1985; ENGESSER 1990; ENGESSER & MÖDDEN 1997; FASEL 1986; KELLER 1989; KISSLING 1974; SCHLUNEGGER et al. 1993; SCHOEPFER 1989).

The relative succession of the stratigraphy is well constrained; however, it has always been a problem to connect it to a timeframe. The results from traditional methods such as lithostratigraphy are unsatisfactory because it is difficult to trace marker horizons over large distances in the continental and shallow marine sediments of the Swiss Molasse Basin.

To calibrate the evolution of the the Swiss Molasse Basin with the timeframe based on magnetostratigraphy three studies have been accomplished within a Swiss National Science Foundation (SNSF) project which was initiated in 1992 by A. MATTER. The first study, carried out by FRITZ SCHLUNEGGER, concentrated on the central part (SCHLUNEGGER et al. 1996; SCHLUNEGGER et al. 1997a, b, c) and the second study, by OLIVER KEMPF, investigated the eastern part of the Swiss Molasse Basin (KEMPF & MATTER 1999; KEMPF et al. 1999; KEMPF

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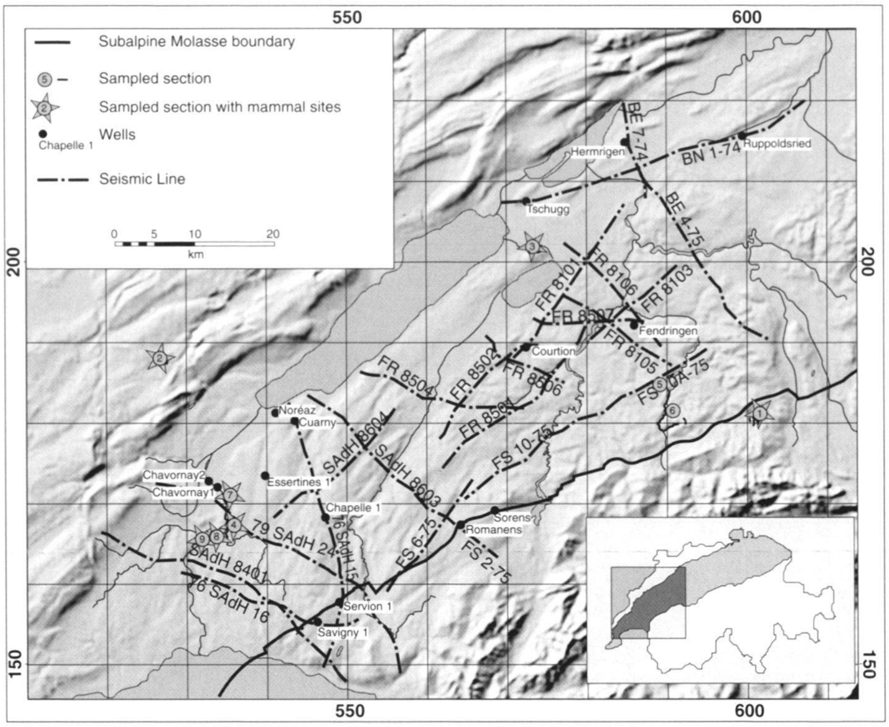


Fig. 1. Dataset used in this study. Sampled sections: 1. Seftigschwand, 2. La Chaux (see STRUNCK 2001, not discussed in this paper) 3. Mt. Vully, 4. Talent south, 5. Heitenried, 6. Sensegraben, 7. Talent north, 8. Oulens, 9. Cridec. The underlying map is drawn from the digital elevation model RIMINI © Bundesamt für Landestopography (BA024110).

et al. 1998). The last study is presented here. It focuses on the western part of the Swiss Molasse Basin extending from Berne in the east to Lake Geneva in the southwest. The study area is bordered by the Alpine thrust front in the south and the Jura Mountains in the north. The aims of this study are:

a) to set up a timeframe using magnetostratigraphy,
b) to refine the dating of the mammal biostratigraphy established by SCHLUNEGGER et al. (1996) and KEMPF et al. (1997) and,
c) to determine the depositional environments and to reconstruct the basin filling history of the Western Swiss Molasse Basin.

To achieve these aims and to get an improved understanding about the relationship between thrusting and exhumation in the Alps and the sedimentary processes in the Molasse Basin a combination of different methods is required.

2 Methods

In order to unravel the depositional history of the sedimentary basin it is necessary to understand the lateral juxtaposition and the vertical succession of the facies through time. For this study eleven sections from different stratigraphic positions distributed in the study area were logged in detail for lithofacies and sedimentary structures. These data were combined with the results of studies found in the literature to develop a facies model (KELLER 1989, SCHOEPFER 1989, BERGER 1985, ALLEN et al. 1985, ALLEN & BASS 1993 (OMM); KISSLING 1974, FASEL 1986, KELLER et al. 1990, PLATT & KELLER 1992, PLATT 1992, REGGIANI 1989 (USM); DIEM 1986 (UMM)). Together with well data they were used to extend the results from the surface to the subsurface.

To find the fossil micro-mammal teeth for ***biostratigraphy***, dark horizons with gastropod shell fragments were sampled (several kilograms per sample), dried, disaggregated with 10 % H_2O_2, then washed through a 0.5 mm sieve. The residue was dried, and the teeth were picked using a binocular microscope and sent to B. ENGESSER (Basel) for identification and determination of the biozone. In the western part of the study area many tooth-rich horizons have been sampled by MARC WEIDMANN in lag deposits of fluvial channels. Fossil bearing layers in sections with magnetostratigraphy were calibrated to the Geomagnetic Polarity Time Scale (GPTS) according to their position within the section.

Magnetostratigraphy is a tool to establish magnetic polarity time scales (OPDYKE & CHANNELL 1996) that can be applied to continental sediments as well as marine sediments of the Molasse (for details see SCHLUNEGGER et al. (1996), KEMPF et al. (1997)). Given long enough sections, no marker horizons are needed and basin-wide correlations are possible. The magnetostratigraphic timeframe serves as a basis to reconstruct the basin history. Additional information for this reconstruction is provided by the analysis of heavy minerals, facies and the paleocurrents. To extend these results basin-wide, ***borehole*** information and reflection ***seismic lines*** were employed. The seismic

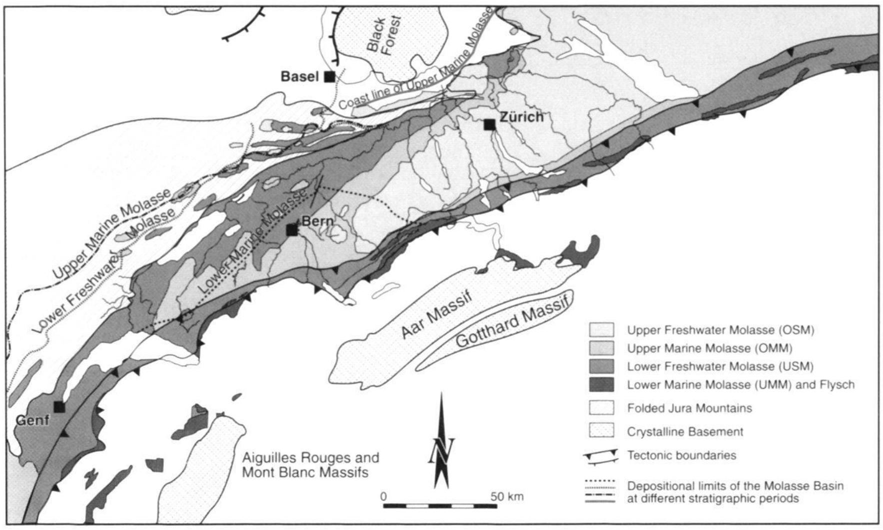


Fig. 2. Geological overview of the Swiss Molasse Basin. The Swiss Molasse Basin extends from Lake Geneva in the southwest to Lake Constance in the northeast. Due to tilting toward the NE and erosion, successively older formations crop out to the SW. Depositional boundaries of the four Molasse units are drawn after RIGASSI in MATTER et al. (1980).

lines were used to correlate the sparsely distributed wells within the study area. For six of the wells, litho-logs were established on the base of drilling reports and partly on wire-line logs (gamma ray logs and sonic logs). The litho-logs were used to interpret facies distribution and to correlate the seismic facies, derived from the analysis of the reflection seismic lines to lithology.

A detailed ***facies analysis*** was carried out on sections that were selected based on their feasibility for magnetostratigraphy. Altogether eleven sections were sampled at nine different locations in the *Subalpine Molasse* and the *Plateau Molasse* for magnetostratigraphy, biostratigraphy, and heavy mineral analysis. This dataset could be strongly extended with heavy mineral data derived from outcrops and wells (MAURER 1983a, b; MAURER et al. 1978; MAURER & NABHOLZ 1980; SCHLANKE et al. 1978); unpublished data from MARIA MANGE) and biostratigraphic sites analysed in previous investigations (BLAU, 1966; BERGER, 1985; WEIDMANN, pers. communication). Figure 1 shows the location of the measured sections, seismic lines and wells on which this study is based.

3 Geological setting of the Swiss Molasse Basin

The Swiss Molasse Basin is part of a peripheral foredeep flanking the northern side of the Alpine orogen (Fig. 1), which resulted from the Tertiary collision between the Apulian microcontinent and the European plate (PFIFFNER et al. 1997b). Flexural bending in response to loading by the advancing Alpine thrust wedge created a basin with an asymmetric cross-section. Its deepest part, where up to 5 km of Tertiary clastic sediments are preserved, lies adjacent to the Alpine front. The entire basin extends approximately 700 km along-strike from the Haute Savoie (France) in the west to Lower Austria in the east. The present-day width varies from about 30 km in the west to more than 150 km in southern Germany, and 25 - 30 km further east, in Lower Austria.

The Tertiary sediments of the Molasse Basin lie disconformably on approximately 1 km of Mesozoic sediments (LEMCKE 1973). These sediments overlie the Hercynian crystalline basement above a major "post-Variscan" erosional unconformity (BURKHARD & SOMMARUGA 1998). The basement contains a series of fault-bounded grabens, trending ENE-WSW, which are filled by up to several kilometres of Permo-Carboniferous clastic sediments. These grabens formed in response to post-Variscan transtension (PFIFFNER et al. 1997a) whereas the overlying Mesozoic sediments represent a typical passive margin series deposited at the European margin of the Tethys ocean.

Onset of compressional deformation at the beginning of the Tertiary caused a phase of non-sedimentation and erosion in the northern part of the Alpine foreland, marking the beginning of the flexural response of the European plate to collision (SINCLAIR et al. 1991). This hiatus is marked by a karstified land surface and by Eocene and early Oligocene laterite deposits, which rest locally on strata as old as Oxfordian (BÜCHI et al. 1965). Near the thrust front up to 200 m of marine sediments of Eocene to Oligocene age record the development of an underfilled basin. Sedimentation in the evolving Molasse Basin progressed first rapidly and later more slowly northward due to advance of the thrust front and forebulge (BURKHARD & SOMMARUGA 1998; CRAMPTON & ALLEN 1995; SINCLAIR & ALLEN 1992). As a result, the Molasse sediments at the southern margin of the basin became incorporated into the orogenic wedge and are now exposed in a stack of southward dipping thrust sheets (SCHLUNEGGER et al. 1997a). This imbricated zone, the *Subalpine Molasse*, defines the present southern border of the Swiss Molasse Basin (Fig. 2). The Molasse sediments north of the *Subalpine Molasse* remained almost undeformed and are referred to as *Plateau Molasse*.

At around 12 Ma the western Swiss Molasse Basin became completely incorporated into the Alpine thrust system

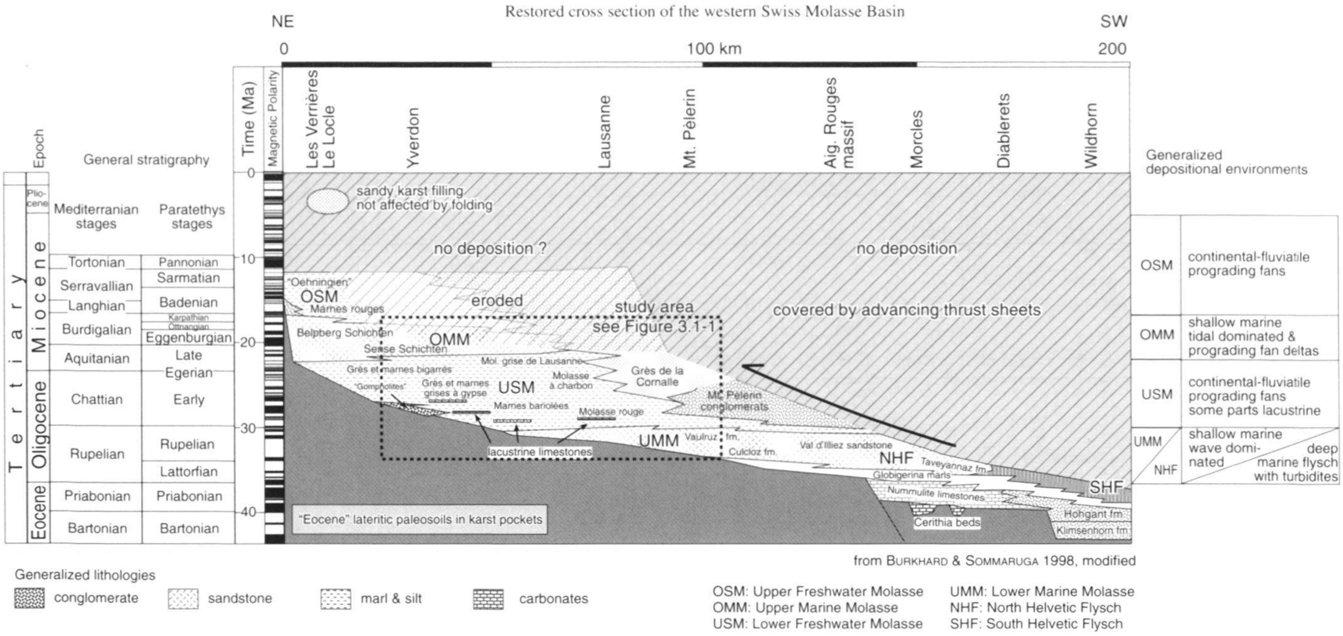


Fig. 3. Generalised section across the western Molasse basin of Switzerland. Geographic names on top give the approximate position of the restored section.

(Burkhard & Sommaruga 1998). Detachment along a Triassic evaporite horizon caused the transfer of compressional energy and displacement of the entire basin fill up to 30 km to the northwest in a piggy-back fashion (Deville et al. 1994). Although the Molasse Basin stayed relatively undeformed, it was uplifted and tilted toward the northeast and its sedimentary fill subjected to erosion (Laubscher 1992). At the northern edge of the basin, where the Molasse units pinch out, the underlying Mesozoic sedimentary rocks became pervasively folded and faulted, forming the Jura Mountains (Fig. 2). Folding dies out to the east, where no Triassic evaporites are present, and detachment did not occur. In this region the compressional deformation was distributed more evenly throughout the basin by faulting. The maximum amount of basin shortening occurred in the western part of the Swiss Molasse Basin (Fig. 2), where both anticlinal structures and thrust faults are observed.

The basin fill consists mainly of erosional debris from the evolving Alps in the south and is traditionally divided into four stratigraphic units, which represent two transgressive-regressive cycles (Fig. 3). Each of these cycles starts with a marine interval, which is followed by a period of continental deposition. The stratigraphic units are from top to base (the notations in brackets are the conventional abbreviations for the German names of these units and will be used throughout this study):

a) Upper Freshwater Molasse (OSM = Obere Süsswassermolasse),
b) Upper Marine Molasse (OMM = Obere Meeresmolasse),
c) Lower Freshwater Molasse (USM = Untere Süsswassermolasse),
d) Lower Marine Molasse (UMM = Untere Meeresmolasse).

Even though this subdivision, which is based on lithological criteria, is traditionally used as a stratigraphic sequence, the boundaries are diachronous and different units were deposited at the same time in different parts of the basin (Kempf et al. 1999; Schlunegger et al. 1997 b, c).

4 Results

4.1 *Sedimentology and magnetostratigraphy of outcrop sections*

As a result of the shape of the Molasse Basin (east-dipping syncline), progressively younger stratigraphic units are exposed from west to east in the *Plateau Molasse* (Fig. 2). For this reason the sections taken in the western part of the study area cover an older time interval than the sections taken in the eastern part (Fig. 4).

Long and continuously exposed sections are the main requirements for magnetostratigraphic studies. These requirements are best matched in the *Subalpine Molasse*, where long and continuous sections can be measured in the tilted thrust sheets over a short horizontal distance. In the eastern part of the study area a composite section could be taken through the *Subalpine Molasse* and three sections were measured in the *Plateau Molasse* that include the USM/OMM boundary south (Sensegraben) and west (Mont Vully) of Berne. Four sections were analysed in the Mormont anticline in the western part of the study area ca. 15 km south of Yverdon. Two of the sections (*Talent south* and *Talent north*) were taken in the Talent valley. Here the river cuts across the center of the Mormont anticline and exposes the complete Molasse series of western

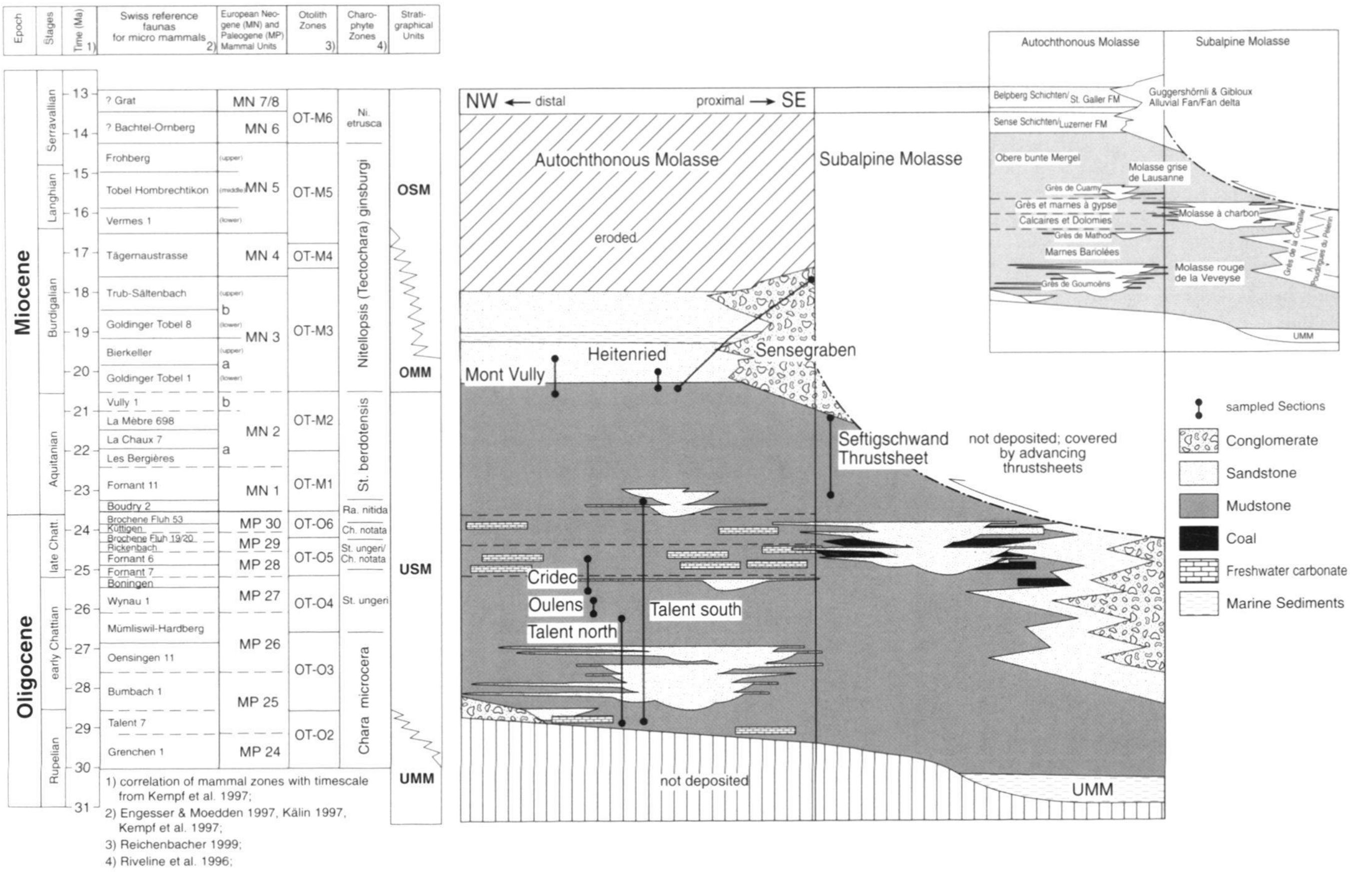


Fig. 4. Stratigraphic position of the sampled sections.

Switzerland, beginning at the base of the Tertiary and covering the entire Chattian in the *Talent south* section. The other two sections (*Oulens*, *Cridec*) were taken at the southeastern limb of the Mormont anticline within sediments of the lower USM.

Even though most sections show a distinct paleomagnetic pattern with several polarity changes, it was only possible in one case (*Sensegraben* section) to correlate the section directly with the Geomagnetic Polarity Time Scale (GPTS), see SCHLUNEGGER (1996) and KEMPF (1997). In all other sections the calibrated biostratigraphy is needed as additional information to accomplish the correlation.

The 750 m thick composite section taken in the *Seftigschwand* thrust sheet (Fig. 5) has a characteristic paleomagnetic pattern of 4 normal and 5 reversed polarity zones and one level in the lower part was dated as Fornant 11[1]. Based on the correlation with the GPTS the section covers a time interval of about 1.8 my from 20.8 Ma to 22.6 Ma. In the lower part it is dominated by floodplain sediments interbedded with minor channel sandstones, the sedimentation rate is about 0.35 m/1000 a. In the upper part of the section thick sandstones of meandering river systems are found in addition to the floodplain sediments, and the sedimentation rate is almost twice as high (0.65 m/1000 a).

The *Sensegraben* section (Fig. 6) in the area of Schwarzenburg is with a thickness of 900 m the longest of the three sections that contain the USM/OMM boundary. The lower 750 m of the section were sampled for paleomagnetics and cover a time interval of about 2.5 my, between 17.8 Ma and 20.3 Ma. The USM/OMM boundary is found at approximately 20.2 Ma. The section starts with floodplain sediments of the USM in the center of the Schwarzenburg anticline and continues through more than 400 m (corresponding to approximately 1.3 my) of tidal flat and tidal channel sediments. In the upper part of the section, starting at about 18.7 Ma, the marine sediments interfinger with prograding alluvial fan deposits that completely dominate the topmost 100 m (at around 17.8 Ma) with massive conglomerates. These conglomerates consist to more than 90 % of clasts derived from flysch sediments. Beginning at 700 m a different clast composition of the conglomerates is

[1] Note: The biostratigraphic age of the section is based on only one dated fossil horizon (BLAU 1966). The sediments of the thrust sheet were defined as *Studweid Formation* by BLAU (1966) and as *Seftigschwand Formation* by SCHMID (1970).

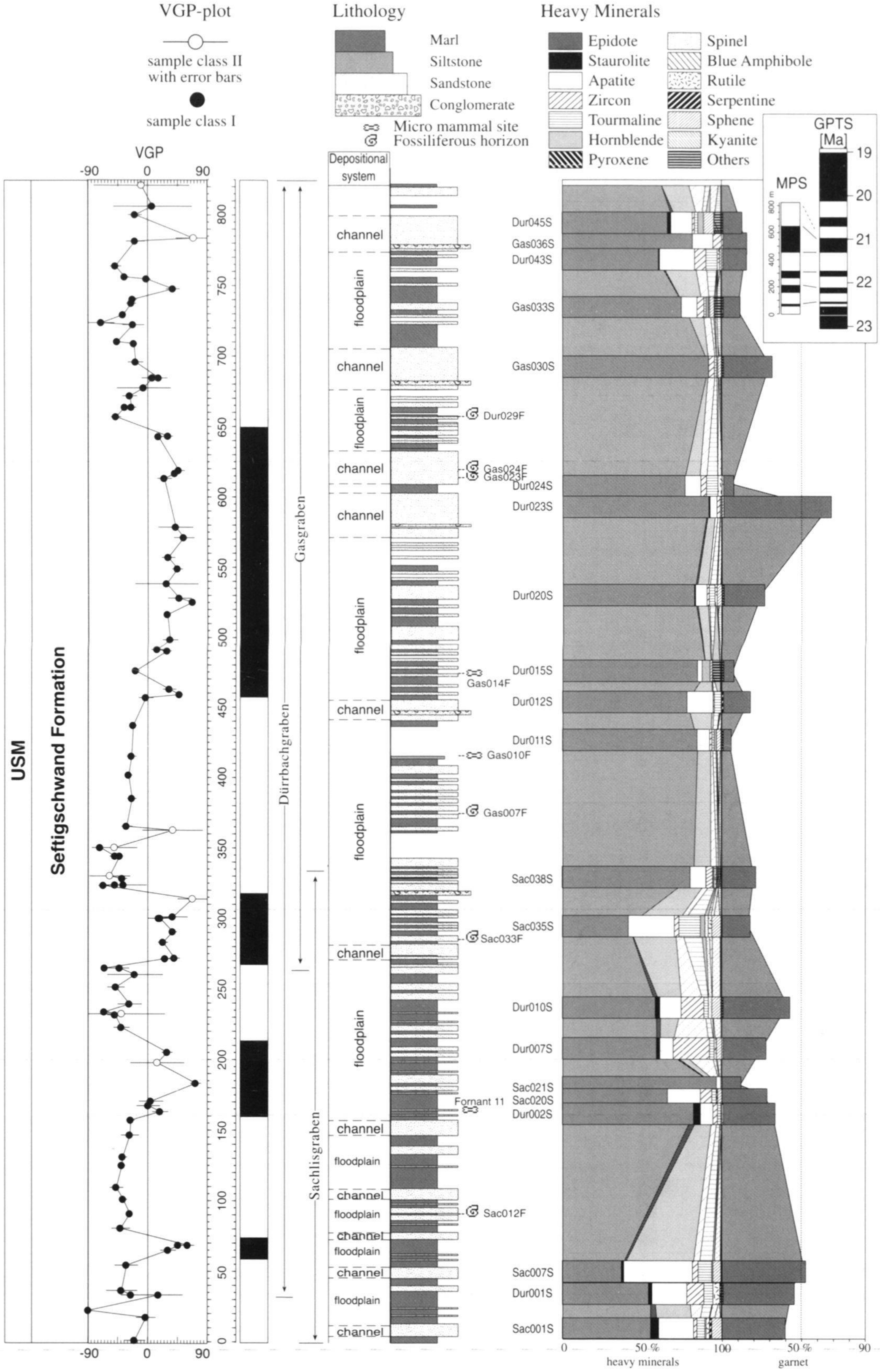


Fig. 5. Lithologic, paleomagnetic- and heavy mineral log of the Seftigschwand thrust sheet (composite section).

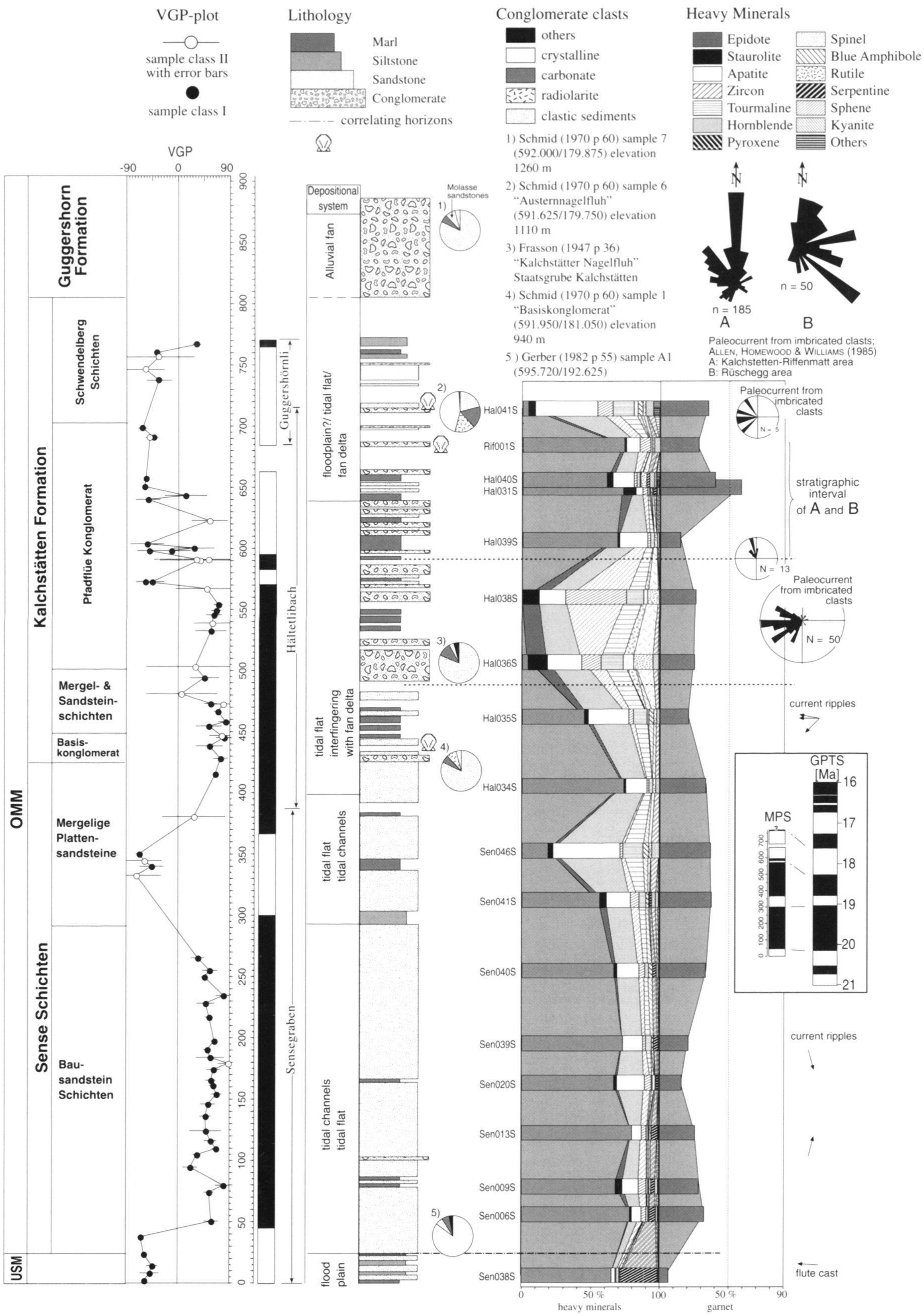


Fig. 6. Lithologic, paleomagnetic- and heavy mineral log of the Sensegraben/Hältetlibach/Guggershörnli section.

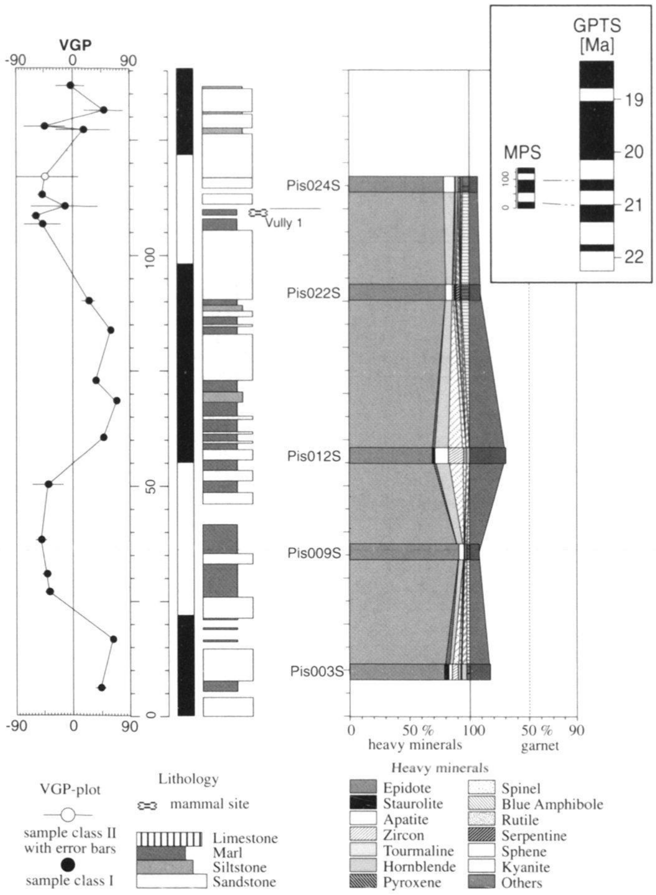


Fig. 7. Lithologic-, paleomagnetic- and heavy mineral log of the Mont Vully section.

found within an interval of about 50 - 100 m thickness. In this interval the flysch clasts make up less than 30 % of the conglomerate, whereas crystalline clasts increase to almost 50 %. From 800 m to the top of the section (*Guggershorn Formation*) the clast spectrum of the conglomerates is again similar to that in the lower part of the section.

In the *Sensegraben* section tidal flat sediments that cover the lower half of the section were deposited with a rate of about 0.25 m/1000 a whereas the interval above, where fan delta sediments interfinger, rates of about 0.5 m/1000 a were reached. The paleocurrents measured in the upper part of the section have north to northwest directions, indicating that these sediments were deposited close to the apex of the *Guggershorn* alluvial fan.

A few kilometres further north of the *Sensegraben* section, a short section with a thickness of less than a hundred metres was sampled for paleomagnetics at *Heitenried*. Although only one reversal is present in the section, it could be correlated to the GPTS through correlation of the USM/OMM boundary in the nearby *Sensegraben* section, where this boundary is well-constrained by paleomagnetics.

The third section that covers the USM/OMM boundary is the *Mont Vully* section (Fig. 7). Although the section has a thickness of only 140 m, it includes five polarity zones with 3 normals and 2 reversals and the micromammal reference zone *Vully 1*. When correlated to the GPTS the section represents a time interval of about 0.8 my between 20 Ma and 20.8 Ma, and the onset of the OMM transgression occurred at about 20.2 Ma within a reversed polarity zone. The correlation also reveals that the thickness of the sediment interval that contains the USM/OMM boundary is reduced compared to the thickness of the other intervals, but no facies change that could explain different sedimentation rates is observed. This suggests a gap in the sediment record of about 200 ka at the USM/OMM boundary due to a phase of non deposition and/or erosion. A different correlation of the polarity pattern below the transgressive horizon is also possible by shifting it down by one normal. This would enlarge the erosional phase by the 6An.1 normal and extend the hiatus to 0.5 my. The low sedimentation rate of approximately 0.15 m/1000 a, that calculates for the undisturbed interval of the lowest reversal and the following normal, reflects the distal position of the section. In all three sections the USM/OMM boundary is situated within a reversed polarity zone close to a normal polarity zone above. This normal polarity can be correlated very well to the GPTS in the *Sensegraben* section and allows the OMM transgression to be pinpointed to 20.2 Ma with an error of about 100 ka. The similar position of the USM/OMM boundary in all three sections suggests that the transgression is isochronous in the eastern part of the study area within the error of 100 ka.

The *Talent south* section (Fig. 8) represents the most important section taken in the western part of the study area, because it starts at the base of the Molasse above the mesozoic carbonates and goes through the complete Chattian. The lower part of the section (0-200 m), covers a time interval of about 3 my and yields the most varied micro mammal faunas. However, only a rough time estimate could be made based on the biostratigraphy because the mammal zones of that time interval are not yet very well calibrated with the GPTS. In this lower part, the section mainly consists of sediments deposited in a meandering river system. High sedimentation rates during short pulses are interspersed with longer time intervals of non deposition and/or erosion. This results in a strongly distorted local magnetic polarity pattern and possibly complete polarity zones are missing. Therefore a reliable correlation of the paleomagnetic pattern with the GPTS was not possible. The upper 200 m of the section document a relatively continuous sedimentation in a palustrine environment with low sedimentation rates over a time interval of 1.5 my (with possibly 0.5 my missing due to a fault). The age (23.8 - 24 Ma) of the uppermost 50 m of the section is well constrained by the calibrated mammal zone (*Küttigen*) which is located in one short polarity zone (KEMPF et al. 1997).

Fig. 9 shows all the analysed sections in the study area and their correlation with the GPTS. In most sections the correlation of the local magnetic polarity patterns is based on the calibrated swiss micro-mammal zonation.

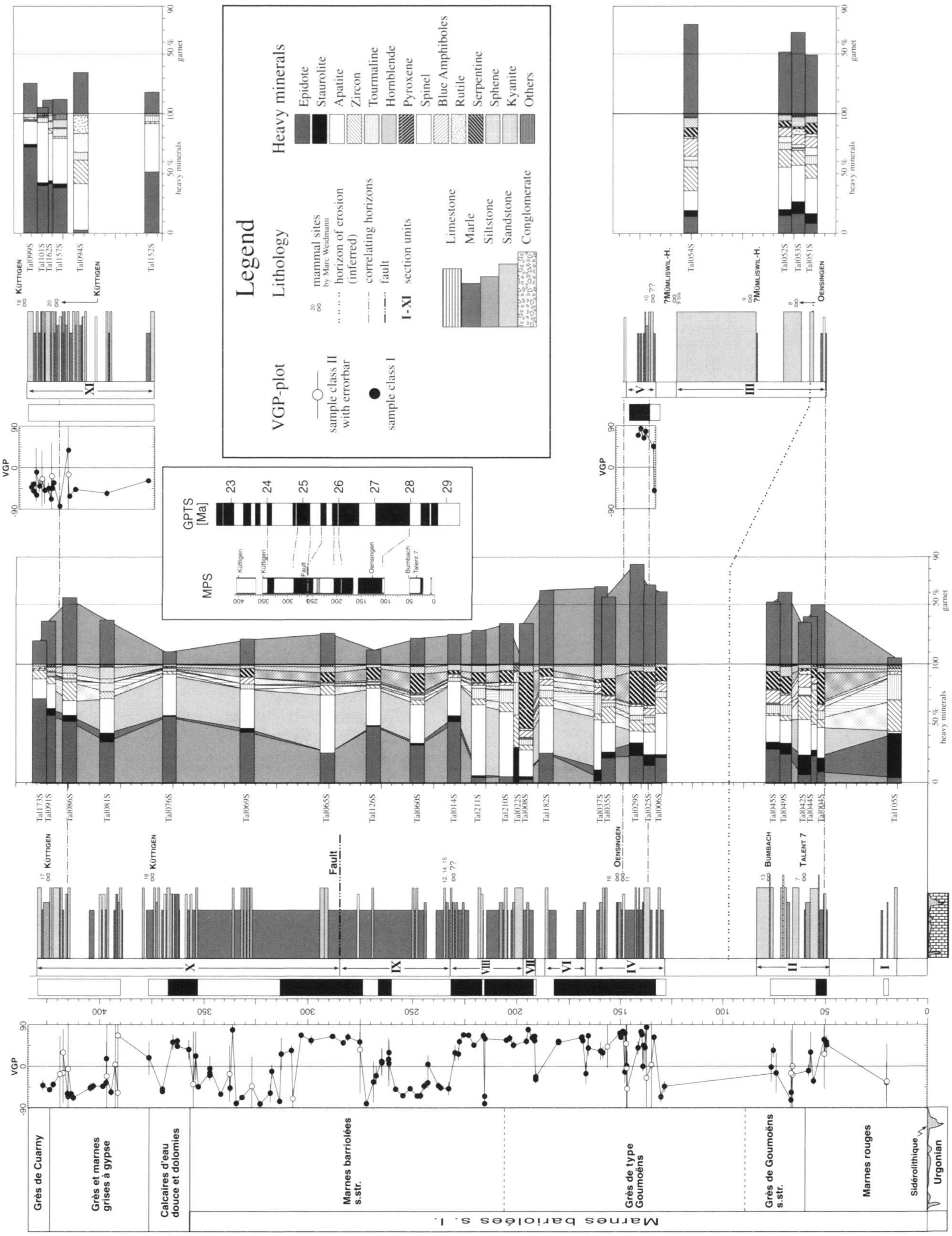


Fig. 8. Lithologic-, paleomagnetic- and heavy mineral log of the Talent south section. The roman numbers between the paleomagnetic polarity pattern and the Litholog indicate individual sections that were used to construct the composite section.

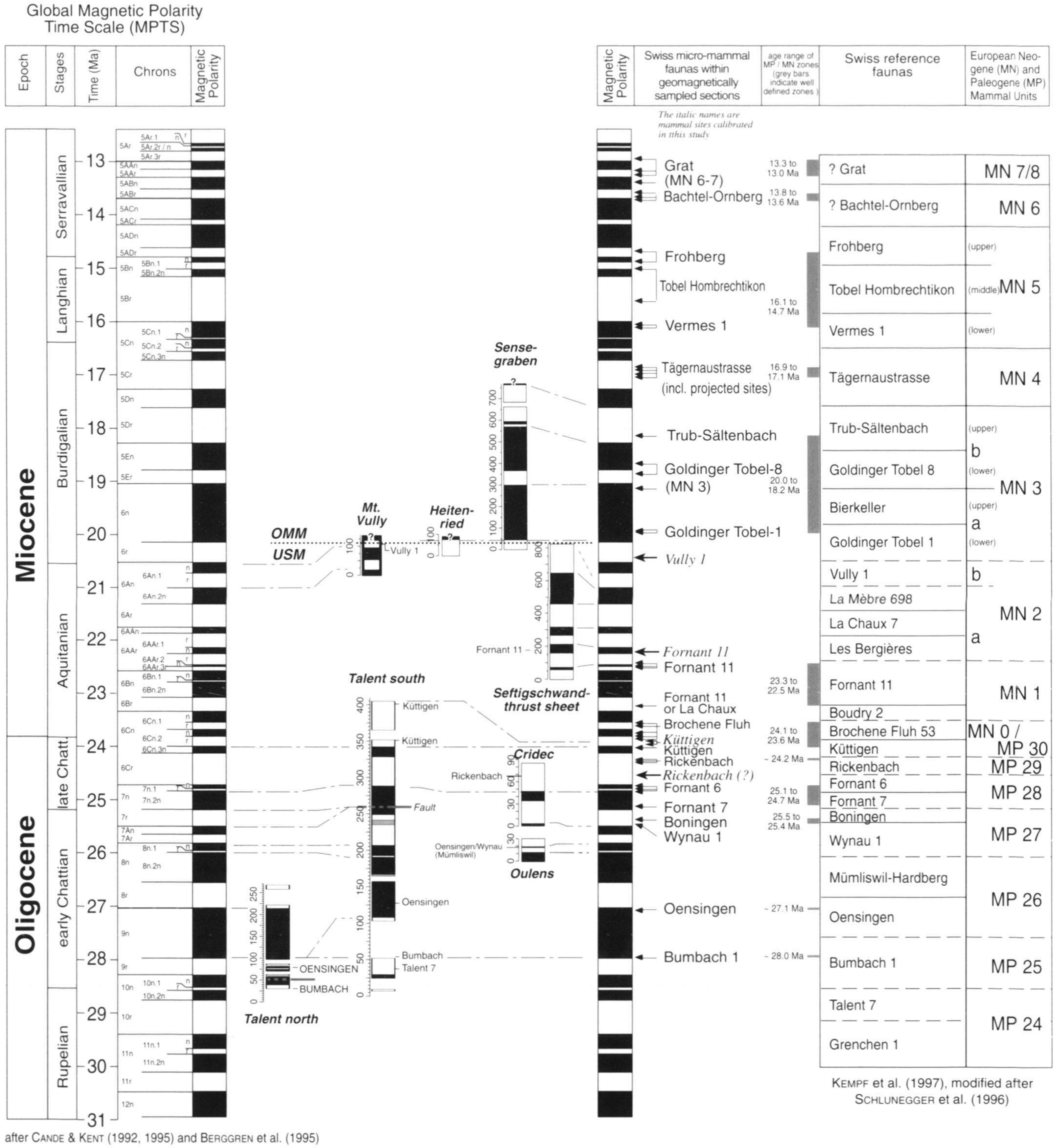


Fig. 9. Correlation of the local paleomagnetic patterns found in the study area with the Global Magnetic Polarity Time Scale (GPTS) based on the calibrated swiss micro-mammal zonation. The position of newly calibrated micro-mammal locations resulting from this correlation is shown in italics.

Tab. 1 Results of the determination of susceptibility and remanent magnetisation of the most typical rocks of the Sant'Antioco area. **R** is the remanent magnetisation, **K** is the susceptibility and **Q** the Koenisgberg ratio.

Unit	e/a ratio	garnet	blue amphibole	spinel	staurolite	ZTR value	other	occurrence
Unit 1	<< 1	> 50 %	√	√	√	10 – 40	–	all wells (except Servion)
Unit 2	1 – 2	20 – 50 %	no (possible at base)	no (possible at base)	√	< 10 or 10 – 40	–	all wells
Unit 3	>> 1	< 20 %	no	no	possible < 10 (mainly at base)	–		all wells (except Essertines)
Unit 4	>> 1	< 20 %	√	√	√	< 10	–	OMM
Unit 5	0 – << 1	20 – 50 %	no	√	√	> 40	–	Romanens, Fendringen, Tschugg, Thun, Linden
Unit 6	0	< 20 %	no	√ (> 30 %)	√	30 – 40	–	Ruppoldsried, Tschugg
Unit 7	–	–	–	–	–		high pyroxene content	Sorens
Unit 8	–	–	–	–	–		high amphibole content	Thun, Sorens

Depending on the position of the sections relative to the center of subsidence in the basin and on the time of deposition, varying sedimentation rates can be observed. In the proximal OMM-section (*Sensegraben* section) where 750 m of sediment cover about 2.5 my, rates of 0.25 to 0.5 m/1000 a are found, whereas 0.15 m/1000 a in the distal OMM-section at *Mont Vully*. The 750 m of proximal sediments in the *Seftigschwand* thrust sheet were deposited within 1.5 my during the Aquitanian and reveal rates between 0.35 and 0.65 m/1000 a. In the *Talent south* section the biostratigraphy indicates that a time interval of about 5 my (between 24 and 29 Ma) is covered by only 400 m of Sediment. No sedimentation rates can be calculated, because huge gaps in the sediment record are present.

4.2 Borehole analysis

Fifteen wells were analysed to extend the information from outcrops across the basin and into the subsurface of the study area (Fig. 1). Most of the wells had been subdivided into stratigraphic units, usually based on lithology, when first published. Many of the wells were later subdivided by other authors using different methods (e.g., Maurer 1983a; NTB 94-10 1994; Rigassi 1977; Zimmermann et al. 1976). All available data from the wells were compiled and the lithologic information of most of the wells was extracted from drilling reports and wire-line logs[2]. Heavy mineral analyses have been carried out for most of these wells (Maurer 1983a, b; Maurer et al. 1978; Maurer & Nabholz 1980; Schlanke et al. 1978) and the heavy mineral data were taken directly from the published figures – a method which may have introduced errors. A cumulative area plot of the heavy minerals is used to present the data. These plots allow several different heavy mineral associations to be distinguished. The boundaries between the different associations are never clear-cut. Therefore, it was important to develop a method to reliably distinguish different units. In a first step a principal component analysis was carried out. With this statistical method the different minerals were compared according to their likeliness of mutual occurrence. This reduced the set of thirteen different minerals to five principal components, which allowed different zones to be distinguished much more clearly. In a second step additional information was searched to further constrain the boundary conditions between different units. It was found, that the combination of the epidote/apatite ratio and the amounts of garnet together with the appearance of selected minerals[3] and the ZTR value[4] could yield the necessary information for distinguishing the units in a reliable and reproducible way. Based on this approach, eight different heavy mineral units are distinguished (Table 1).

4.2.1 Heavy mineral associations

The wells in the central part of the basin consist of a simple succession of only three units (Fig. 10). The lowermost unit (Unit 1) has a low epidote/apatite ratio (<< 1) and a high gar-

[2] Since the data of many wells have not been released to the public, detailed litho-logs and wire-line logs can not be presented in this study.

[3] Blue amphibole, spinel, staurolite, pyroxene and amphibole.

[4] The amount of the ultra stable minerals **Z**ircon, **T**ourmaline and **R**utile relative to the total amount of heavy minerals in percent.

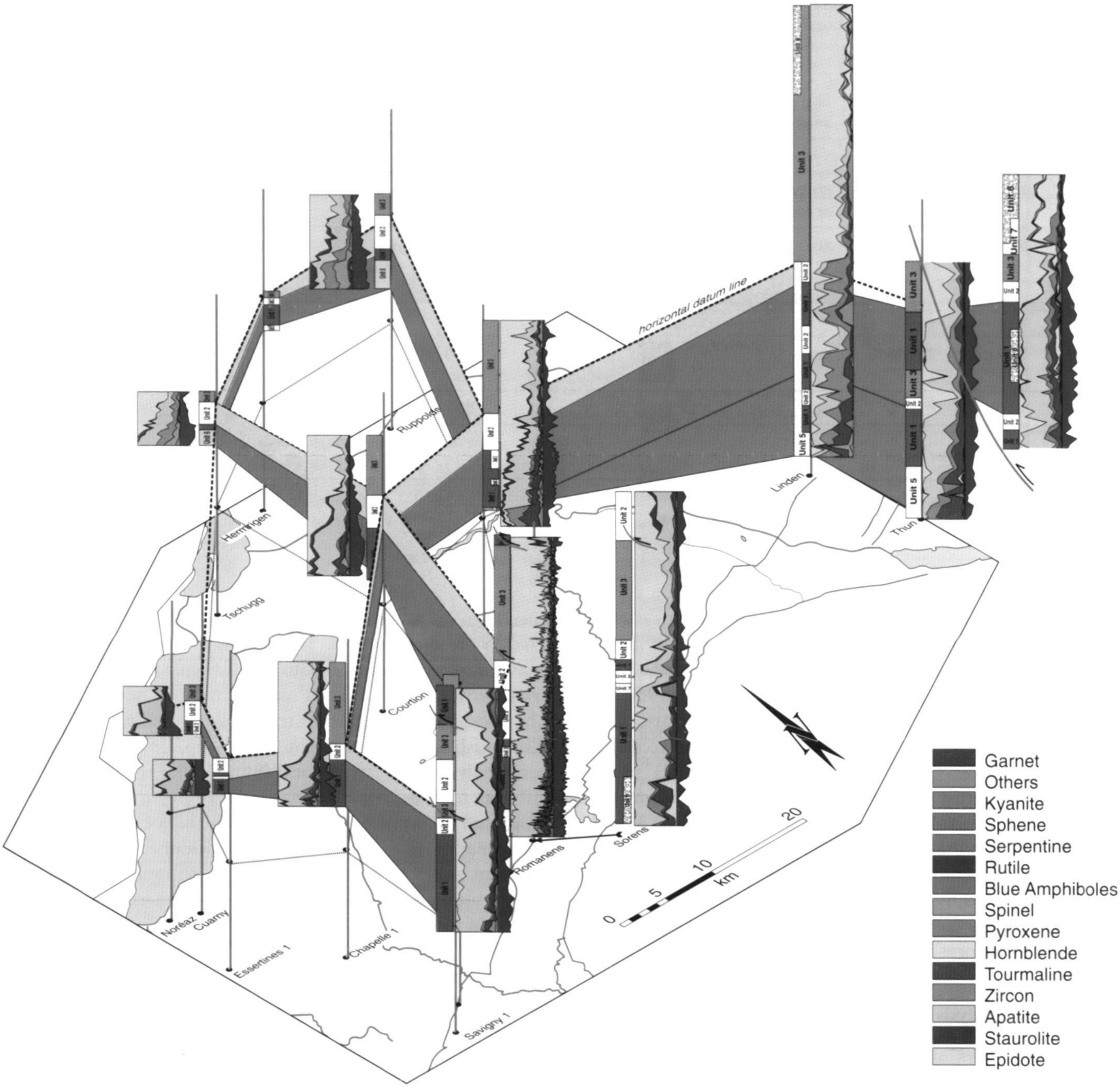


Fig. 10. Fence diagram showing of the spatial distribution of the heavy mineral units in the study area. The top of unit 2 is used as horizontal datum line. Unit 3 is not correlated because the difference in the thickness distribution is due to erosion at the top. Dashed lines indicate intervals of 1000 m.

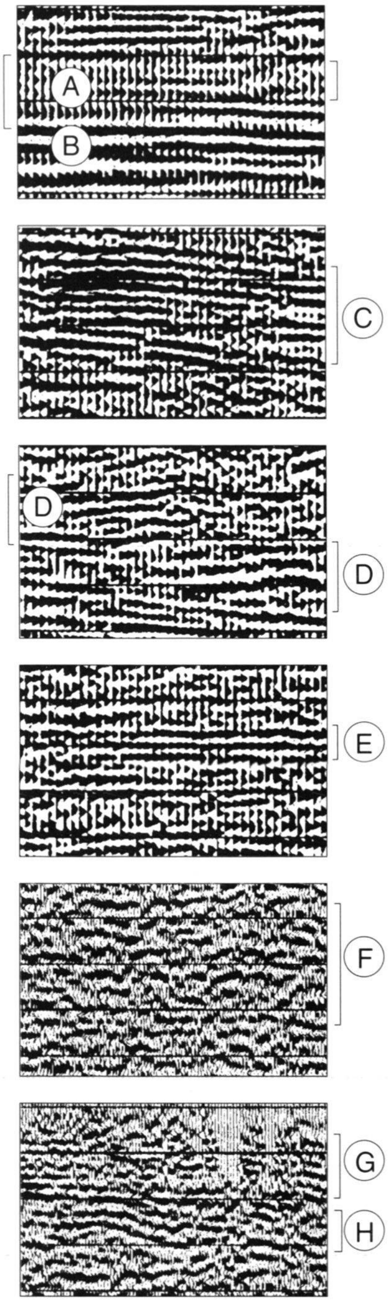
net content. It also contains spinel and staurolite, and in the western part of the study area, blue amphibole as index minerals. A high amount of garnet is present throughout Unit 1 independent of the abundance and the grain-size of the sandstone (Fig. 10). Unit 2 that follows above Unit 1 is characterised by an intermediate epidote/apatite ratio (∽1), a high to intermediate garnet content and only staurolite as ubiquitous accessory mineral (Fig. 10). Unit 3 is present on top of Unit 2 in all wells except for the westernmost well *Essertines*, where the upper part of the Molasse is missing due to erosion. This unit typically shows a high epidote/apatite ratio (>> 1) and a low garnet content. None of the accessory minerals are continuously present. Parallel and perpendicular to the basin axis several trends in the thickness distribution of Unit 1 to 3 can be observed (Fig. 10). In the central part of the basin, a minor increase of the thickness of Unit 1 occurs parallel to the basin axis towards the east. The thickness of Unit 2 increases by a factor of two from the westernmost to the easternmost well. The thickness distribution of Unit 3 varies significantly throughout the study area as a result of erosion at the top and does not reflect any depositional trends. Perpendicular to the basin axis a significant decrease in thickness of Unit 1 can be observed from south (ca. 900 m) to north (ca. 100 m), whereas the thickness of Unit 2 does not change very much. Most of the other units (Units 4 to 8 except Unit 6) are only found in the wells at the southern margin of the *Plateau Molasse* where they are either interbedded with Unit 1 or present at the base of the Tertiary (i.e., below Unit 1). Unit 5 is the most abundant of these units. Unit 6 is only present in the northeastern part of the study area below Unit 1 of the wells *Ruppoldsried 1* and *Tschugg 1* and possibly also of well *Hermrigen 1*. This heavy mineral association mainly consists of apatite, zircon and spinel and is similar to the association found in sediments of lower Chattian age in the Rhine-Graben (MAURER 1983a). The distribution of the heavy mineral association of Unit 1 throughout the study area shows that the axial drainage system (*Genfer See* dispersal system) was the most important system with the largest contribution to the sedimentation. The succession from Unit 1 to Unit 3 seems to represent a development in the catchment area of the *Genfer See* dispersal system. The Units 4, 5, 7 and 8 are considered to be the result of different dispersal systems that enter the basin perpendicular to the basin axis. Their rather subordinate distribution suggests that no major river system entered the basin from the *Subalpine Molasse* between Lake Thun and Lake Geneva. On the other hand, the uniform heavy mineral pattern could indicate that in the catchment area of these rivers similar rocks were eroded, as in the catchment area of the axial system. Their heavy mineral associations would then be not distinguishable.

However, the general distribution of a low epidote/apatite ratio in Unit 1 is not found in the northeastern part of the study area (wells *Linden, Ruppoldsried*, and *Tschugg,* Fig. 10). In these wells the apatite content of Unit 1 is much less than in the other wells with correspondingly higher amounts of zircon. This low amount of apatite is not considered to be caused by diagenetic dissolution. It is interpreted to be due to sedimentary processes, which has a large impact on the interpretation of the paleoflow during the Chattian. Especially since the heavy mineral pattern of the *Thun* well (situated about ten kilometres SSE of well *Linden*) is very similar to the pattern found in the western part of the study area. Sediment with a heavy mineral association of low apatite and high zircon content was delivered by a fluvial system from the north which entered the basin in the area of well *Ruppoldsried* and prograded south into the area of well *Linden* while mixing with the axial drainage system (*Genfer See* dispersal system) occurred. This interpretation is supported by the findings in the *Tschugg* well, where a mixture of the heavy mineral pattern typical for the western part of the basin (high amount of apatite) and the high zircon and spinel content as present in the *Ruppoldsried* well can be observed. Furthermore, it suggests that the western margin of the influence of the system coming from the north is situated west of the *Tschugg* well. However, this approach only explains the high amount of zircon, but not the fact that only small amounts of spinel are present in the *Linden* well. This could be explained by assuming that the zircon-rich heavy mineral association was introduced by a drainage system coming from the east that merged with the axial system coming from the west in the area of the wells *Tschugg* and *Hermrigen* and left the Molasse Basin northward towards the Rhine-Graben. The *Linden* well contains the mixed heavy mineral associations of the axial system coming from the east and a system coming from the south (*Honegg fan*) that drained towards the north and/or northwest.

Another explanation could be that the heavy mineral association with low apatite and high zircon content comes from a drainage system in the south that enters the basin somewhere between the wells *Sorens* and *Thun* and joins the axial system. The *Linden* well then shows the result from mixing of the different heavy mineral associations. While this explanation is possible (due to the lack of data between the wells *Sorens* and *Thun*) it only explains the different heavy mineral pattern of well *Linden*, but not the pattern found in the wells *Tschugg* and *Ruppoldsried*.

4.2.2 Lithology

The lithology of the Lower Freshwater Molasse is very similar in all studied wells. It consists mainly of a succession of interbedded variegated marls and sandstones and the thickness of individual layers is mostly below sampling resolution of the cuttings (< 5 m). Only on rare occasions cuttings of one lithology are found over an interval of several tens of metres. Even though the lithology does not change much, different zones exist, where one or the other lithology dominates, allowing the well sections to be subdivided into different lithostratigraphic units. These intervals roughly coincide with the heavy mineral Units 1 to 3 described above. In general, the lower part of the wells (Unit 1) contains several thick sandstones interbedded with thick layers of marls, i.e., enough floodplain sediments were deposited to separate the sandbodies. This suggests that the input of coarse material into the system was low and/or the subsidence rate of the basin was high enough to prevent the migrating meandering channels from amalgamation. Unit 2 consists mostly of marls indicating that less sand was transported into the study area than during earlier and later times. This could be due to a change in the dispersal systems and/or the transport directions of the material. On the other hand, it could be the result from a change in the depositional area where a higher base level and/or a lower gradient led to the deposition of the coarse sediments closer to the basin boundary. Unit 3 has the highest amount of sandstones, although these sandstones are frequently interbedded with marls. This suggests an increased sediment input into the system and/or reduced subsidence rates



A: aseismic zone with few reflectors of low amplitude and medium continuity above the Tertiary/Mesozoic contact; this reflection pattern is mainly present in the western part of study area;
Possible explanations: (i) karstification; (ii) residual Eocene clays (Siderolithique); (iii) distal floodplain; (iv) lake deposits.
B: well defined reflectors of high amplitude and high continuity; interpreted as Mesozoic;

C: parallel, horizontal reflectors with high amplitude and intermediate continuity;
no lithologic verification possible from wells;
turbidites?;
interpreted as UMM; found in western part of study area in Autochthonous Molasse below thrust sheets of Subalpine Molasse;

D: sigmoid reflectors; downlap; intermediate to high amplitude;
prograding delta or alluvial fan; USM;

E: horizontal reflectors;
intermediate to high amplitude; intermediate continuity; meanderbelt sandstones; USM;

F: wavy reflectors; low to intermediate amplitude; low continuity; same level as Facies Type E; flood plain deposits; USM;

G: parallel, low frequency (closely spaced reflectors); intermediate to low amplitude; low to intermediate continuity;
marine deposits; OMM;

H: inclined, parallel, wavy, closely spaced reflectors; intermediate to high amplitude; low to intermediate continuity; marine deposits?; prograding delta deposits? USM/OMM contact;

Fig. 11. Typical reflection patterns of the Tertiary in Western Switzerland are shown on the left hand side of the figure. The brackets at the side of the pictures indicate intervals with a distinct reflectivity pattern. On the right hand side the seismic facies are described for those intervals.

of the basin, which allowed the migrating meandering channels to amalgamate with previously deposited channel sandstones. Coarse sandstones and conglomerates are very rare in the western part of the study area and are only found in small amounts in wells that were drilled in the *Subalpine Molasse*. In contrast, the easternmost wells (*Linden* and *Thun*) penetrated more than a thousand metres of conglomerates attributed to the *Napf* alluvial fan by SCHLUNEGGER et al. (1993). Freshwater carbonates which form marker horizons in outcrops of the area around Yverdon are present in several wells, but only in wells close to Yverdon (*Noréaz, Cuarny*) the carbonates are found at the same stratigraphic position in the upper Chattian. In other wells, these carbonates and the anhydrite rich zone, which is usually located on top of the carbonates in the outcrops around Yverdon, appear at different stratigraphic positions. Sometimes anhydrite or gypsum occurs below the carbonates (as in the wells *Savigny* and *Chapelle*). Some coal was also observed at varying stratigraphic levels in several of the wells.

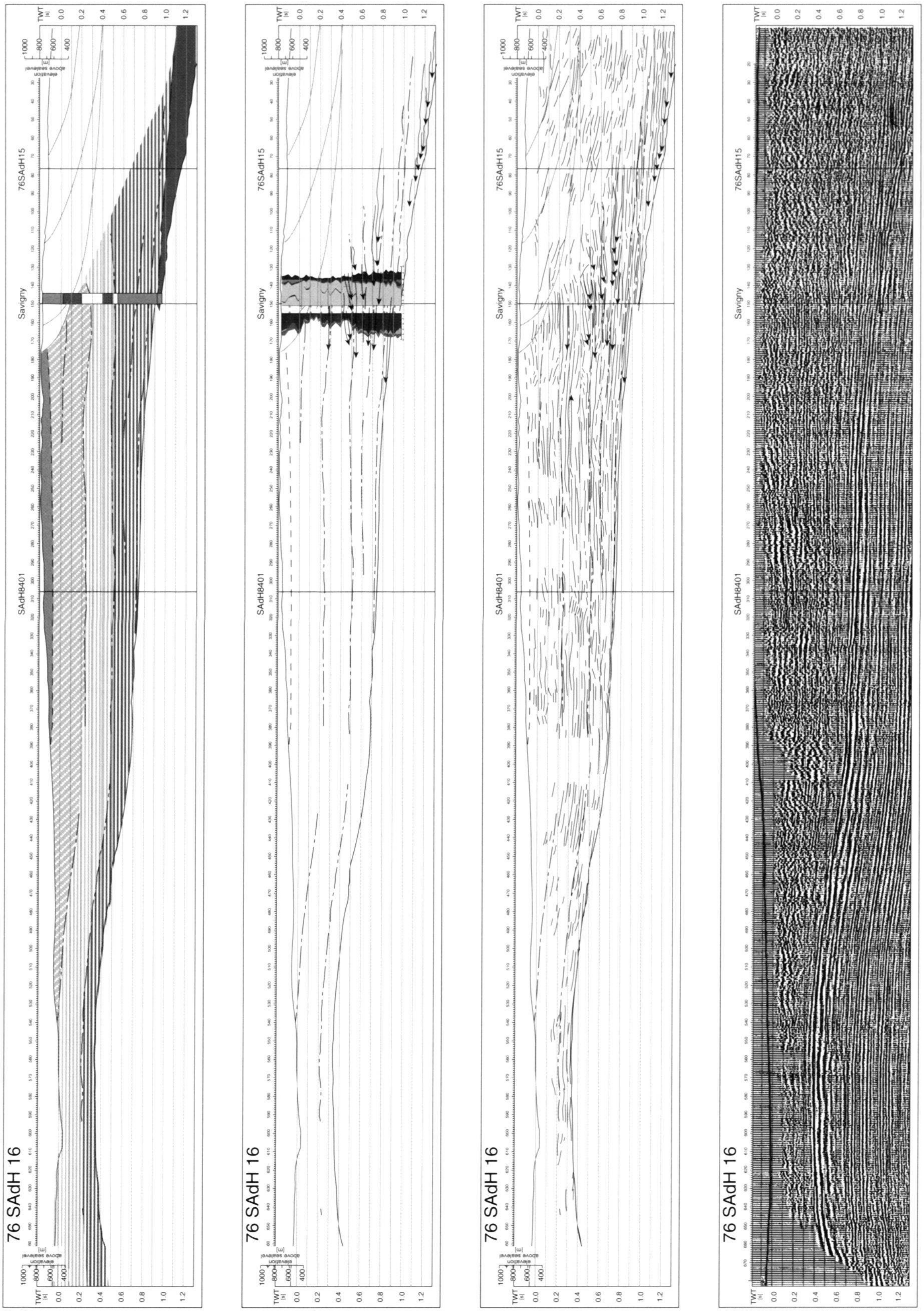


Fig. 12. Interpetation of seismic line 76 SadH 16

4.2.3 Correlation with time scale

Finally the wells are correlated with the outcrop sections. The findings in the *Talent south* section suggest that the boundary between Unit 2 and Unit 3 coincides with the Chattian/Aquitanian boundary. This boundary is used as a horizontal datum line when correlating the wells. However, it is not possible to determine from the data set whether the boundary given by the change of the heavy mineral associations represents

a) an isochronous boundary such as an erosional surface due to a hiatus followed by sedimentation through a different dispersal system (possibly after a phase of non-sedimentation and erosion) or
b) a diachronous facies change through the progradation of a different depositional system.

4.3 Seismic stratigraphy

A grid consisting of 21 seismic lines parallel and perpendicular to the basin axis, intersecting the wells and studied outcrops was selected (Fig. 1). Two of those lines are presented here (Fig. 12, Fig. 13). Although the different lithologic units with sandstones, marls and carbonates have a high enough impedance contrast to produce good seismic reflectors, the conditions for seismic studies in the Tertiary in Western Switzerland are not ideal. Outcrop data and GRLs of wells show that lithologic units change on scales of metres whereas the resolution of the seismic lines is in the order of tens of metres – one order of magnitude larger. Therefore, the reflectors mostly represent a composite signal from several reflecting horizons. As shown by MOREND et al. (1998), the application of high-resolution reflection seismic reveals much more detail.

Furthermore the interval of interest – especially in the western part of the study area – is very close to the surface. This results in a low signal-to-noise ratio that obscures the reflectors. The lines were also processed and optimized for a deeper interval of interest (Mesozoic).

The interpreted seismic lines often show zones of diffuse reflectivity, which extend through the complete Tertiary. It is not possible to clearly distinguish whether this disturbance comes from:

a) a bad signal transmission due to unconsolidated Quaternary sediments at the surface and/or noise from other disturbances (e.g., electric power lines),
b) fault zones with small movements on many faults that destroy impedance contrasts between the different layers,
c) different lithology with diffuse reflectivity behavior due to the change of facies.

The interpretation of the seismic lines was achieved in several steps. First, the base of the Tertiary was defined and the consistency was checked by correlating all analysed lines in the study area. Second, the Tertiary was subdivided into units, by distinguishing intervals of similar reflection behavior. The boundaries between the intervals are either visible directly through more or less continuous reflectors, or indirectly by accumulation of truncated reflectors in the interval below and/or onlap and downlap of the reflectors in the interval above[5]. However, such horizons could only be identified reliably in the lines with the highest resolution, which all come from one survey in the area southwest of Fribourg (FR 8501 – FR 8507). In the other lines only intervals with similar reflection behavior could be distinguished.

4.3.1 Mesozoic/Tertiary boundary

The Mesozoic/Tertiary boundary is the only boundary that could be found in all analysed seismic lines. It is usually marked by a strong, uniform and continuous positive reflector, generated by the interface of low velocity Tertiary mudstones (floodplain sediments) overlying high velocity Mesozoic carbonates (see B in Fig. 11). A somewhat seismically diffuse interval often lies between the upper reflector of the Mesozoic carbonates and the base of the Tertiary (see A in Fig. 11), which possibly represents a weathered zone at the top of the carbonates (karstification) together with the Eocene *Boluston* (*Sidérolithique*). However, several long, continuous reflectors (see B in Fig. 11) which are typical for the Mesozoic allow the Mesozoic/Tertiary boundary to be defined within a relatively narrow interval of 0.05 s TWT, corresponding to approximately 100 m thickness, above those reflectors. Reflectors of similar high amplitude and continuity are also generated by UMM sediments, which makes it difficult to define the base of the Tertiary where UMM is present. In these areas the Mesozoic/Tertiary boundary is defined by extrapolating the boundary reflector from zones lacking UMM.

4.3.2 Seismic reflectivity of the Tertiary

As mentioned above, continuous reflectors of high amplitude are found in areas where UMM is deposited. Below the *Subalpine Molasse* these reflectors onlap the Mesozoic rocks (see C in Fig. 11), but in some cases these onlaps could also be contacts of thrust sheets. In the area of the *Plateau Molasse* the UMM deposits are restricted to the southern margin and are usually thin – often no more than one or two reflectors are present. The sediments of the USM have a more variable reflection pattern. In the westernmost sections, which are of low and intermediate resolution, a zone with a transparent reflection configuration is found above the Mesozoic/Tertiary boundary. Further east, where the available lines have a better resolution, this transparent zone is not found, or at most is restricted to a short interval directly above the Mesozoic/Tertiary boundary. Instead, several reflectors with intermediate amplitude and a continuity of several kilometres parallel and perpendicular to the basin axis are resolved in an interval of otherwise low reflectivity. Above this "transparent" zone lies an interval with much shorter and undulated reflectors in both directions

[5] For explanation of the reflection terminations see (MITCHUM & VAIL 1977).

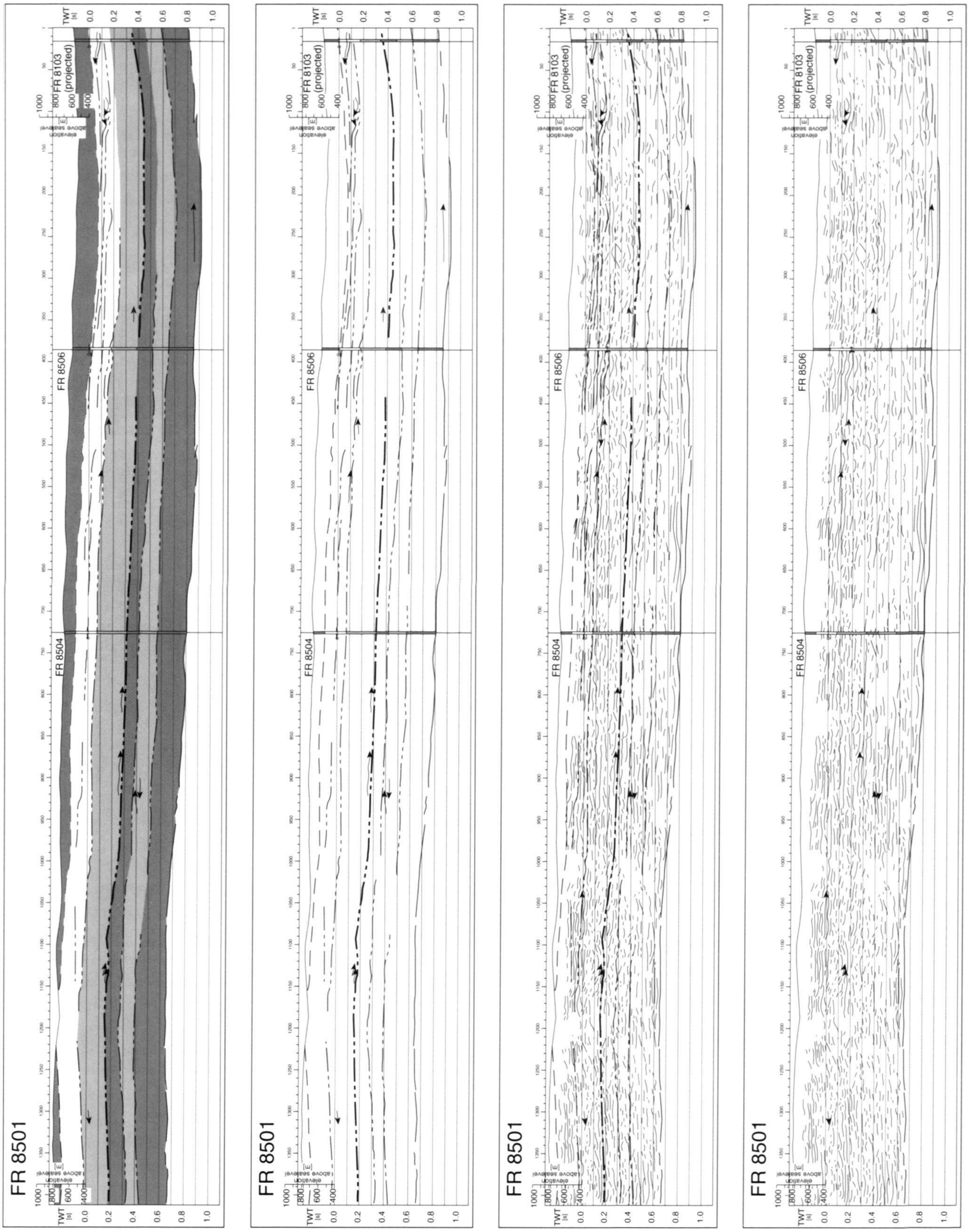


Fig. 13. Interpetation of seismic line FR 8501

(perpendicular and parallel to the basin axis, see F in Fig. 11). Within this zone, parallel and continuous reflectors are also present, but their occurrence is less frequent (see E in Fig. 11). Several reflectors can be connected to continuous horizons across the lines of the FR 81 and FR 85 surveys. However, a correlation of those horizons across different seismic lines is only possible in case they were processed in the same survey. Between lines of different surveys the correlation is often ambiguous. The correlating horizons are best developed in lines with the highest resolution and in regions where the interval of interest is covered by the thickest stack of sediments. These requirements are only met in the eastern part of the study area. Due to these restrictions a basin-wide correlation of the horizons was not possible.

The sediments of the OMM are represented by a zone of continuous and parallel reflectors of high frequency, high amplitude and intermediate continuity (see G in Fig. 11). The USM/OMM boundary is not directly marked by a reflector, but can be determined clearly by the distinctly different reflectivity pattern of the two formations. In addition, in line FR 8501 (Fig. 13), between the intervals of typical OMM and USM reflections, eastward dipping reflectors occur that truncate the underlying reflectors. Only in the eastern part of the study area the sediments of the OMM are thick enough to reach below the 0.2 s TWT where the signal-to-noise ratio is high enough to allow an analysis of the reflectors. A calibration and interpretation of the seismic facies in the OMM was not possible because no well data for this stratigraphic unit were available in the study area. Usually the wells are located on the top of anticlinal structures, where the OMM is eroded.

4.3.3 Seismic facies

As described above, several reflectivity patterns can be distinguished. After identification of these patterns, a correlation with lithologic data and definition of seismic facies was attempted. A correlation of the seismic information with outcrop data is possible at two locations where the seismic lines cross the outcrops (FR 8105 and FS 10A-75; 79SAdH24). Due to poor resolution of the seismic lines in the interval close to the surface, it could not be identified which changes in the lithology are responsible for the individual reflectors and only a rough estimate of correlating zones could be achieved. A similar result is found when correlating the wells with the seismic lines. The wells are all situated in zones with a rather chaotic seismic reflectivity pattern. Because the wells are usually located on structural elements where also a vertical movement on faults is observed, it is mostly impossible to correlate seismic reflectors directly with lithologic units, and again only a rough estimate could be achieved.

4.3.4 Discussion of seismic results

Based on the reflectivity pattern, the Tertiary succession can be subdivided into four large-scale units, representing the lower and upper Chattian, the Aquitanian and the Burdigalian. In addition, several boundaries can be defined by correlating reflectors. In the lines with the highest resolution these boundaries can be correlated over a larger area.

The two units within the Chattian can be distinguished as follows:

The lower unit contains horizontal, long and continuous reflectors. The individual reflectors are clearly visible in a matrix with low impedance contrasts. This lower zone can be correlated to heavy mineral Unit 1 as defined in section 3.2.1.

In the upper part of the Chattian less continuous and more undulated reflectors are present.

The Chattian/Aquitanian boundary coincides with the boundary between the heavy mineral Unit 2 and 3 in the studied outcrop sections. If this boundary between the heavy mineral units is transferred from the wells into the corresponding seismic lines, it lies sometimes in different reflectivity units (76SAdH15, FR 8101, FR 8507). This could either mean that the boundary between the seismostratigraphic units is heterochronous, or if it is considered to represent a timeline, the change of the heavy mineral units is diachronic.

The seismic reflectivity pattern of the Aquitanian consists of mostly short and wavy reflectors; long and horizontally continuous reflectors are missing. This occurs since the lithological units are too thin to be individually resolved. Furthermore, less distinct grain-sizes in the lithology cause a reduction of the impedance contrast between individual units. In the lower part of the Aquitanian, a well developed reflector is found, in the eastern part of the study area in the sections with the highest resolution.

In Line FR 8501, below the interval with reflectors typical for OMM sediments, eastward dipping reflectors are present. They can be interpreted as a fluvial deltaic sequence, which demonstrates the interaction between fluvial sedimentation from the west and marine transgression from the east. However, this interpretation does not explain the observation that the eastward dipping reflectors truncate the reflectors of the underlying sediments indicating erosion, which is not a common feature at the base of prograding deltas. This can be explained by erosion that occurred during a regressive phase when the axial fluvial system again prograded towards the east and eroded down into the deltaic sequence before the following deltaic sequence was deposited during the next transgressional cycle.

Onlap of Tertiary sediments on Mesozoic can only be observed in the southern part of the basin. Onlapping reflectors are found in both UMM and USM sediments. In the northern part of the basin the reflectors of the Tertiary are roughly parallel to the reflectors of the underlying Mesozoic.

The large increase of the thickness of the *Plateau Molasse* towards the south has two reasons. On the one hand, it is due to additional sediment at the base of the Molasse which onlap northward onto the Mesozoic. On the other hand an increase of the thickness of each stratigraphic unit is observed towards the south. Whereas the latter observation indicates a higher subsidence rate in the southern part of the basin throughout the depositional history, the former observation either indicates significant higher subsidence rates during the early times of the basin history (UMM, possibly up to lower Chattian) or that the relief of an underfilled basin that had existed during UMM (HOMEWOOD et al. 1986), was filled.

Faults which are visible in the Mesozoic through the offset of reflectors cannot be seen in the Tertiary. The movements that occurred along few major faults in the Mesozoic are possibly transferred to movements along many subordinate faults in the Tertiary sediments.

On average the seismic velocities of the Molasse sediments are around 3500 m/s. However, in some intervals the velocities are above 4000 m/s. These velocities which are unusually high for siliciclastic sediments were interpreted by BURKHARD & SOMMARUGA (1998) as a result of horizontal compaction due to tectonic strain and/or vertical compaction caused by overlying OMM and OSM sediments which are now eroded (KAELIN et al. 1992). Indications for a transpressional stress field are found in line FR 8506.

Dipping reflectors in the Mont Pèlerin area suggest a prograding alluvial fan in the lower part of the USM. However, it is not always possible to distinguish this reflection pattern from structures caused by thrust sheets (76 SAdH 16, Fig. 12).

5 Depositional environments and basin filling history

Sediments were transported by rivers into the study area from Rupelian to Langhian times. A river whose paleoflow direction was parallel to the basin axis (*Genfer See* dispersal system) is the most important. The location of its drainage area is still unknown, but was probably situated southwest of the study area and the heavy mineral composition indicates that oceanic crust was eroded there throughout the Chattian. The other systems where radial fluvial systems of varying size that entered the basin perpendicular to the basin axis from the southern and the northern margin. The southern radial systems had their catchment area in the advancing Alpine Nappes. Depending on their size and their catchment area, they built up large alluvial fans (*Mont Pèlerin* alluvial fan) with a mixed clast composition or smaller fans (*Guggershörnli* alluvial fan) with a rather monotonous clast composition, when entering the Molasse Basin. During marine conditions fan deltas were deposited.

5.1 Rupelian

Marine conditions existed in the southern part of the study area during the Rupelian time (DIEM 1986). In the seismic lines of the western part of the study area northward onlapping reflectors that represent the sediments of the UMM and the lower USM are visible only up to the center of the present Molasse Basin. No northward onlap of the reflectors is visible in the northern part of the basin. This reveals that the subsidence histories of the northern and southern parts of the basin were quite different during Rupelian time, and only the southern part experienced pronounced subsidence as a result of flexure caused by the load of the Alpine wedge. The hinge possibly represents the northern margin of the underfilled Rupelian Molasse Basin whose base level was significantly lower. An indication for this low base level is the karstification of the Mesozoic limestones, which form the paleosurface. When applying the model of ALLEN et al. (1991), this hinge represents a forebulge that existed in the early history of the Molasse Basin. However, a northward onlap beyond the forebulge, as postulated for the following extensional phase of the basin by these authors, is not observed in the seismic lines of the study area, as described above.

The sedimentary sequence, which is interpreted as UMM based on the reflection pattern in the seismic lines, stops significantly below the hinge. A fluvial sequence fills up the remaining relief and then extends northward beyond the hinge. It is dated by micro-mammals in the *Talent south*[6]. The heavy mineral association of this sequence is characteristic of the axial *Genfer See* dispersal system, which supports the interpretation of DIEM (1986) that in the western part of the Molasse Basin the first phase of marine sedimentation (UMM) ended earlier than in its eastern part.

5.2 Chattian

5.2.1 Lower Chattian

After the basin widened in the late Rupelian, an axial meandering river system (PLATT & KELLER 1992) migrated across the whole area that belongs to today's *Plateau Molasse*. A higher rate of subsidence still existed in the south as documented by the heavy mineral Unit 1, which is found throughout the study area, but decreases in thickness from south to north. At that time the Alpine thrust front was so far south that no evidence of sediment input by the southern radial fluvial systems is documented in the sedimentary record of the study area.

5.2.1.1 Sediment input from the north

The northern dispersal systems are of little importance on the basin fill because they delivered small amounts of sediment[7]. Detritus of northern provenance (*Grès et Calcaires à glauconie* and "*gompholites*") is mainly found in the lowermost Chattian when the northern basin margin was close. Subsequently the basin widened to the north and the sediments were deposited in the area that was later involved in the Jura folding and

[6] The biostratigraphic zone of Talent 7 is thought to have Rupelian age, but it could not be calibrated to the geomagnetic polarity time scale in this study.

[7] Their presence can be clearly identified by their distinct heavy mineral association (high amounts of the ultra stable heavy minerals zircon and tourmaline) and the composition of the sandstones (high amount of carbonate clasts) which represents reworked Cretaceous from the area of the present Jura Mountains. See *Talent south* section, Fig. 8, samples Tal022S and Tal105S

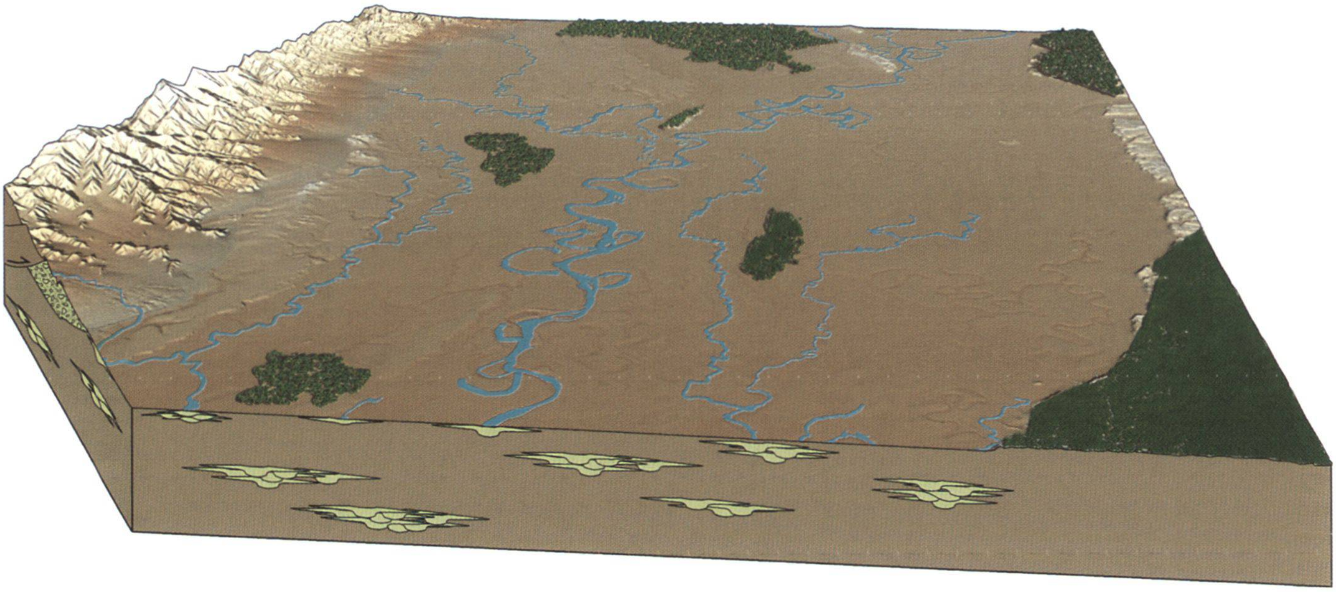


Fig. 14. Reconstruction of the depositional environment in the lower Chattian. View towards southwest. Bajadas and alluvial fans are deposited at the thrust front whereas most of the basin is occupied by an axial fluvial system. Due to slight differences in topography (forebulge) the formation of a proximal and a distal axial system is possible.

where the Molasse sediments are mostly eroded today. In addition, the drainage area between Bresse-Graben and Rhine-Graben was small and most of the rocks were carbonates, which weathered by chemical solution leaving residual clays (*Sidérolithique*) rather than by physical disintegration. As a result only relatively minor amounts of detritus were transported into the basin from the north.

Little can be said about the relief in the catchment area of the northern dispersal systems. In general the Mesozoic sediments north of the Molasse Basin are thought to have been eroded to a peneplain by chemical weathering with little or no relief. On the other hand, it is very likely that in a deeply karstified landscape not everything was eroded to the same level and that some relief existed. This is supported by conglomerates (*gompholites*), which are found at several locations at the northern margin of the Molasse Basin. Their occurrence at different stratigraphic levels indicates a relief throughout the time of deposition of the Molasse sediments.

5.2.1.2 Sediment input from the southwest

As mentioned above, a fluvial system whose paleoflow is along the axis of the basin, migrated across the entire area of the present *Plateau Molasse* as documented by the presence of a characteristic heavy mineral pattern (Unit 1) throughout the study area. As described in section 4.2.2, the heavy mineral Unit 1 represents an interval with meandering channel sandstones separated by floodplain sediments. Moreover, the individual reflectors found in the respective interval of the seismic lines suggest a system of single meander belt units (Fig. 14). Sheet sandstones were deposited by a single sweep of a migrating channel and the mudrock-dominated units are the products of poorly confined and unconfined flow during floods (MIALL 1991).

The fact that a meandering river system was established in the distal part of the Molasse Basin indicates that this part of the basin was a very low gradient plain close to the base level during deposition of the USM.

The question about the source area of the axial drainage system (*Genfer See* dispersal system) still remains to be answered. A very similar heavy mineral pattern to that found in the *Talent south* section is present in the sections of *Fornant* and *Findreuse*[8] in Haute Savoie. These findings suggest that both areas are part of the same depositional system, which means that the source area was somewhere south and/or southeast of Haute Savoie. The high serpentine content indicates that oceanic crust was eroded in the catchment area throughout the Chattian.

The erosional gap of about 40 m, which is present in the *Grès de Goumoëns Formation* in the *Talent south* section, covers almost one million years. It could be the result of erosion by downcutting meandering channels or the result of a phase

[8] A biostratigraphic and magnetostratigraphic dating of these sections is published by BURBANK et al. (1992) which was revised by SCHLUNEGGER et al. (1996). The heavy mineral analyses are unpublished data by MARIA MANGE.

of uplift and erosion that occurred at some stage around 27 Ma (±0.5 Ma). According to the model of SINCLAIR et al. (1991) this uplift could be caused by the forebulge.

5.2.1.3 Sediment input from the south

During the Rupelian and beginning Chattian the radial fluvial systems that entered the basin from the Alpine nappes were too far south to be documented in the sedimentary record of the study area. This changed at around 26 Ma when the *Mont Pèlerin* alluvial fan started to build up and prograded into the basin, an interpretation supported by ± north dipping reflectors in the *Mont Pèlerin* area (see seismic line 76SAdH16, Fig. 12). The conglomerates form a massive thrust sheet that dominates the *Subalpine Molasse* in the area east of Lake Geneva. How much further south this fan originated relative to its present day position cannot be said, for the tectonic shortening could not be reconstructed based on the seismic lines available in the western part of the study area. However, a northward movement of some tens of kilometres is possible (BURKHARD & SOMMARUGA (1998) give a value of up to 20 km).

The conglomerates of the *Mont Pèlerin* alluvial fan pass northwards into the *Grès de la Cornalle*, which is supported by the similar heavy mineral association found in both formations. However, this heavy mineral association is not observed in the *Plateau Molasse*, e.g., in the *Savigny* well, which is located directly in front of the *Mont Pèlerin* alluvial fan thrust sheet. Abundant staurolite, which is a typical heavy mineral of the *Mont Pèlerin* dispersal system is present in the *Subalpine Molasse* units of the wells *Romanens* and *Sorens* about 20 km northeast of well *Savigny*. This leads to the conclusion that the detritus of the *Mont Pèlerin* alluvial fan was transported towards the northeast in a fluvial system separated from the main axial fluvial system. The necessary difference in topography to separate the two axial systems could be caused by a forebulge as postulated by ALLEN et al. (1991). On the other hand, at the equivalent stratigraphic position of the *Mont Pèlerin* alluvial fan sediments either an increase or the first appearance in staurolite is observed in many wells of the study area. This suggests admixture of *Mont Pèlerin* detritus, which was however small compared to the amounts of sediment distributed by the axial system.

5.2.2 Upper Chattian

The fact that in the *Plateau Molasse* of the study area the heavy mineral associations stay constant throughout the Chattian implies that no significant changes in the dispersal pattern occurred. However, distinct changes can be observed in the facies of the upper Chattian (24.5 ±1 Ma). An increase in freshwater carbonates and in some places dolomites (*Calcaires d'eau douce et dolomie*), which can be correlated over several kilometres in the area southwest of Lake Neuchâtel (JORDI 1955) is observed. The *Calcaires d'eau douce et dolomie* are followed by a series with anhydrite and gypsum (*Grès et marnes gris à gypse*) and climatic changes towards dryer conditions are thought to be the reason for the observed facies changes.

The *Calcaires d'eau douce et dolomie* were interpreted as lake or pond deposits by earlier authors (PLATT 1992; REGGIANI 1989). Brackish conditions are supported by very rare findings of marine fossils (e.g., a cyrene, a shark tooth (JORDI 1955; RIGASSI 1957) and brackish ostracods (CARBONNEL et al. 1985; OERTLI 1956)).

Biostratigraphy based on micro-mammals correlates the *Calcaires d'eau douce et dolomie* and the *Grès et marnes gris à gypse* with the *Molasse à charbon* of the *Subalpine Molasse*. This correlation is supported by the fish faunas, which are found to be similar in both formations (REICHENBACHER 1996). According to former interpretations, different climatic conditions are required to develop the different formations. Whereas the swamps of the *Molasse à charbon* indicate humid conditions the *Calcaires d'eau douce et dolomie* and *Grès et marnes gris à gypse* require semi-arid to arid conditions. Another model proposed by PLATT & WRIGHT (1992) reconciles the observations for two of the formations: Their model postulates a palustrine (swamp) environment as depositional system for the *Calcaires d'eau douce et dolomie* that can be compared to the Everglades of Florida and this interpretation would also correspond to the environment found in the *Molasse à charbon*. The lack of organic content in the *Calcaires d'eau douce et dolomie* can be explained with low sedimentation and subsidence rates in the distal part of the basin, which allowed a complete oxidation of the organic matter. This model is also supported by freshwater carbonates at different stratigraphic levels in several wells within the study area, indicating that similar depositional conditions prevailed over a relatively long stratigraphic interval.

The PLATT & WRIGHT (1992) model only requires minor changes in the depositional conditions within the existing meandering river system. The low gradient fluvial system is converted to a more swampy system only by reduced drainage rates, which could be due to a rise of the base level (i.e., rise of the sealevel in the eastern part of the Molasse Basin). This low gradient depositional environment would also allow marine transgressions into the study area at some stages. The fish faunas described by REICHENBACHER (1996) would also fit into this model. Although most modern members of the families are marine and live in temperate and tropical seas, many species are confined to freshwater and others inhabit brackish waters or enter coastal rivers.

Another possibility to explain the reduced run-off in the study area could be the increased sediment input by the prograding *Napf* alluvial fan system which could have built up a barrier just east of the study area at that time.

The depositional model also explains the reduced amounts of sediment with a grain-size above the silt fraction in the *Calcaires d'eau douce et dolomie* and *Grès et marnes gris à gypse* formations. As a result of the low gradient the coarser fraction of the bedload was deposited before entering the study area.

5.3 Aquitanian

With the onset of the Aquitanian, fluvial conditions were established again across the entire basin including its distal reaches. As in the earlier Chattian, a meandering river is the main depositional system and palustrine conditions are rare. Despite the similar lithofacies a significant change of the heavy mineral association is observed, which coincides with the Chattian/Aquitanian boundary in the western part of the study area. The high apatite content is reduced in favour of epidote and, in addition, the amount of garnet, which has been high throughout the Chattian is now found in only small amounts.

Changes in the architectural setting of the depositional system can also be inferred from well and seismic data. Instead of clearly distinguishable units of either fluvial channels or floodplain sediments, which characterized the Chattian, the sandy units are thinner and more frequently interbedded with floodplain fines, which are also of reduced thickness.

The picture of the landscape that can be drawn when all observations are put together is not that different from that of the Chattian: a meandering river system parallel to the basin axis in the area of the *Plateau Molasse* with paleoflow towards the east. The different fluvial architecture with a higher proportion of sand either reflects the progradation of the Alpine front and more proximal conditions in the study area, or an increased avulsion of the axial system, allowing the coarser fraction to be further distributed into the basin. Since many factors such as climate, tectonics, or changes in the catchment, can be responsible for the increase of avulsion (LEEDER 1999) several interpretations are possible. The cause of the change of the heavy mineral composition of the axial dispersal system could not be explained based on the data obtained during this study. The large amounts of epidote that enter the system in the Aquitanian in the eastern part of the Swiss Molasse Basin (KEMPF & MATTER 1999) are interpreted to have been derived either from Penninic ophiolites or greenschists (FÜCHTBAUER 1964).

Sediments of Aquitanian age are also found in the northernmost thrust sheet (*Seftigschwand* thrust sheet) of the *Subalpine Molasse* in the eastern part of the study area. In this thrust sheet the same heavy mineral association (high epidote, low apatite, low garnet content) is found as in the *Plateau Molasse* of the study area, suggesting that the sediments were deposited by the same depositional system (*Genfer See* dispersal system). The change from a floodplain dominated sedimentation at the base, with sedimentation rates of 0.35 m/1000 a, to coarser sediments and more abundant channels with sedimentation rates of 0.65 m/1000 a in the upper part of the section indicates the shift from distal to more proximal conditions. This northward shift of the depositional systems reflects a progradation of the corresponding alluvial fan system in the south, which in turn could be caused by the northward progradation of the Alpine thrust front. However, the fact that conglomerates are rare suggests that the thrust front and the associated alluvial fan systems had not yet reached the study area. The clast composition of the conglomerates (mainly quartzites and red and green granites) indicates that mainly crystalline rocks were exposed in the hinterland.

At the top of the Aquitanian indications of the marine transgression are found long before the complete flooding of the basin occurred. In the eastern part of the study area, eastward dipping reflectors are observed in an interval below the OMM in seismic line FR 8501 (Fig. 13). This interval clearly documents an interaction between the axial fluvial system and the marine transgression and is interpreted as a deltaic sequence. Two conclusions can be drawn from this interpretation:

a) The transgression was cyclic, interrupted by several short term regressions.
b) The transgression is diachronous along the basin axis and while the observed transgressional succession was deposited in the study area, marine conditions existed further east.

Moreover, erosion occurred during one or several phases of regression when the axial fluvial system prograded eastwards, cutting down into the deltaic sequence before the following deltaic sequence was deposited during the next transgressional cycle.

5.4 Burdigalian

The nature of the marine transgression at the USM/OMM boundary in the Swiss Molasse Basin has long been a point at issue. Here an attempt is made to merge some of the contradicting observations into one model.

As described above, at the onset of the transgression the western Swiss Molasse Basin was a very low gradient floodplain just above base level. Therefore, flooding of a large area in the distal part of the basin does not require a major sea level rise. The presence of the transgressional interval indicates that complete flooding of the basin occurred in several steps. By about 20.2 Ma ±0.1 Ma)[9] the entire basin was flooded and a narrow seaway connected the central and western Paratethys with the western Mediterranean and shallow marine conditions with strong tidal influence were maintained throughout the OMM stage.

The question whether the transgression occurred from the west or the east was also raised several times in the past with varying answers (ALLEN & BASS 1993; BERGER 1985; RIGASSI 1957; SCHLUNEGGER et al. 1997c). According to the results of this study the transgression occurred from the east in the distal part of the basin. Based on the assumption that the gradient of the basin was towards the east, a transgression from the west is very unlikely. If the sea had reached the divide of the basin from the southwest, the water would have flown eastward fol-

[9] This time estimate matches well with the observation of (SCHLUNEGGER et al. 1996) in the *Sihl* section. If an erosional gap at the base is assumed the error of the age is up to 0.5 Ma in the central part of the basin (see section 3.1.1).

lowing the gradient through a channel (or canyon) and the basin would still have been filled from the east. In addition only some erosion of the underlying sediments, but no deposition of a transgressional interval should be expected. In *Haute Savoie* the flooding occurred from the south (ALLEN & BASS 1993) which implies that a "continental divide" existed in the basin that was located somewhere southwest of the study area and north of the *Haute Savoie*.

Marine faunas are found in the southwestern part of the study area (BERGER 1985) in sediments which are dated older than *Vully 1* (*La Chaux 7* and *Mèbre 698*). They are interpreted as indication of an earlier transgression from the southwest (BERGER 1996). This interpretation has several consequences for the model. The "divide" between the eastern and western sea would have been situated somewhere between Yverdon and Berne and no meandering river system could have existed parallel to the basin axis during this time. Furthermore the source area of the meandering river system could not have been situated somewhere southwest of the study area in the Alps, but rather somewhere in the west (BERGER 1996). However, the authors interpret the sediments as remnants from earlier, short-term floodings of the basin as described in the chapter above. Furthermore the age of the sediments could appear older due to mixing with faunas from eroded underlying sediments.

Perpendicular to the basin axis the transgression is diachronous because continental sediments were laid down by prograding alluvial fans in the proximal parts of the basin while the distal parts were already flooded by the Burdigalian sea (Fig. 15).

Two of the alluvial fans/fan deltas that developed north of the Alpine thrust during the Burdigalian are preserved in the *Plateau Molasse* in the eastern part of the study area (*Guggershörnli* and *Mont Gibloux* alluvial fan). The onset of the progradation of the *Guggershörnli* alluvial fan into the *Plateau Molasse* is dated in the *Sensegraben* section at 18.6 Ma ±0.2 Ma. The position of the *Guggershörnli* alluvial fan just north of the *Subalpine Molasse* and the fact that the sediments are tectonically undisturbed[10] suggests that this fan evolved directly in front of the Alpine thrust after the formation of the northern most thrust sheet. The appearance of the first conglomerates at 18.6 Ma therefore gives the approximate time of the formation of this northernmost thrust in the eastern part of the study area. Furthermore, the high abundance of flysch clasts (80 % flysch clasts and less than 10 % carbonate clast) indicates that the *Guggershörnli* fan was either built by a small fluvial system that had its catchment area directly in the frontmost thrust sheets and the *Gurnigel flysch*, or further in the south where the carbonates of the *Klippendecke* were mostly covered by flysch at that time. From the erosional remnants of the *Guggershörnli* alluvial fan, it can not be decided, whether the movement at the northernmost fault stopped before or shortly after the fan started to build up. Movements shortly before are documented by the Fall anticline, which shows deformed marine sediments directly below the conglomerates.

5.5 Langhian and later

No sediments of the *Upper Freshwater Molasse* exist in the study area. Only some distal remnants are found within synclines of the Jura fold-and-thrust belt, but their deposition within the study area can be inferred for several reasons.

It is commonly accepted that the sediment transport occurred from east to west during the deposition of the OSM (BÜCHI & SCHLANKE 1977). If this is true, the subsidence rates must have been at least as high in the west as in the east, otherwise the gradient would have changed and the sediments would have been transported towards the east. This should have resulted in the accumulation of at least the same amounts of sediment during a similar time interval in the west as in the east, even though no sediments younger than Langhian are found in the western part of the Swiss Molasse Basin.

6 Summary and Conclusions

Three different drainage systems delivered their detritus into the Molasse Basin from Rupelian to Langhian times (i.e. during 20 my) to the Alpine foredeep. The fluvial system parallel to the basin axis (*Genfer See* dispersal system) was the most important. The location of its source area is still unknown, but was probably situated southwest of the study area. The other fluvial systems entered the basin perpendicular to the basin axis from the southern and the northern margin as radial fluvial systems. The southern radial system consisted of rivers that had their catchment area in the advancing Alpine Nappes, and which formed partly large detrital cones (e.g., *Mont Pèlerin*) when entering the Molasse Basin. During marine conditions in the basin, the radial fluvial systems persisted and fan deltas (e.g., *Guggershörnli*) were deposited.

During the Rupelian time a narrow marine basin existed in the southern part of the study area. This changed in the late Rupelian when the Molasse Basin widened significantly towards the north and a meandering river system was established in its distal part. It swept across a very low gradient plain close to base level during deposition of the USM in the Chattian and Aquitanian times. Palustrine conditions indicate a reduced drainage at some stages of the USM, possibly triggered by sea level changes and/or prograding alluvial fans in the central or eastern Molasse Basin. Shallow marine conditions were established again during the following OMM stage (Burdigalian). The complete flooding and opening of the E-W OMM seaway occurred at about 20.2 Ma within a relatively short time interval, connecting the central and western Paratethys with the western Mediterranean Sea across the Rhone and Swiss Molasse Basin. Perpendicular to the basin axis, the marine transgression is diachronous because of the interaction with the radial dispersal systems at the southern

[10] Whereas the sediments just a few 10s of metres below are folded (SCHMID 1970).

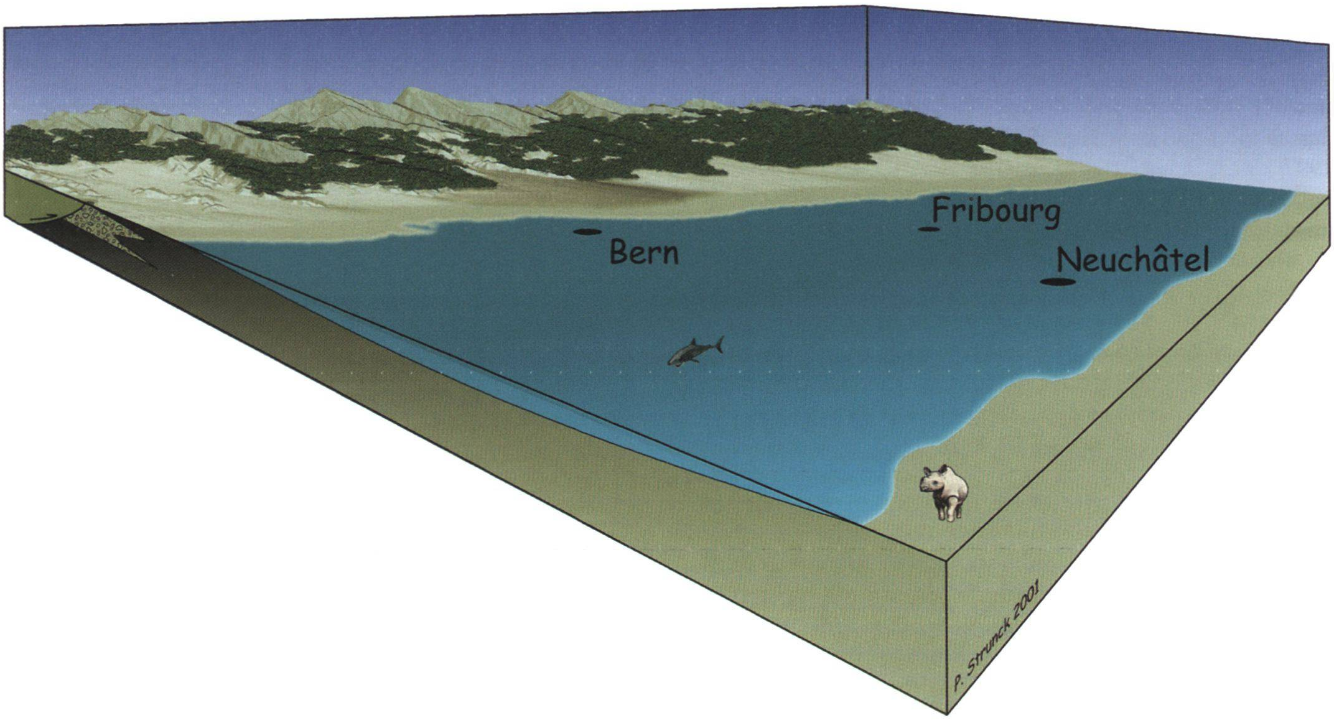


Fig. 15. Reconstruction of the depositional environment during the Burdigalian. View towards the south. A shallow sea fills the distal part of the basin. Close to the southern boundary of the basin, terrestrial deposition is continued by the radial fluvial systems.

margin of the basin. While continental facies conditions prevailed in the proximal parts of the basin dominated by prograding alluvial fans, the distal parts were already flooded by the Burdigalian sea.

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