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Magnetostratigraphic chronology, mammalian faunas, and stratigraphic evolution of the Lower Freshwater Molasse, Haute-Savoie, France

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ABSTRACT

Across the broad spatial and temporal expanse of the Alpine foreland basin, reliable correlation and synthesis of diverse stratigraphic, structural and paleontological data has been thwarted by the absence of a well defined chronologic framework. The Lower Freshwater Molasse of the Fornant and Findreuse sections in Haute-Savoie with a combined stratigraphic thickness of ca. 400 m yielded 31 vertebrate bearing horizons, 18 of which contained rich and diverse faunas representing the most complete micromammal faunal record of the Western Molasse Basin. Magnetostratigraphic dating of these sections provides a greatly improved temporal calibration of the depositional and faunal record between 26 and 21 Ma in this part of the Alpine foreland. Time-transgressive, lacustrine deposition began at ~26 Ma. During the subsequent 0.5 Ma of rapid subsidence, locally sourced, braided rivers flowed eastward toward the proximal foreland where lacustrine conditions prevailed. A similar facies geometry prevailed between 23.8 and 24.2 Ma, and both may be a response to Alpine thrust loading. In between those episodes, fluvial conditions prevailed with meandering rivers transporting alpine detritus northwards into the basin. Lacustrine and ensuing playa conditions during late Chattian and early Aquitanian times may also correspond with a climatic change from moist to more arid and cooler conditions inferred from oxygen isotopes and plant macrofossils associated with the Oligo-Miocene boundary. The new chronologies allow a provisional calibration of the boundary ages of 6 assemblage zones: some of which can be specified to < 0.1 Ma and most of which require some modification of previously used assemblage-zone boundary ages. Assemblage zones are shown to vary in duration by at least 3-fold and may have durations of < 200–300 Kyr.

RÉSUMÉ

Nos connaissances sur l'histoire de l'avant-pays alpin se fondent sur de nombreuses données stratigraphiques, paléontologiques et structurales; mais la synthèse de toutes ces données était jusqu'ici limitée par l'absence d'un cadre chronologique bien défini. Ce travail est un premier pas vers l'établissement d'une telle chronologie. La Molasse d'eau douce inférieure (USM) affleure sur une épaisseur d'environ 400 m dans les profils de la Findreuse et du Fornant (Haute-Savoie). On y a trouvé 31 horizons à vertébrés, parmi lesquels 18 contiennent une faune riche et diversifiée, ce qui représente la succession d'assemblages à micromammifères la plus complète de tout le bassin molassique occidental. La datation magnétostratigraphique de ces deux profils permet de retracer la succession des faunes et des milieux de dépôt dans cette partie de l'avant-pays alpin entre 26 et 21 Ma. La sédimentation est tout d'abord lacustre et débute il y a ~ 26 Ma. Puis, pendant 0.5 Ma, la subsidence est rapide et des rivières tressées transportant des matériaux d'origine locale coulent tout d'abord vers l'E, en direction de l'avant-pays proximal où règnent des conditions surtout lacustres; un système identique s'installe à nouveau entre 23.8 et 24.2 Ma et cela pourrait être une réponse à la surcharge de l'avant-pays due aux chevauchements alpins. Entre ces épisodes, la

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sédimentation est fluviale, principalement dirigée du S vers le N et les matériaux transportés sont d'origine alpine. Des lacs, puis des playas, occupent la région durant le Chattien supérieur et l'Aquitainien inférieur à la suite d'un changement climatique qui tend à davantage d'aridité et correspond à une certaine baisse de la température, ce qu'indiquent par ailleurs les macrofossiles végétaux et les résultats des analyses des isotopes stables de l'oxygène. La nouvelle chronologie permet d'estimer l'âge des limites entre 6 zones d'assemblage de mammifères, parfois avec une précision de < 0.1 Ma. On constate ainsi que ces zones ont des durées très variables, allant de $\sim 200\,000$ – $300\,000$ ans à 1 Ma.

ZUSAMMENFASSUNG

Das in grossen Zügen bekannte Bild der Geschichte und des Baus des nordalpinen Molassebeckens beruht auf einer Fülle stratigraphischer, paläontologischer und struktureller Informationen. Ungenügende chronostratigraphische Kontrolle bildet das Haupthindernis einer Synthese dieser Daten. Die vorliegende Arbeit ist ein Schritt zu einer detaillierten Chronostratigraphie.

Die in den Profilen des Fornant und der Findreuse (Haute-Savoie) aufgeschlossene Untere Süsswassermolasse weist eine stratigraphische Mächtigkeit von ca. 400 m auf. Hier wurden 31 Horizonte mit Säugetierresten gefunden, wovon 18 mit reicher und diverser Kleinsäugerfauna, welche die vollständigste Faunenabfolge des westlichen Molassebeckens darstellt.

Die magnetostratigraphische Datierung dieser Profile ermöglicht für die Zeit von 26–21 Ma eine genaue Kalibrierung der faziellen und biostratigraphischen Entwicklung in diesem Teil des Molassebeckens. Die heterochronen lakustrischen Sedimente setzten um ca. 26 Ma ein. Während der folgenden 0.5 Ma, die durch hohe Subsidenz geprägt waren, transportierten verflochtene Flüsse Sedimentschutt lokaler Herkunft (aus dem Gebiet des heutigen Jura) in das immer noch von lakustrischen Milieus geprägte Vorland. Ähnliche Schüttungs- und Ablagerungs-Verhältnisse herrschten auch von 23.8–24.2 Ma; die beiden identischen Situationen sind möglicherweise das Ergebnis der Auflast der alpinen Schubmasse. Zwischen diesen beiden Episoden herrschten fluviale Bedingungen mit mäandrierenden Flüssen, die alpines Material von S gegen N ins Vorland verfrachteten. Die im späten Chattian / frühen Aquitanian beobachtete Ablösung lakustrischer Verhältnisse durch ein Playa-Milieu dürfte den Wechsel von feuchtem zu aridem und kühlerem Klima widerspiegeln, der aufgrund von Sauerstoff-Isotopendaten und Makropflanzenresten postuliert worden ist.

Die Magnetostratigraphie ermöglicht die absolute Datierung von 6 Säugetierzonen, z. T. auf < 0.1 Ma genau. Ihr zeitlicher Umfang ist höchst unterschiedlich und variiert von < 200 – 300 Kyr bis zu 1 Ma.

1. Introduction

The Molasse Basin on the northern side of the Alps is a classical foredeep whose depocenter migrated across the foreland in response to the orogenic activity in the adjacent Alps. In order to understand the history of the Molasse Basin, it is therefore necessary to consider the sequence of deformational events in the Alps, as well as the stratigraphical and facies relationships in the basin. Sedimentological studies carried out over the past decade have greatly furthered the understanding of the facies relationships and depositional processes of both the Marine and Freshwater Molasse Groups (e.g. Bürgisser 1980; Homewood & Allen 1981, Berger 1985, Fasel 1986, Diem 1986, Keller 1989, Schoepfer 1989). Until present, however, the scarcity of biostratigraphically relevant fauna and flora has limited the reliability of geophysical models and any attempted reconstructions of the basinal history (e.g. Büchi & Schlanke 1977, Matter et al. 1980, Homewood et al. 1986, Pfiffner 1986).

More than 30 years ago, Rigassi (1957a) suggested that the Molasse in the Geneva, Haute-Savoie and Ain area should be studied in detail because this area could provide valuable geological information, including a reference framework for the understanding of the entire perialpine Molasse of Switzerland. Indeed, in this region, the diagenesis is less pronounced than in the Molasse of the Swiss Plateau, deformation is moderate, and

fossils are relatively abundant and well preserved. Moreover, the geology is well known due to excellent regional studies, several oil wells, and related seismic data (Favre 1867, Maillard 1889, 1891, Douxami 1896, Doncieux 1932, Gignoux & Moret 1939, Michel & Caillon 1957, 1960, Rigassi 1957a,b, 1977, Wagner & Wellhäuser 1966, Donzé & Enay 1972, and unpubl. documents).

Initial studies in Haute-Savoie of the Findreuse and Fornant river sections revealed nearly continuous exposures of the Lower Freshwater Molasse (USM) and an abundance of mammalian fossils (Jung 1982). Both sections were measured by D. Rigassi and a simplified version of his detailed logs was published in Weidmann (1982). These sections yielded numerous fossiliferous levels which were particularly rich in micromammal and charophyte remains. These levels have been repeatedly exploited over the past 10 years. At present the Fornant and Findreuse river sections represent the most complete and well documented micromammal sequences of the western Molasse. They contain several reference faunas for assemblage zones of the Lower Freshwater Molasse (Engesser & Mayo 1987). However, the absence of a reliable chronologic framework makes correlation with marine sequences and even with other European continental sections difficult.

In order to resolve some of the problems resulting from the lack of reliable chronologic constraints, magnetic polarity stratigraphies have been created for the two highly fossiliferous sections in Haute-Savoie. In addition to improving the chronological control on the faunal, depositional and tectonic history recorded by the Lower Freshwater Molasse adjacent to the western Alpine fold- and thrust-belt, these new data allow comparison of the local mammal biozones with the established marine biozonations, and they permit a temporal calibration of the facies response in this part of the basin to tectonic events in the Alps and to climatic changes during the late Oligocene/early Miocene.

2. Geological setting

The studied sections are exposed along the Findreuse and Fornant rivers, located ca. 30 km SW of Geneva in Haute-Savoie, France (Fig. 1). The present-day width of the Molasse Basin is restricted in this area, measuring approximately 30 km. Here, the basin is bounded to the E by the Alpine frontal thrusts, and its feather-edge W margin is situated within the Jura. The Molasse Basin in this area is cut by several NW-SE trending left-lateral strike-slip faults, such as the Vuache fault shown on Figure 1.

The Findreuse and Fornant sections are situated on this feather-edge margin of the Molasse Basin in the synclines of Bellegarde-Seyssel and Rumilly, respectively (Donzé & Enay 1972), which are separated by the Jura anticline of the Gros Faoug (Fig. 1). The Lower Freshwater Molasse Group (USM) in this area, as well as in the other parts of the basin, comprises the "Chattian" and "Aquitanian" units. In the absence of formal units of formation rank, stage terms are used in a lithostratigraphic sense.

In the study area, the Lower Freshwater Molasse rests with unconformable contact on Lower Cretaceous substratum. However, W of the Rhône river, Upper Marine Molasse lies directly on the Mesozoic limestones. As a result of the general thinning of the Molasse clastic wedge towards the north and west, the Lower Freshwater Molasse decreases in thickness from > 1000 m near the Alpine front to < 400 m in the Fornant

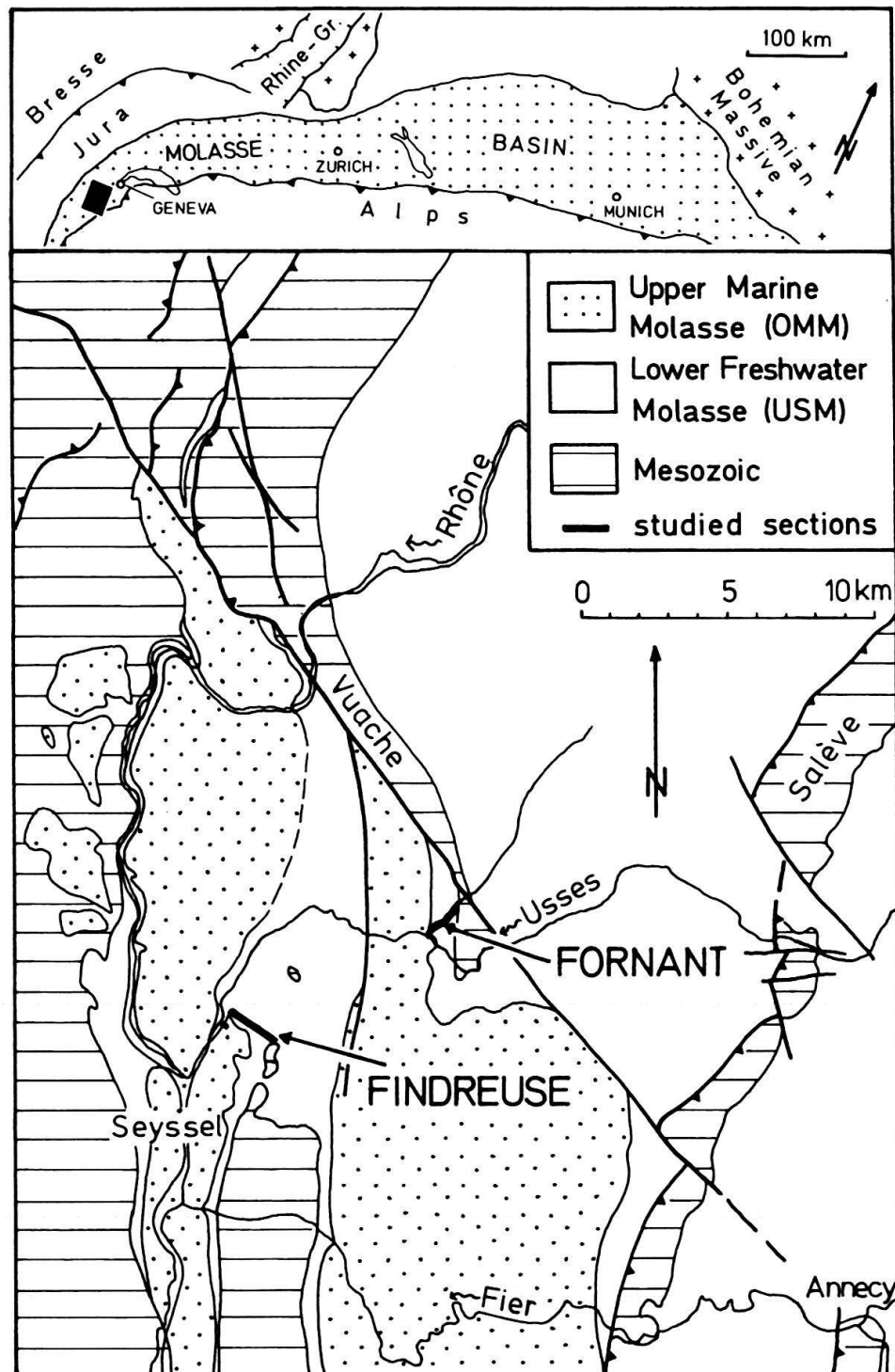


Fig. 1. Schematic geological map of the Molasse Basin between Geneva and Annecy with location of the studied sections (modified after Rigassi, unpubl. data). Inset map shows the location of the study area within the north Alpine Molasse Basin.

section and < 300 m in the Findreuse section, which lies within 5 km of the pinch-out (Fig. 1). These condensed sections represent the distal, predominantly fine-grained facies of the USM that were deposited mainly in lacustrine and palustrine environments with

a relatively rich fauna and flora and were favourable for the accumulation and preservation of these biota.

3. Methodology

3.1 Magnetostratigraphy

Because of the extensive, prior paleontological and stratigraphic studies in this region, the magnetic sampling sites were located (Fig. 1) with respect to the previously created stratigraphies for the Fornant and Findreuse sections (Rigassi unpubl., Weidmann 1982). Magnetic sites were collected every 2–10 m, depending on available exposures and appropriate lithologies (gray to tan mudstones, siltstones, and freshwater carbonates). Three to four oriented samples were collected at each sampling site, such that a total of ~ 500 specimens was obtained.

Ten pairs of specimens were selected from the two sections as pilot specimens for demagnetization analysis. The criteria for selection were that (1) various sample lithologies would be represented and (2) nearly the entire stratigraphic extent of the section would be spanned. The pilot specimens were subjected to stepwise, thermal demagnetization in $\sim 100^\circ\text{C}$ steps up to 400°C and then 50°C steps up to 600°C .

Strikingly different behaviors emerged during this demagnetization process (Figs. 2 and 3). Both initial and final magnetic intensities varied by as much as 100-fold between specimens. Whereas a few specimens (e.g. FI 305A and B, Fig. 2) were relatively strongly magnetized ($\sim 10^{-5}$ emu/cc) and had lost less than 10% of their initial intensity by 600°C , other specimens were weakly magnetized initially ($\sim 1-3 \times 10^{-7}$ emu/cc) and plummeted to near the noise level of the cryogenic magnetometer by $100-200^\circ\text{C}$. These

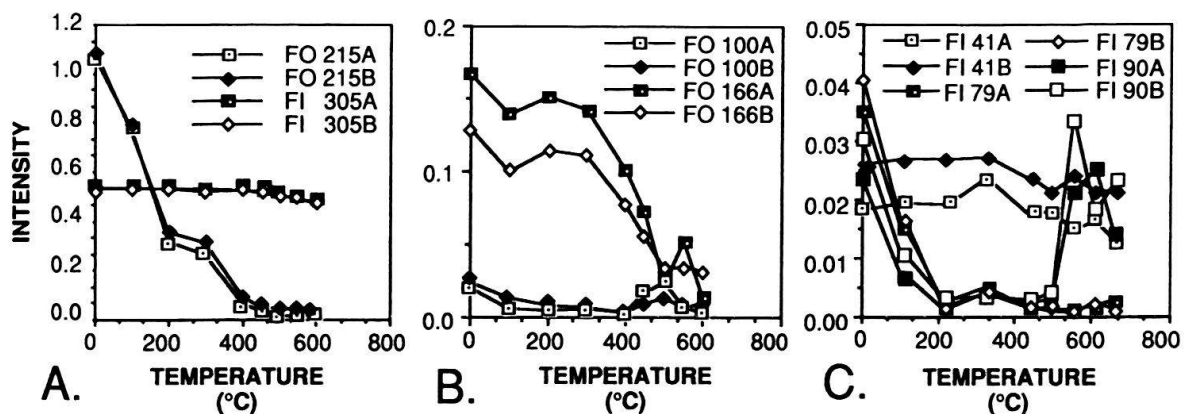


Fig. 2. Changes in the intensity of magnetization revealed during step-wise thermal demagnetization (vertical scale in units equal to 10^{-5} emu/cc). Large variations between sites in the strength of the initial remanence and in the response to thermal demagnetization are observed, but each pair of specimens from a site exhibits comparable behaviour. A) Specimens dominated by a hematite signal (FI 305) versus ones with a strong viscous overprint and a predominantly magnetite carrier (FO 215). B) FO 166 shows removal of a normal overprint below 200°C and rapid loss of intensity up to 500°C , whereas FO 100 is much weaker, shows a steady decay to 400°C , and reveals increased intensity due to oxidation of magnetic minerals during heating above 450°C . C) Comparison of hematite-dominated specimens (FI 41) with those showing a large viscous overprint (FI 79, FI 90), some of which exhibit extensive alteration and oxidation above 500°C .

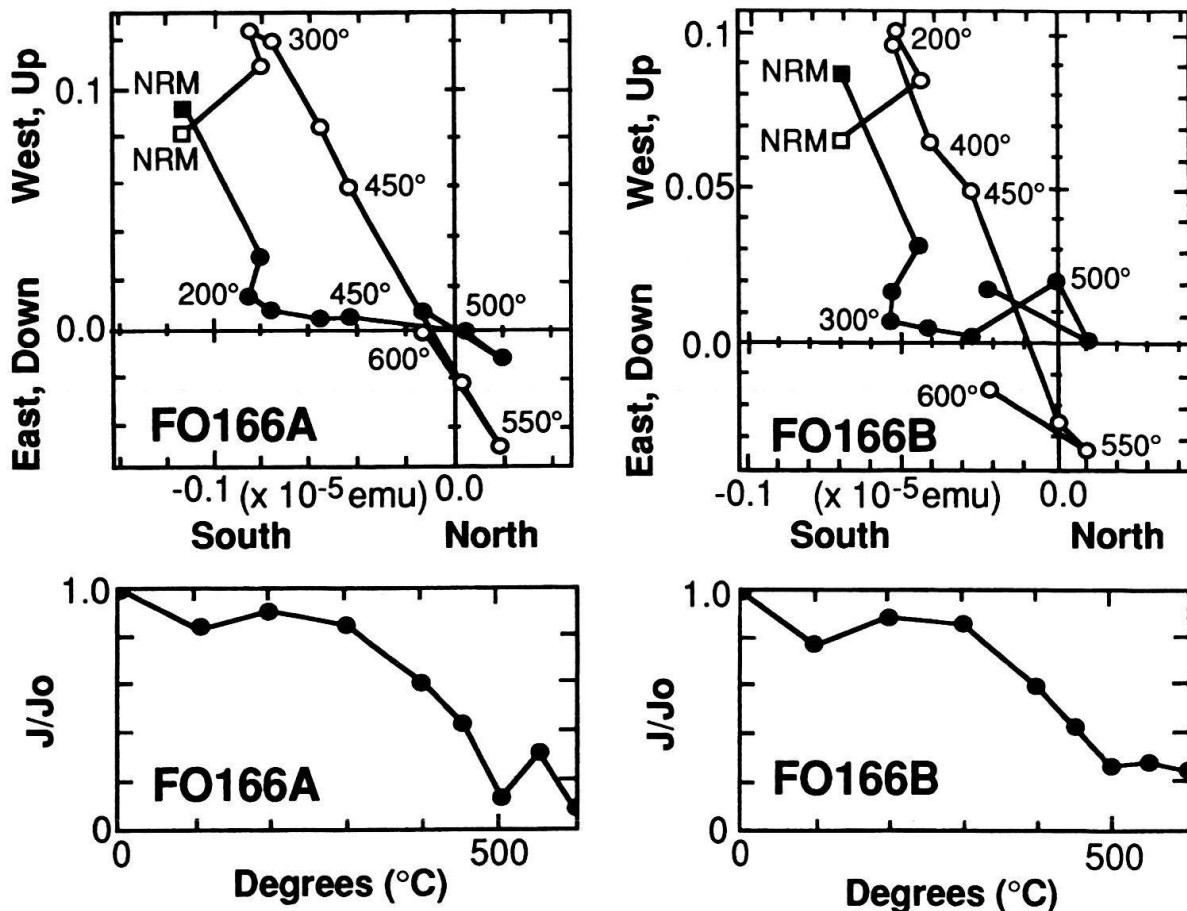


Fig. 3. Demagnetization plots (top figures) and intensity-loss (J/J_0) plots (lower figures) for specimens FO 166A and B. These specimens show removal of a viscous overprint below 200 °C, they exhibit reversed characteristic remanence directions between 300 °C and 450 °C, and, above 500 °C, they show either a normally magnetized hematite component or a newly acquired, nonsystematically oriented, high-temperature component.

latter specimens yielded generally inconsistent directional data, whereas the former group yielded coherent and generally invariant magnetic directions.

After an initial decrease at 100 °C, most of the pilot specimens increased in intensity up to 200–300 °C (Figs. 2 and 3). Reversely magnetized sites illustrate this behavior most clearly. A concurrent steepening of the inclination vector usually occurs during this intensity increase and is interpreted to represent the removal of a normal polarity overprint. At higher temperatures, these specimens show a steady decrease in intensity, although several show a secondary peak at ~500–550 °C and only minor additional decreases up to 600 °C (Fig. 2).

We interpret these demagnetized data as representing up to three magnetic components. Below 200 °C, a viscous normal overprint is evident in many specimens. Magnetite appears to carry the primary depositional remanence in most specimens, although in those specimens for which there is no significant intensity decrease below 600 °C (FI 305 A and B; Fig. 2), hematite is a more probable magnetic carrier. In other specimens, 2–10% of the total remanence may be carried by hematite, which is possibly of a post-depositional origin.

Despite both the somewhat variable behavior during demagnetization and the strong differences in magnetic intensity, a characteristic remanence direction can be defined within a 250–450 °C thermal window (for all sufficiently strongly magnetized specimens). Consequently, the measured directions at 200, 250, 300, 350, and 400 °C were used to delineate the remanent magnetic vector for all remaining specimens. The coherence of the specimen data for each site was assessed using Fisher (1953) statistics. Sites were classified as “Class I”, if Fisher $k > 10$; “Class II”, if $k < 10$, but the site showed an unambiguous polarity; and “Class III”, if the polarity was indeterminate. The mean inclination and declination of Class I and II sites were used to calculate the virtual geomagnetic pole (VGP) for each. The latitude of the VGP formed the basis for the local magnetic polarity stratigraphy (MPS). An alpha-95 error envelope was calculated and plotted for each VGP latitude.

Antipodal directions displayed by stereonet plots of the Class I data (Fig. 4) indicate that these data pass a reversal test (McElhinny 1973). Within the uncertainties of these data, no statistically significant rotation can be defined. Because of the gentle dips of the strata through the Findreuse section and the rather uniform dip of the strata in the Fornant section, the magnetic data do not pass a fold test. The successful reversal test and the observation that, among the numerous, juxtaposed magnetozones uncovered by this sampling program, magnetic polarity is not controlled by either lithology or alteration indicates that reliable characteristic remanences have been delineated for these sites and that these directions are depositional or very early post-depositional in nature.

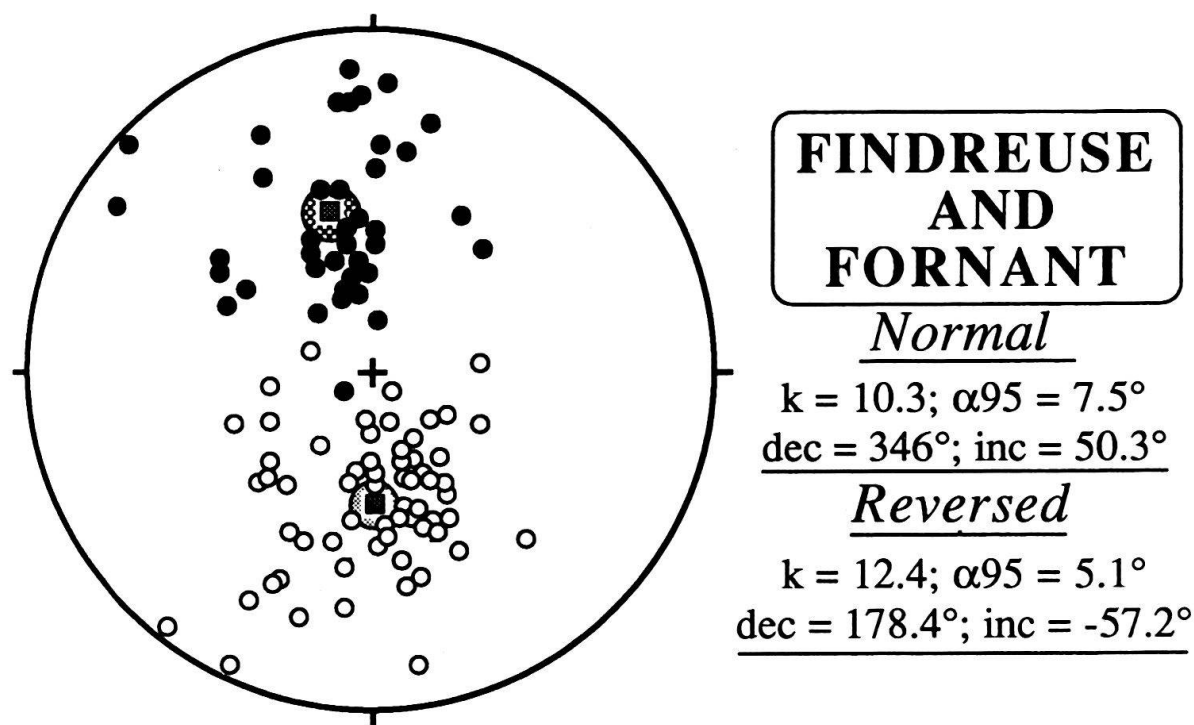


Fig. 4. Stereonet plot of Class I normally (filled circles, lower hemisphere) and reversely (open circles, upper hemisphere) magnetized data from both the Findreuse and Fornant sections. The generally antipodal mean directions display no significant tectonic rotation.

3.2 *Micromammals*

Two facies that are prone to contain micromammals are dark coloured silty or argillaceous marl containing molluscs, which were deposited in a palustrine environment (= facies E 1 of Reggiani 1989, p. 347), or coarse-grained sandstone and intraformational clay-pebble conglomerate occurring as basal lags in fluvial channels. All beds of these facies were systematically sampled in both sections. Subsequently, the samples were dried, and then disaggregated and washed through a 0.5 mm sieve. The dried residue coarser than 0.5 mm was then studied under a binocular microscope, and the microfossils were hand-picked. The vertebrate remains, including bones and more or less fragmented teeth, are normally associated with other faunal (molluscs, ostracods) and floral remains (charophyte gyrogonites, fruits, seeds, wood and sometimes leaves).

All the beds which provided vertebrate remains were re-sampled several times with the total amount of material collected varying from 50 to 1000 kg per locality. The often rather difficult access to the sample localities and the painstaking labour retrieving the material ultimately limited the amount collected. Because field work was carried out over a period of more than 10 years the samples "Fin" and "For" are not numbered in stratigraphic order, but rather in consecutive order of collection. The vertebrate collections are stored in the museums of Basel (NMB) and Lausanne (MGL) and at the Département des Sciences de la Terre of the University of Lyon (FSL).

In this study, we use the mammal biozonation of Engesser and Mayo (1987), which was established in the western Molasse Basin of Switzerland and Haute-Savoie. This scheme recognises a succession of 18 assemblage zones that are defined by reference faunas. It is based on faunas from more than 100 localities. In contrast to previous mammal biozonations of the Molasse, whole faunas were used whenever possible. The individual fossil groups are, of course, of different biostratigraphic value: the theriodomyids, eomyids, cricetids, lagomorphs, and also certain artiodactyls turned out to be the biostratigraphically most important groups. Each assemblage zone is characterised primarily by the evolutionary level of its faunal elements and next by the appearance or disappearance of taxa (first and last record).

The regional zonation of Engesser & Mayo (1987) has a much higher resolution than the MP and MN zonations (Schmidt-Kittler 1987, Mein 1975, 1989, Fahlbusch 1991) which are valid for the whole of Europe. The MP and MN zonations are based only on the evolutionary level of faunas and are unrelated to lithostratigraphy. The fact that the MP and MN zonations were defined on the basis of reference faunas from all over Europe is another drawback which becomes evident when a fauna from, for example, Central Europe has to be calibrated within a MN zone established in Spain and the two faunas have no species in common. Another disadvantage of the MP and MN zonations is that many of the reference faunas used come from fissure fillings in palaeokarst. Although these faunas are often extremely rich, it always remains uncertain whether they represent a mixture of different zones or not. The high variability found in such faunas is often explained by the large number of mammal remains, but it is certainly possible that the variability reflects the long time span of filling of the fissure. Thus the MP and MN zonations only represent a first step towards a more refined mammal zonation which, in our opinion, should be derived from a number of detailed regional zonations.

The paleontological results will be presented as faunal lists in sections 4.1.2 and 4.2.2, and they are summarised in Figure 9. The lists contain the information on all the fossil remains, including tiny tooth fragments, if at least the order or the family could be determined. However, the number of teeth listed refers only to mammal teeth (incl. the identified tooth fragments).

Almost all the samples contain gastropod remains. Gastropods were only mentioned in the faunal lists, if especially well preserved specimens were found.

For the identification of the age, only paleontological evidence was used. In some samples, the mammal remains were not sufficient for an identification of the age. In such cases, it would have been possible to indicate an age based on the lithostratigraphical position of the locality within the section. In order to avoid circular reasoning, however, this was not done.

The charophyte biozonation shown on Figures 5 and 6 is that of Riveline (1984) adapted to the Molasse floras by Berger (1983, 1986).

4. Results

4.1 *Findreuse section*

4.1.1 Stratigraphy

An almost continuous section of Lower Freshwater Molasse (USM), measuring 270 m in thickness, is exposed along the Findreuse river, a small west-flowing tributary of the Usses river (Fig. 1). The USM lies unconformably on Lower Cretaceous ("Urgonian") karst substratum and, locally, on Eocene continental quartzarenites and ferruginous shales ("Sidérolithique") which mainly fill depressions in the erosional relief and karst holes. This erosional unconformity represents a major time gap, including the Paleocene and Eocene (except for the local Sidérolithique) and portions of the Cretaceous and Oligocene. The USM is transgressively overlain by the dominantly sandy Upper Marine Molasse.

In Haute-Savoie, the USM comprises an alternating sequence of five basic rock types: sandstone, siltstone, marl, carbonate, and gypsum. These strata exhibit a broad variety of sedimentary structures and a variable faunal and floral content. Vertical facies analysis enabled Homewood et al. (1989) to subdivide the 270-m-thick USM of the Findreuse section into six units representing different depositional episodes as shown on Figure 5.

The basal lacustrine limestone unit measuring 20 meters is the equivalent to the "Calcaires de Grilly" of the local terminology (Michel 1965, Rigassi 1957b). It contains a basal conglomerate layer made up of rounded clasts derived from the underlying Urgonian limestone and is followed by a sequence of grey marls, siltstones and beige lacustrine limestones. They were subject to episodic, but extensive pedogenesis as revealed by the investigation of outcrops some 5 km SE of the Findreuse by Hornisberger (1989).

The basal lacustrine limestones are overlain by a 65-m-thick succession dominated by erosively based and frequently amalgamated cross-bedded sandstones. The pebbles are

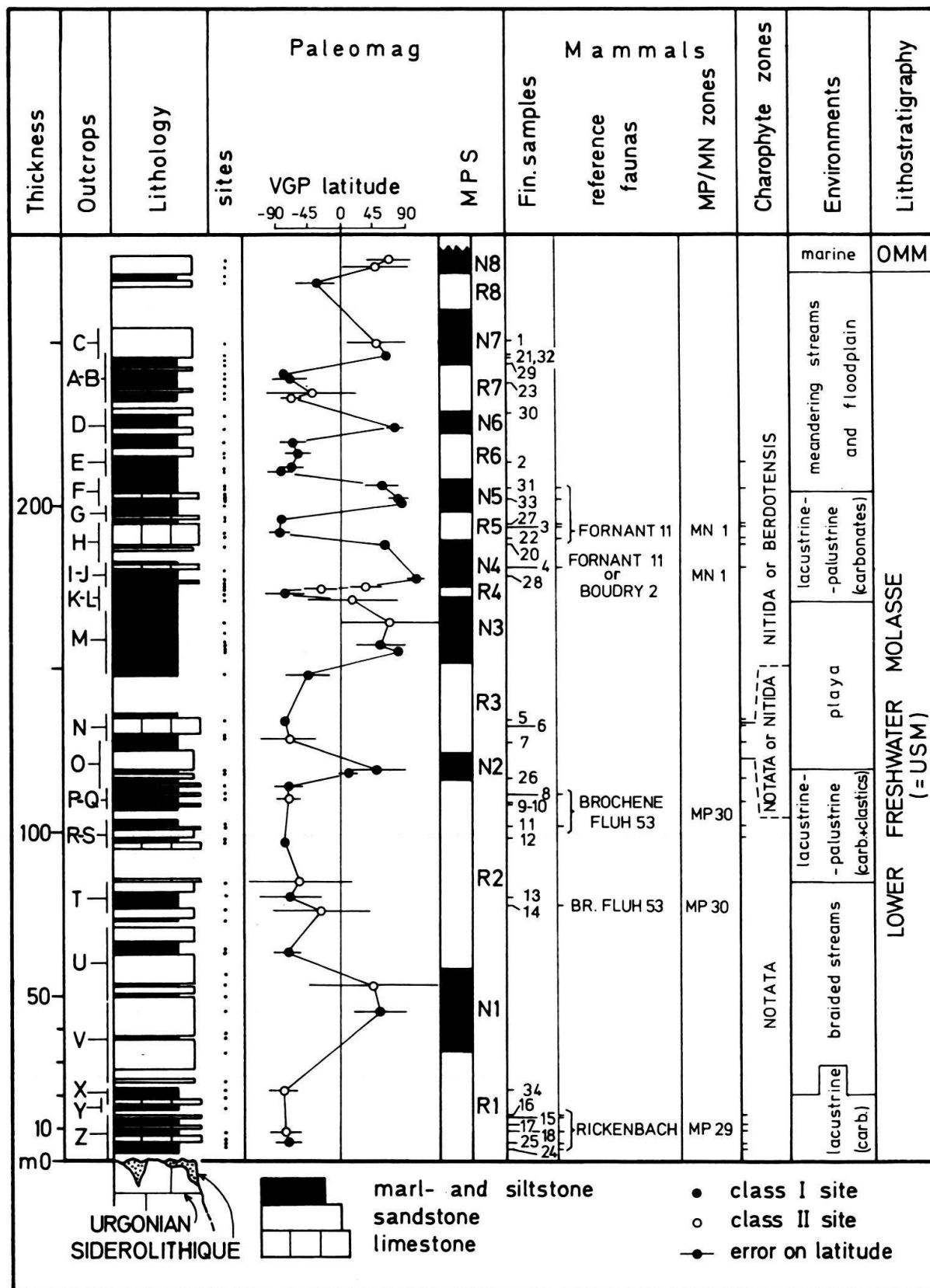


Fig. 5. Schematic log of the Findreuse section showing magneto- and biostratigraphic data and inferred depositional environments. Letters A-Z refer to location map published by Weidmann (1982, fig. 7). Section above ca. 255 m (top USM/base OMM) was measured and sampled on the slope above R. N. 92 (approx. coord. 872.1/115.8).

mainly Lower Cretaceous limestones which indicate a western source out of the area which is now the Jura, rather than an Alpine origin. The presence of an ultrastable heavy mineral assemblage (M. A. Mange, pers. comm.) resulting from multiple reworking of these minerals into the Sidérolithique and from there into the Molasse supports such an interpretation. According to Homewood et al. (1989), this sandy succession results from deposition by braided streams. The symmetrical coarsening-, and fining-upward trends of this unit indicate that initial progradation of the fan was followed by fan retreat.

The fluvial series is succeeded by a lacustrine and palustrine sequence of clastic strata and limestones, subdivided by an intervening gypsiferous interval into a lower and upper unit measuring about 35 m each. According to Reggiani (1989), the limestones form m-thick, shallowing upward cycles. A thin layer with marl intraclasts representing the transgression of the lake is often found at the base of the cycle. It passes upwards into argillaceous white to yellow and often dark grey to black packstones topped by a paleosol (Reggiani 1989). The abundance of charophyte gyrogonites, freshwater ostracods and gastropods clearly indicates a lacustrine depositional environment. In addition to this assemblage, the dark coloured packstones contain bones and teeth of micromammals, plant debris, fish and reptile bones and insect remains, suggesting a palustrine environment. The characteristic succession of the different facies in the cycle reveals that the rapid transgression led to an initially shallow, well-oxygenated lake (argillaceous limestones) which became progressively less deep with deposition of a peaty limestone facies until final emergence (Reggiani 1989).

The clastic strata of this lacustrine/palustrine succession are mainly dm- and more rarely m-thick, fine- to medium-grained sandstones which also form small shallowing upward cycles up to several metres thick. The sequence of sedimentary structures with micro-hummocky cross-bedding, overlain by symmetrical and asymmetrical wave ripples and flat lamination in the upper part was regarded by Reggiani (1989) to be indicative of a shallowing upward nearshore lacustrine sequence. Pedogenic features such as caliche nodules and rootlets in the uppermost part of many cycles indicate frequent periods of emersion.

The approximately 50-m-thick evaporitic sequence separating the lower unit from the upper lacustrine-to-palustrine unit consists mainly of grey and varicoloured silty dolomitic marls with rare dolomite and black siltstone beds containing the terrestrial gastropod *Helix*. The marls are criss-crossed by satin spar veins and also contain small rosettes of discoidally shaped gypsum crystals, as well as some gypsarenite beds. The ultrastable heavy mineral suite found in this unit indicates that the detritus was derived from a western source (present-day Jura Mountains), whereas in the underlying lacustrine/palustrine unit the heavy mineral composition reveals an Alpine source (M. A. Mange, pers. comm.). The clay mineral suite in the gypsiferous unit consists mainly of corrensite with lesser proportions of kaolinite, smectite, illite, and illite/smectite (Mujito 1981). Corrensite is a regularly interstratified smectite/chlorite clay mineral which forms under evaporitic conditions (Millet 1970). The association of dolomite and primary gypsum in a dominantly muddy sequence suggests low relief and evaporitic conditions typical of a playa depositional environment. The regressive trend of the facies in the dolomite beds was interpreted by Reggiani (1989) to be the result of fluctuating levels of closed lakes in an arid climatic regime.

The Lower Freshwater Molasse of the Findreuse section ends with ca. 65 m of clastic deposition, consisting of medium-grained pebbly sandstones with erosive bases and trough cross-bedding. A basal lag of intraformational clay pebbles is often observed on the scoured surfaces. Thin beds of non-erosive, fine-grained sandstones alternate with varicoloured heterolithic intervals consisting of siltstones and marls, which contain caliche nodules and rootlets. These facies represent meandering stream, crevasse-splay, and floodbasin deposits. The heavy mineral assemblage (M. A. Mange, pers. comm.) reveals an Alpine origin for these rivers.

The base of the overlying Upper Marine Molasse (OMM) is marked by a transgressive conglomerate with bored cobbles and pebbles, oysters, shark teeth, and other marine macro- and microfossils. The OMM, which was not further investigated in this study, consists of frequently cross-bedded glauconitic sandstones alternating with thinner siltstone and rare shale beds. A strong tidal influence in the OMM in the study area was demonstrated by Meylan (1982). The material is derived from the Alps according to the heavy mineral studies by Mange (pers. comm.).

4.1.2 Paleontology

A total of 34 levels were sampled for paleontological investigations, of which 22 contained vertebrate remains. Mammal and fish remains are most abundant, fragments of turtles, crocodiles and lacertilia occur more rarely, and amphibian remains were only exceptionally found. However, only the following 14 levels delivered determinable mammal teeth which allowed dating (Fig. 5).

Findreuse 2

material: 1 tooth fragment: Eomyid cf. *Rhodanomys schlosseri* Depéret & Douxami. Characeae.
 age: Probably assemblage zone of Fornant 11, MN 1.
 remarks: The only mammal remain of this locality is a fragment of an eomyid milk tooth, of which the identification is difficult.
 literature: Engesser & Hugueney (1982).

Findreuse 3

material: 11 isolated teeth
 Erinaceidae indet.
Paratalpa sp.
Rhodanomys schlosseri Depéret & Douxami
Eucricetodon gerandianus (Gervais)
Plesiosminthus myarion Schaub
Piezodus sp.
 non-mammals: Crocodilia
 Pisces
 Characeae
 age: Assemblage zone of Fornant 11, upper part of the zone MN 1.
 remarks: With the species *Rh. schlosseri*, documented by 5 teeth, the fauna of Findreuse 3 can safely be calibrated within the zone of Fornant 11.
 literature: Engesser & Hugueney (1982), Engesser (1990)

Findreuse 4

material: 1 molar
Plesiosminthus myarion Schaub
 Characeae

age: Assemblage zone of Boudry 2 or Fornant 11, MN 1.
 remarks: This M2 shows a double protoloph, and therefore certainly belongs to *P. myarion*. This species is known only from the earliest MN1.
 literature: Engesser & Hugueney (1982), Engesser (1987).

Findreuse 5

material: 1 tooth fragment
 Lagomorpha indet.
 Characeae
 age: Not older than the assemblage zone of Küttigen, MP 30.
 Literature: Engesser & Hugueney (1982).

Findreuse 6

material: 1 molar, few tooth fragments
Eucricetodon sp.
 Lagomorpha indet.
 non-mammals: Pisces
 Gastropoda
 Characeae
 age: Not older than the assemblage zone of Küttigen, MP 30.
 remarks: The M2 of *Eucricetodon* looks very much like that of *E. collatus*. With only one tooth, this species cannot be identified safely. However, a maximum age can be indicated because in the Molasse the lagomorphs occur for the first time in the zone of Küttigen (Fig. 9). The teeth are conspicuously rolled.

Findreuse 7

material: 4 tooth fragments
Rhodanomys sp.
 Lagomorpha indet.
 age: Not older than the assemblage zone of Küttigen, MP 30.
 remarks: See under Findreuse 6.

Findreuse 8

material: 149 isolated teeth
 Didelphidae indet.
 Heterosoricinae indet.
 Soricidae indet.
Paratalpa sp.
 Uropsilinae indet.
Rhodanomys aff. *hugueneyae* Engesser
Pseudotheridomys aff. *bernensis* Engesser
Gliravus cf. *bruijni* Hugueney
Peridyromys murinus (Pomel)
Microdyromys praemurinus (Freudentberg)
Glirudinus glirulus (Dehm)
Bransatoglis fugax (Hugueney)
Adelomyarion vireti Hugueney
Pseudocricetodon thaleri (Hugueney)
Melissiodon sp.
Allomys sp.?
Palaeosciurus sp.
Steneofiber sp.
Archaeomys sp.
 Carnivora indet.
Caenotherium sp.
 non-mammals: *Ophisaurus* sp.
 Lacertilia

Amphibia

Pisces

Numerical composition of the mammal fauna:

Eomyidae 45 %, Gliridae 32 %, Cricetidae 8 %, Theridomyidae 2 %, Sciuridae 0,7 %, Castoridae 0,7 %, Aplodontidae 0,7 %, Insectivora 7 %, Carnivora 2 %, Didelphidae 1,4 %, Artiodactyla 0,7 %.

age: Assemblage zone of Brochene Fluh 53, MP 30.

remarks: Because of the presence of *Archaeomys* (few tooth fragments) the fauna of Findreuse 8 might be somewhat older than the reference fauna of Brochene Fluh 53. The high percentage of eomyids (42 %) and glirids (32 %) in this fauna is very conspicuous. Cricetids on the other hand are rather rare. The usually very common genus *Eucricetodon* is completely lacking. This peculiar composition of the fauna might have ecological reasons.

literature: Engesser & Hugueney (1982), Mojon et al. (1985), Engesser (1987), Engesser & Mayo (1987), Engesser (1990).

Findreuse 11

material: 19 isolated teeth

Talpidae indet.

Rhodanomys aff. *hugueneaye* Engesser

Pseudotheridomys aff. *bernensis* Engesser

Microdyromys praemurinus (Freudentberg)

Glirudinus glirulus (Dehm)

Eucricetodon sp.

Adelomyarion vireti Hugueney

Plesiosminthus winistoerferi Engesser

non-mammals: Pisces

Characeae

Seeds

age: Assemblage zone of Brochene Fluh 53, MP 30.

remarks: The faunal composition of Fin. 11 is almost identical with that of Fin. 8. An additional indication for the age of Brochene Fluh 53 gives *P. winistoerferi*, a species so far found only in this assemblage zone.

literature: Engesser & Hugueney (1982), Engesser (1987), Engesser & Mayo (1987), Engesser (1990).

Findreuse 13

material: Bone and tooth fragments, not identifiable

Findreuse 14

material: 1 molar, several tooth fragments

Plesiosminthus winistoerferi Engesser

cf. *Archaeomys*

Artiodactyla indet.

non-mammals: Crocodilia

Ophisaurus sp.

Pisces

Gastropoda

Characeae

age: Assemblage zone of Brochene Fluh 53, MP 30.

literature: Engesser (1987).

Findreuse 15

material: 7 isolated teeth

Eomys cf. *ebnatensis* Engesser

Eomys huerzeleri Engesser

Microdyromys praemurinus (Freudentberg)

Glirudinus glirulus (Dehm)

Issiodoromys sp.

Caenotherium sp.

- non-mammals: Crocodilia
Ophisaurus
 Lacertilia
 Pisces
- age: Assemblage zone of Rickenbach, MP 29.
- remarks: *E. huerzeleri* is so far known only from the assemblage zone of Rickenbach. In this zone we have also the last record of *Issiodoromys* (Fig. 9).
- literature: Engesser & Hugueney (1982), Engesser (1990).
- Findreuse 16*
- material: 1 maxillary with P4–M3 (*Eomys huerzeleri*)
 13 isolated teeth
Eomys cf. *ebnatensis* Engesser
Eomys huerzeleri Engesser
 Gliridae gen. et sp. indet.
Eucricetodon praecursor (Schaub)
Plesiosminthus promyarion Schaub
Caenotherium sp.
- age: Assemblage zone of Rickenbach, MP 29.
- literature: Engesser & Hugueney (1982), Engesser & Mayo (1987), Engesser (1990).
- Findreuse 17*
- material: 13 isolated teeth
Peratherium sp.
Eomys huerzeleri Engesser
Pseudocricetodon cf. *thaleri* (Hugueney)
Archaeomys cf. *helveticus* Vianey-Liaud
 Artiodactyla 1 indet.
 Artiodactyla 2 indet.
- non-mammals: Crocodilia
 Pisces
 Gastropoda
 Characeae
- age: Assemblage zone of Rickenbach, MP 29.
- literature: Engesser (1990).
- Findreuse 18*
- material: 43 isolated teeth
Peratherium sp.
 Soricidae indet.
 Dimylidae indet.
Eomys huerzeleri Engesser
Eomys cf. *ebnatensis* Engesser
Glirudinus glirulus (Dehm)
Adelomyarion vireti Hugueney
Eucricetodon cf. *dubius* (Schaub)
Pseudocricetodon sp.
Melissiodon sp.
Archaeomys cf. *helveticus* Vianey-Liaud
Issiodoromys cf. *terminus* Stehlin & Schaub
Caenotherium sp.
Amphitragulus sp.
- non-mammals: *Ophisaurus* sp.
 Lacertilia
 Crocodilia
 Testudinata

- Pisces
Characeae
- age: Assemblage zone of Rickenbach, MP 29.
literature: Engesser & Hugueney (1982), Engesser & Mayo (1987), Engesser (1990).
- Findreuse 22*
material: 10 isolated teeth
Rhodanomys schlosseri Depéret & Douxami
Microdyromys praemurinus (Freudentberg)
Plesiosminthus myarion Schaub
Artiodactyla indet.
- non-mammals: *Ophisaurus* sp.
Lacertilia
Pisces
Characeae
- age: Assemblage zone of Fornant 11, upper part of MN1.
literature: Engesser (1987).
- Findreuse 24*
material: 9 isolated teeth
Peratherium sp.
Sciuridae gen. et sp. indet.
Gliridae gen. et sp. indet.
Eucricetodon praecursor (Schaub)
Melissiodon sp.
Archaeomys sp.
Issiodoromys sp.
Artiodactyla indet.
- non-mammals: *Ophisaurus* sp.
Lacertilia
Pisces
Gastropoda
Characeae
- age: Assemblage zone of Rickenbach, MN 29.
remarks: With this material alone, the fauna of Findreuse 24 cannot be calibrated precisely. Certainly *E praecursor* is characteristic for the assemblage zone of Rickenbach, but this species or a very similar form may occur also in older zones. Since the position of Findreuse 24 in the section is very close to that of Findreuse 25, which safely can be attributed to the assemblage zone of Rickenbach, it is likely that the fauna of Findreuse 24 lies within the assemblage zone of Rickenbach.
- Findreuse 25*
material: 27 isolated teeth
Peratherium sp.
Talpidae gen. et sp. indet.
Eomys huerzeleri Engesser
Eomys cf. *ebnatensis* Engesser
Eomyodon volkeri Engesser
Microdyromys cf. *praemurinus* (Freudentberg)
Adelomyarion vireti Hugueney
Eucricetodon praecursor (Schaub)
Pseudocricetodon thaleri Hugueney
Issiodoromys sp.
Amphitragulus sp.
- non-mammals: *Ophisaurus* sp.
Crocodilia
Pisces

- Gastropoda
Characeae
- age: Assemblage zone of Rickenbach, MP 29.
literature: Engesser & Mayo (1987), Engesser (1990).
- Findreuse 27*
material: 15 isolated teeth
Rhodanomys schlosseri Depéret & Douxami
Glirudinus glirulus (Dehm)
Plesiosminthus myarion Schaub
Caenotherium sp.
- non-mammals: Lacertilia
Crocodilia
Pisces
Characeae
- age: Assemblage zone of Fornant 11, upper part of MN 1.
remarks: Even though the material of Findreuse 27 is small, this locality can be well correlated with Fornant 11: the three most common taxa of the latter fauna are also represented in Findreuse 27. *Rh. schlosseri*, very characteristic for the assemblage zone of Fornant 11, and by far the most frequent mammal of its reference fauna, is represented in Findreuse 27 by 9 teeth.
literature: Engesser & Mayo (1987), Engesser (1990).
- Findreuse 28*
material: 1 molar
Plesiosminthus sp.
- age: Not younger than the assemblage zone of Fornant 11.
- Findreuse 30*
material: 6 tooth fragments
Castoridae gen. et spec. indet.
Caenotherium sp.
Amphitragulus sp.
Pisces
Characeae
- age: No precise identification possible
- Findreuse 31*
material: 8 isolated teeth
Soricidae gen. et sp. indet.
Dimylidae cf. *Pseudocordylodon*
Talpidae gen. et sp. indet.
Rhodanomys schlosseri Depéret & Douxami
Gliridae gen. et sp. indet.
Caenotherium sp.
- non-mammals: *Ophisaurus* sp.
Lacertilia
Pisces
Characeae
- age: Assemblage zone of Fornant 11, upper part of MN 1.
remarks: This identification of the age is based only on one tooth of *Rhodanomys schlosseri*. This P4 shows a very advanced pattern and could therefore be attributed to *Ritteneria molinae* or *Ritteneria manca* as well. It is here identified as *Rh. schlosseri* because in Findreuse 22, which is higher in the section, *Rh. schlosseri* and *Plesiosminthus myarion* are present. In levels with *Ritteneria*, *Plesiosminthus* has already disappeared.
- Findreuse 33*
material: 8 isolated teeth, 5 fragments
Dimylidae gen. et sp. indet.

	<i>Rhodanomys schlosseri</i> Depéret & Douxami
	<i>Glirudinus glirulus</i> (Dehm)
	<i>Plesiosminthus myarion</i> Schaub
	<i>Caenotherium</i> sp.
non-mammals:	<i>Ophisaurus</i> sp.
	Lacertilia
	Pisces
	Characeae
age:	Assemblage zone of Fornant 11, upper part of MN 1.
<i>Findreuse 34</i>	
material:	5 tooth fragments
	<i>Peratherium</i> sp.
	<i>Archaeomys</i> sp.
	<i>Issiodoromys</i> sp.
	<i>Plesiosminthus</i> sp.
non-mammals:	Cyprinidae
	Characeae
age:	Not younger than MP 29.

4.1.3 Magnetostratigraphy

Except for the topmost two sites which were collected from the Upper Marine Molasse, the entire section is within the Lower Freshwater Molasse. Within this 270-m-thick sequence, 70 magnetic sites were collected. Due either to very low magnetic intensities and incoherent directions or to inadvertent initial heating to over 400 °C, approximately one-third of the sites had to be discarded. Of the remaining 45 sites, 66 % yielded Class I and 34 % defined Class II sites. The VGP latitudes of these sites delineate 16 magnetozones (Fig. 5). All except two of these magnetozones (R6 and R8, Fig. 5) are based on two or more superposed magnetic sites. Although it is possible that some polarity zones have been missed, the density of site spacing and the alpha-95 error limits on the VGP latitudes (Fig. 5), in combination with the multiple sites in each magnetozones, lend considerable confidence to the local magnetic polarity stratigraphy (MPS) shown here.

The correlation of the Findreuse MPS with the Magnetic polarity time scale (MPTS) is guided by two considerations. First, the existing faunal data indicate that the Aquitanian-Chattian boundary lies between 115–180 m and that the base of the section does not extend into the Lower Chattian. Second, magnetozones R2 to R5 display an irregular and distinctive pattern of reversals that appears to correlate well with a portion of the Late Oligocene-early Miocene MPTS (Berggren et al. 1985). The resultant correlation of the entire Findreuse section (Fig. 7) indicates that it spans from 25.7 to 21.5 Ma. On the basis solely of the reversal pattern, the base of the Findreuse section (R1) might be correlated with the reversed magnetozones between 26.0 and 26.4 Ma (Fig. 7). However, comparative faunal data from the Findreuse and Fornant sections (see discussion) indicate that the correlation depicted here is more likely. Given the presently defined ages of the MPTS magnetozones, sediment accumulation at Findreuse would have been fairly rapid at first (> 30 cm/Kyr), but would have slowed to 5–10 cm/Kyr after 25.5 Ma (Fig. 8).

4.2 Fornant section

4.2.1 Stratigraphy

The Fornant section is located along a SE-flowing stream near the village of Frangy, approximately 8 km northeast of the Findreuse section (Fig. 1). The 370-m-thick exposure of Lower Freshwater Molasse is considerably thicker and also covers a longer stratigraphic interval (see below) than that preserved in the Findreuse section. However, the same lithostratigraphic units can be distinguished in both sections (Figs. 5 and 6).

The lacustrine limestone unit (ca. 10 m) which is resting on the Lower Cretaceous substratum is lithologically identical to that in the Findreuse, but the overlying 60-m-thick clastic unit shows contrasting facies. In its lower and upper part, it consists of an alternating sequence of decimetre- to metre-thick fine-grained sandstones and grey to reddish brown silty marls with caliche nodules, whereas in its middle part up to several m-thick medium-grained sandstones with erosive bases, clay-pebble lags and trough-cross-bedding are found. These facies are interpreted as meandering channel, crevasse and floodplain deposits.

The sedimentary facies of the overlying units does not differ from those of the Findreuse section, except for the sparse occurrence of gypsum in the playa unit which is dominantly sandy. The heavy mineral association reveals that the detritus of the USM of the Fornant is of Alpine derivation throughout the section (M. A. Mange, pers. comm.).

4.2.2 Paleontology

In the Fornant section, 13 levels were sampled for paleontological studies, and 9 contained vertebrate remains, 6 yielded mammal teeth which could be determined and only 4 sites could be dated.

Nevertheless the Fornant section is of great importance because it contains three rich mammal faunas, which were chosen as reference faunas for mammal zones (Fornant 6, 7, 11; see Engesser & Mayo 1987).

Fornant 3

material: 1 tooth fragment: Eomyidae gen. et sp. indet.
age: Identification of the age not possible

Fornant 6

material: 713 isolated teeth
Didelphidae gen. et sp. indet.
Soricidae gen. et sp. indet.
Heterosoricinae gen. et sp. indet.
Paratalpa sp.
Talpidae sp. 2, cf. *Mygatalpa*
Talpidae 3 gen. et sp. indet.
Erinaceidae gen. et sp. indet.
Dimylidae gen. et sp. indet.
Chiroptera indet.
Palaeosciurus sp.
Eomys ebnatensis Engesser

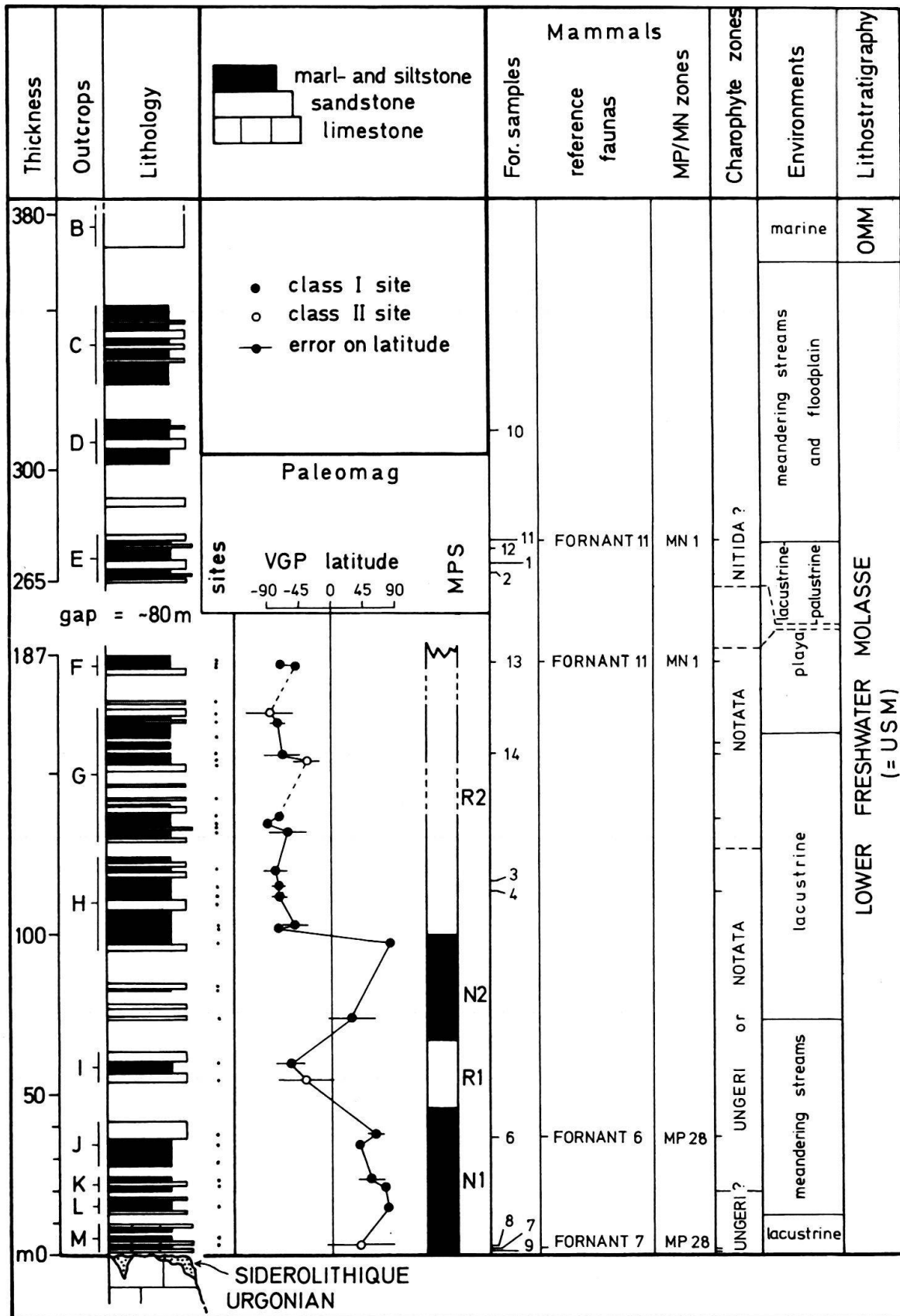


Fig. 6. Schematic log of the Fornant section showing magneto- and biostratigraphic data and inferred depositional environments. Letters B – M refer to location map published by Weidmann (1982, fig. 5).

- Eomys major* Freudentberg
Eomyodon volkeri Engesser
Gliravus cf. *bravoi* Hugueney, Adrover & Moissenet
Gliravus sp. 2
Peridyromys cf. *murinus* (Pomel)
Peridyromys sp. 2
Oligodyromys cf. *planus* Bahlo
Glirudinus glirulus (Dehm)
Bransatoglis cf. *fugax* (Hugueney)
Steneofiber dehmi Freudentberg
Eucricetodon dubius (Schaub)
Eucricetodon cf. *dubius* (Schaub)
Pseudocricetodon aff. *thaleri* (Hugueney)
Adelomyarion cf. *vireti* Hugueney
Melissiodon quercyi Schaub
Plesiosminthus promyarion Schaub
Archaeomys kaelini Mayo
Issiodoromys oppligeri Mayo
Caenotherium sp.
 Artiodactyla indet.
- non-mammals: Crocodilia
 Lacertilia
 Pisces
 Characeae
- numerical composition of the mammal fauna:
 Theridomyidae 36 %, Eomyidae 26 %, Cricetidae 20 %, Gliridae 6,5 %, Dipodidae 4 %, Castoridae 2,1 %, Insectivora 2,1 %, Artiodactyla 1,5 %, Didelphidae 1,1 %, Sciuridae 0,4 %, Chiroptera 0,3 %.
- age: Assemblage zone of Fornant 6, MP 28.
- remarks: The fauna of Fornant 6 is the reference fauna of the assemblage zone with the same name (Engesser & Mayo 1987). This zone is characterized by the following mammal taxa: *Eomys major*, *Archaeomys kaelini*, and *Issiodoromys oppligeri*. In addition this zone is typified by the first record of the eomyid genera *Eomyodon* and *Pseudotheridomys*. From the next older zone of Fornant 7, that of Fornant 6 is distinguished by the absence of the cricetids *Heterocricetodon* and *Pseudocricetodon incertus* and by the higher evolutionary level of the therodomyids. Besides *Eucricetodon dubius* the fauna of Fornant 6 contains another *Eucricetodon* form which is listed here as *E. cf. dubius*. This form is somewhat larger than *E. dubius*, its M2 shows no lingual anteroloph, its M1 and M2 have mostly a long mesoloph, and the sinus of M1 and M2 is directed distinctly anteriorly. This *E. cf. dubius* seems also to occur in the assemblage zone of Rickenbach (e.g. in Findreus 18, see Engesser & Hugueney 1982).
- literature: Engesser & Hugueney (1982), Engesser, Mayo & Weidmann (1984), Mojon et al. (1985), Mayo (1987a), Mayo (1987b), Engesser & Mayo (1987), Engesser (1987), Engesser (1990).
- Fornant 7*
- material: 142 isolated teeth
 Didelphidae gen. et sp. indet.
 Talpidea gen. et sp. indet.
Dimylus sp.
 Erinaceidae gen. et sp. indet.
 Chiroptera indet.
 Sciuridae gen. et sp. indet.
Eomys ebnatensis Engesser
Gliravus sp.
Microdyromys praemurinus (Freudentberg)
Bransatoglis cf. *fugax* (Hugueney)
Eucricetodon dubius (Schaub)

- Pseudocricetodon incertus* (Schlosser)
Pseudocricetodon cf. thaleri (Hugueney)
Heterocricetodon stehlini Schaub
Melissiodon sp.
Plesiosminthus promyarion Schaub
Archaeomys sp.
Issiodoromys weidmanni Mayo
Caenotherium sp.
- non-mammals: *Ophisaurus* sp.
Crocodilia
Pisces
- numerical composition of the mammal fauna:
 Cricetidae 30,5%, Eomyidae 26,7%, Theridomyidae 15,5%, Gliridae 11,2%, Insectivora 3,5%, Artiodactyla 3,5%, Sciuridae 2,8%, Dipodidae 2,1%, Didelphidae 1,4%, Chiroptera 1,4%, Carnivora 1,4%.
- age: Assemblage zone of Fornant 7, MP 28.
- remarks: The fauna of Fornant 7 is the reference fauna of the assemblage zone with the same name (Engesser & Mayo 1987). This zone is characterized by *Issiodoromys weidmanni* and by the last record of *Heterocricetodon* and *Pseudocricetodon incertus*. From the younger zone of Fornant 6, that of Fornant 7 is distinguished by the absence of the newcomers *Eomys major*, *Eomyodon*, and *Pseudotheridomys*.
- literature: Engesser & Hugueney (1982), Engesser et al. (1984), Engesser & Mayo (1987), Mayo (1987a), Engesser (1987), Engesser (1990).
- Fornant 11**
- material: about 3500 isolated teeth
 Didelphidae gen. et sp. indet.
 Erinaceidae gen. et sp. indet.
 Talpidae gen. et sp. indet.
Pseudocordylodon sp.
Palerinaceus sp.
 Soricidae gen. et sp. indet.
Palaeosciurus cf. feignouxii (Pomel)
Heteroxerus sp.
Peridyromys murinus (Pomel)
Peridyromys sp. 2
Glirudinus glirulus (Dehm)
Microdyromys sp.
Rhodanomys schlosseri Depéret & Douxami
Eucricetodon cf. gerandianus (Gervais)
Plesiosminthus myarion Schaub
Steneofiber sp.
Piezodus tomerdingensis Tobien
 Carnivora indet.
Caenotherium sp.
Amphitragulus sp.
 Suidae gen. et sp. indet.
- non-mammals: Crocodilia
Cyprinidae
Pisces
Characeae
- numerical composition of the mammal fauna:
 Eomyidae approximately 60%, Dipodidae 20%, Gliridae 15%, others 5%.
- age: Assemblage zone of Fornant 11, upper part of the zone MN1.
- remarks: The fauna of Fornant 11 is the reference fauna of the assemblage zone with the same name (Engesser & Mayo 1987). It is best characterized by *Rhodanomys schlosseri*, an evolutionary

stage in the development of *Rhodanomys* which is limited to the assemblage zone of Fornant 11. In the next older zone, that of Boudry 2 (correlatable with Paulhiac) the more primitive *Rh. transiens* is found. In the younger zone of La Chaux, the genus *Ritteneria* is present, which probably can be derived from *Rh. schlosseri* (Engesser 1990).

Fornant 12

- material: 2 isolated teeth and several fragments
Glirudinus glirulus (Dehm)
 Artiodactyla indet.
- non-mammals: Crocodilia
 Characeae
 Identification of the age not possible

Fornant 13

- material: 7 isolated teeth
 Talpidae cf. *Paratalpa*
Peridyromys murinus (Pomel)
Rhodanomys schlosseri Depéret & Douxami
 Lagomorpha indet.
Caenotherium sp.
 Artiodactyla indet.
- non-mammals: *Ophisaurus* sp.
 Pisces
 Ostracoda
- age: Assemblage zone of Fornant 11, upper part of two zone MN1.
- remarks: The identification of the age of Fornant 13 is based only on two *Rhodanomys*-teeth. Unfortunately these teeth are a M3 and a D4, both teeth which usually show a great variability. With its dimensions the M3 lies in the upper part of the size range of *Rh. schlosseri*. Considering its size and also its morphology, this tooth could either belong to *Rh. schlosseri*, or to *Rh. transiens* as well. The D4 is too small for *Rh. transiens*. In addition the D4 of this species almost always shows a first syncline, lacking in the specimens of Fornant 13. Therefore we can identify this tooth as *Rh. schlosseri*, a species which is limited to the assemblage zone of Fornant 11.
- literature: Engesser (1990).

4.2.3 Magnetostratigraphy

Because there are large covered intervals in the upper portion of the Fornant section, only the lower half was sampled during the magnetic studies. Within this 190-m-thick succession, 36 magnetic sites were collected. Due to low intensities, unstable directions, or inadvertent overheating, 12 sites were discarded. Of the remaining 24 sites, 83 % were Class I and 17 % were Class II. The resultant magnetostratigraphy comprises four magnetozones (Fig. 6), each of which is defined by two or more superposed magnetic sites. Due to covered intervals and to unusable magnetic data from some sites, there are gaps in portions of the magnetic record. It is certainly possible that some reversals have been missed within these gaps.

Because of the brevity of the section and the presence of only four magnetozones, the correlation of the Fornant MPS with the MPTS is guided by the Fornant faunal record and by comparison with the longer and more readily correlated Findreuse sequence. Given that the Rickenbach assemblage zone is younger than Fornant 6, and the likely absence of significant diachrony between these nearby sections, the base of the Fornant section must be older than that of the Findreuse section. We therefore correlate magnetozone R1 between both sections (Fig. 7) and assign magnetozone N1 at Fornant to the

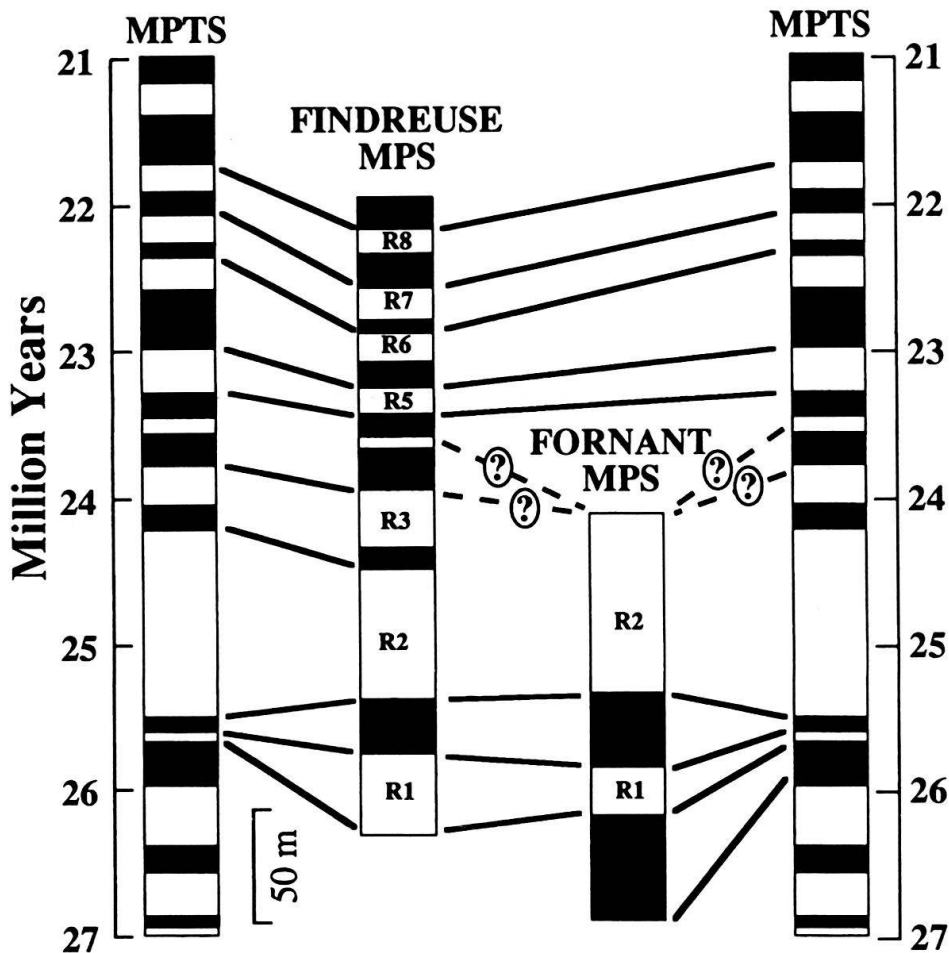


Fig. 7. Correlation of the local magnetostratigraphies from Findreuse and Fornant with the magnetic polarity time scale (MPTS) of Berggren et al. (1985). The reversed magnetozones (R1–R8) correspond to the designations of figures 5 and 6. In conjunction with faunal data, the R2 to R5 patterns from Findreuse guide the correlation. The correlation of the top of the Fornant MPS with either Findreuse or the MPTS is uncertain because one or two normal magnetozones appear to be missing. On the basis of faunal and magnetic data, the Aquitanian-Chatian boundary is placed at ca. 24.2 Ma.

base of chron C7N. The thickness of magnetozones N1–N2 (Fig. 6) precludes a reasonable correlation with older chrons.

The top of the magnetically sampled sequence contains a Fornant 11 fauna (site For 13, Fig. 6). Given the position of this assemblage zone in the Findreuse section, the reversed, upper part of the Fornant section must correlate with either magnetozones R3, R4 or R5 of the Findreuse section. Due to the gaps in the Fornant section, it is likely that we have missed magnetozones N2 found in the Findreuse section. Although it is possible that we have also missed magnetozones N3, this latter possibility appears to be less likely given our sample spacing. We, therefore, tentatively correlate the top of the Fornant magnetic section with the top of R3 in the Findreuse section (23.8 Ma, Fig. 7). This correlation indicates that the base of the Fornant section dates from ~26.0 Ma and the top from ~23.8 Ma. Like the correlative portion of the Findreuse section, sediment-accumulation rates at Fornant were most rapid (~30 cm/Kyr; Fig. 8) during early deposition.

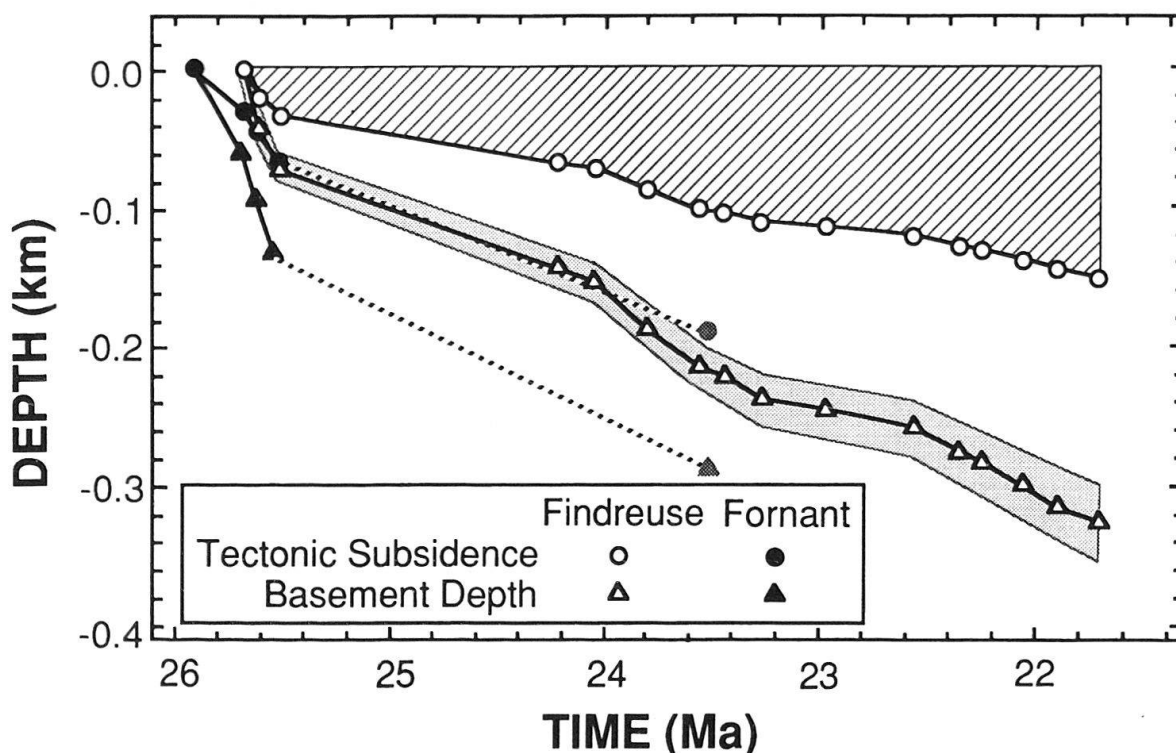


Fig. 8. Geohistory plot for the Findreuse and Fornant sections. The uncertainty in reversal positions is less than the size of the symbols, but uncertainties in decompaction coefficients indicate likely errors of $\sim 10\%$. The stippled area depicts a 10% error envelope on the basement subsidence curve. The dashed lines indicate the uncertain correlation of the top of the Fornant section. The hatched area represents the calculated tectonic subsidence of the Findreuse section. The most rapid tectonic and basement subsidence occurs between 26 and 25.5 Ma. A second interval of apparently modestly accelerated subsidence occurs beginning at 24.1 Ma.

5. Discussion

5.1 Magnetic polarity time scale and magnetic chronologies

The new magnetic polarity stratigraphies presented here represent the best calibration of the terrestrial land mammal stages presently available for this region. Because of the relatively short duration of magnetozone in this portion of the MPTS, the resolution provided on the stratigraphic record is approximately ± 0.25 Myr in the interval between 24.3 and 21.5 Ma. Assuming that the correlations with the MPTS are correct, these new data provide a very precise time framework within which to analyze the stratigraphic record of the Lower Freshwater Molasse. More importantly, they also represent a first step towards a high resolution chronologic control of the late Oligocene to early Miocene land-mammal stages of west-central Europe.

The combination of abundant faunal data with distinctive patterns of magnetozone enables an apparently reliable correlation of the local MPS's with the MPTS. Nonetheless, there are some inherent ambiguities in these correlations. At the top of the Findreuse section, there is a recognized unconformity at the base of the Upper Marine Molasse (Fig. 5). Although magnetozone N8 is correlated with the chron dated at ~ 21.5 Ma, a

hiatus of considerably longer duration could be represented by this contact. Because there is little evidence for significant erosion at the top of the Lower Freshwater Molasse, we tentatively suggest that little time is missing here, and we base our correlation of the Upper Marine Molasse on this assumption. Despite the relatively close sample spacing, there are single-point reversals in the Findreuse section, and both sections contain segments in which, given the absence of reliable sites, the possibility of additional reversals can not be precluded. Few of these magnetozone, if they did exist, are likely to be of significant duration, and they would probably not affect our large scale correlations with the MPTS. The major remaining uncertainty concerns the correlation of the top of the Fornant MPS. The correlation chosen here (Fig. 7) appears to be the most likely.

In order to reconstruct sediment-accumulation rates, the sections were decompacted according to the techniques of Sclater & Christie (1980). The accuracy of these calculations is reduced by numerous uncertainties. The position of local magnetozone boundaries is a function of sample spacing, which is irregular within each section. Neither the depth of burial of each section nor their cementation history is well known. Finally, because most previous decompaction studies have focused on marine sediments, the empirical data available for terrestrial strata are limited. The uncertainties suggest that error limits of $\pm 20\%$ should be placed on the decompacted rates.

5.2 Calibration of mammalian assemblage zones

At present the Findreuse and the Fornant section are the best mammal sections of the western Molasse. They not only yielded a great number of mammal faunas in superposition; these faunas also cover a considerable interval of time: Their range extends over 7 assemblage zones, from the late Oligocene to the early Miocene (Fig. 9). The Fornant section is especially important because it contains 3 reference faunas of Molasse assemblage zones: Fornant 6, Fornant 7 and Fornant 11. Whereas the Fornant section yielded only 4 datable – 3 of them very rich – faunas, that of Findreuse contains 14 faunal levels, which mostly are not very rich.

Taking into account the correlations presented in Figure 7 and presented earlier, one can place our fossiliferous sites into the chronological framework of the MPTS. This allows us to propose temporal limits between the assemblage zones of Haute-Savoie.

Most of these ages have a rather wide range due to an absence of appropriately spaced sites that could serve to define assemblage zone boundaries. However, the boundary between Fornant 6 and Fornant 7 can be precisely defined stratigraphically and can be assigned very tight temporal limits (Table 1).

Given this calibration of the faunal record, the temporal duration of individual assemblage zones is seen to be highly variable. Some zones like Fornant 6, can be limited to < 300 Kyr, whereas others, like Fornant 11, span more than 1 Myr. In the absence of tight chronologic constraints, uncalibrated assemblage zones have often been assumed to be of roughly equal duration. These results suggest a high degree of variability.

Because the boundary between the Boudry 2 and Brochene Fluh 53 assemblage zones is generally accepted as correlative with European assemblage zones MN1 and MP30, respectively, and with the Aquitanian and Chattian stages, our data indicate that this boundary has an age of 24.15–24.25 Ma. This age is approximately 1 Myr older than the

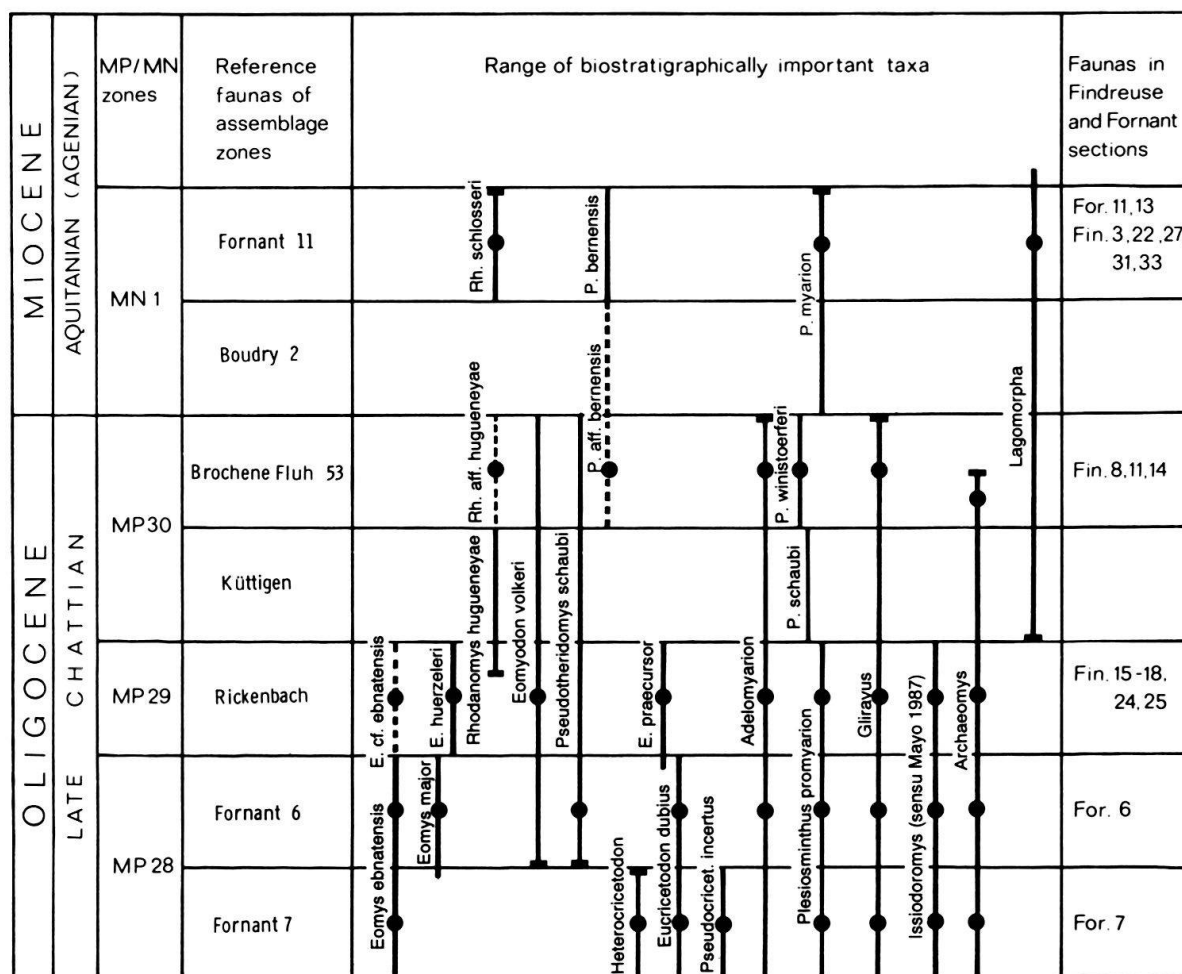


Fig. 9. Summary of mammalian biostratigraphy. The stratigraphic range of taxa in the western Molasse Basin is shown by solid lines. Broken lines indicate the range of taxa with open nomenclature ("aff." or "cf."). First appearance and disappearance is shown by horizontal bars. Occurrence of taxa in the Fornant and Findreuse sections indicated by points.

limit proposed by Steininger et al. (1990) and ~ 0.6 Myr older than the boundary age of Berggren et al. (1985).

5.3 Stratigraphic evolution

5.3.1 Subsidence analysis

The geohistory analysis of the Findreuse and Fornant sections shows three phases of subsidence in the distal foreland basin. Between 26 and 25.5 Ma, subsidence was rapid, it slowed considerably during the succeeding 1 Myr, and then, within the calculated uncertainties, it appears to have accelerated moderately again at ca. 24 Ma (Fig. 8). When these results are compared with other published subsidence curves from the western Molasse basin (e.g. Homewood 1986, Homewood et al. 1986), it appears that the subsidence record from Haute-Savoie mimics that of the western Molasse to the extent

Assemblage zone	MP/MN zone	Age (Ma)
Fornant 11	late MN1	- ?
Boudry 2	early MN1	- ~23.85-23.95
Brochene Fluh 53	late MP30	- ~24.15-24.25
Küttigen	early MP30	- ?
Rickenbach	MP29	- ?
Fornant 6	late MP28	- ~25.65-25.70
Fornant 7	early MP28	- ~25.80-25.95
		- ?

Table 1. Chart showing correlation of mammal assemblage zones in the Molasse Basin with European mammal zones. Zone boundaries may be dated from magnetostratigraphy (as shown in right hand column).

that there is an indication of accelerated subsidence at ca. 24. Ma. Overall, there is evidence for a variability in the subsidence regime on the scale of 1 Myr. It is also noteworthy that the long-term rate of subsidence over the entire record decreases: a result that is contrary to expectations for subsidence trends resulting from tectonic loads that systematically encroach on a foreland basin. Although it is tempting to draw inferences regarding the relationship of enhanced subsidence to tectonic loading (Flemings & Jordan 1989, Allen & Allen 1990), at present we have insufficient data to interpret the loading history, because the complexities of possible responses within the foreland to loading (Flemings & Jordan 1990) preclude unambiguous interpretation.

5.3.2 Provenance

Although magnetic data are available only for the basal part of the Fornant section, heavy mineral analyses have been extended through the entire Lower Freshwater Molasse into the Upper Marine Molasse in both sections (M. A. Mange, pers. comm.) as well as in the Aquitanian-Burdigalian section farther to the west (Meylan 1982). Two contrasting source areas are definable: an ultrastable suite of multi-cyclic origin derived from localized sources to the west and a suite representing the main, axial depositional system (Genferseeschüttung) of Alpine derivation.

Despite the proximity of the two studied sections, there are contrasts between them. Whereas the entire Fornant section is dominated by Alpine source areas, the Findreuse section and some areas farther to the west (Meylan 1982) show an alternation of Alpine with local source areas (Fig. 10). Thus, the more distal part of the basin exhibits responses to more localized uplifts at considerable distances from the main orogenic activity. The earliest non-Alpine influx in the Findreuse section (Fig. 10) is associated with a clearly different depositional facies: a braided fluvial system that apparently prograded east-

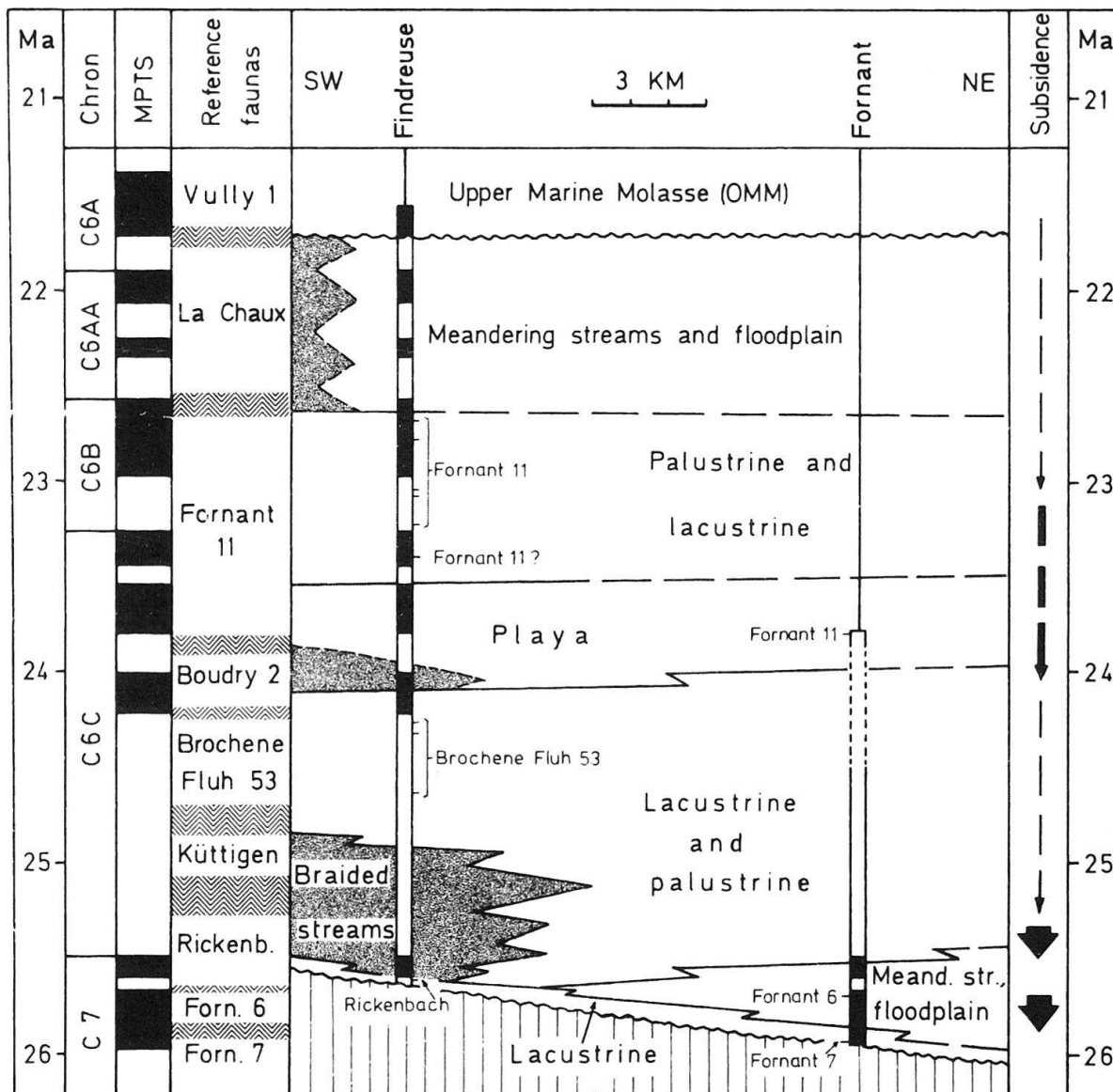


Fig. 10. Summary chart showing correlation of magnetostratigraphy with lithostratigraphy and inferred depositional environments. Sediments derived from western source are shown by stipple, other sediments are of alpine source. Width of vertical arrows is proportional to calculated sedimentation rates. Mammalian reference faunas are shown on the left of the figure; thickness of wavy lines indicates the degree of uncertainty on the limits.

ward toward a more proximal part of the basin. This progradation occurs during a time of rapid subsidence (Figs. 8 and 10), and it may represent a time when the forebulge was migrating toward the hinterland due to tectonic loading, as suggested by several recent models (Flemings & Jordan 1990, Allen & Allen 1990). However, it is also possible that the uplift of the western area is instead related to inversion of N-S oriented extensional faults during alpine compression (pers. comm. P. A. Allen 1992).

5.3.3 Depositional facies

The main body of deposition of the Lower Freshwater Molasse at both sections is represented by a symmetrical, fining- and coarsening-upward cycle of 250–350 metres

thickness and 4 Myr duration. The central part of this depositional cycle is represented by fine-grained, playa deposits that span 0.5 to 1 Myr (Fig. 10).

In the earliest stages of deposition throughout the study area a time-transgressive lacustrine limestone directly overlies the unconformity with the Mesozoic rocks (Rigassi, in: Charollais & Amberger 1983). Stratigraphically above this, two contrasting fluvial styles are evident. In the eastern, proximal part of the basin, meandering rivers grade westward into lacustrine facies (Fig. 10). In the western area at the same time and for 0.5 Myr longer into late Oligocene times, braided rivers representing a western source area grade eastward toward the incipient Alps. During a time of rapid subsidence, these braided rivers are coeval with lacustrine deposits in the more proximal part of the basin. Although less pronounced, a similar facies pattern prevails between 23.8 and 24.2 Ma (Fig. 10) and is also associated with an interval of accelerated subsidence. Such geometries are predicted by geophysical models of depositional responses to thrust loading (e.g. Flemings & Jordan 1989, 1990). In Haute-Savoie, there is clear evidence for one interval of rapid loading and subsidence at ~ 26 Ma and suggestive evidence for a second, lesser loading event beginning at ~ 24 Ma.

5.3.4 Climatic inferences

Proxy climatic data from two different sources have recently been summarised for the central and western Molasse basin (Berger 1990). Oxygen isotopic data from charophyte gyrogonites suggest a long-term trend toward increased wetness and/or decreased temperatures during late Oligocene time. A dramatic excursion to warmer and/or drier followed by cooler and/or wetter conditions occurs between the Fornant 6 and Küttigen faunal zones. The lacustrine and palustrine sedimentation that dominates the central part of the Findreuse and Fornant depositional records (Fig. 10) may correspond with the suggested, prolonged interval of enhanced effective moisture.

A second climatic reconstruction is based on plant macrofossils and suggests that hot and humid conditions prior to faunal zone MP29 (Fig. 9) gave way to cooler, drier conditions in latest Oligocene times, which were then superseded by warmer and only marginally wetter conditions during the earliest Miocene (MN1, Fig. 9). Although we see no clear evidence in the study area for either of the first two conditions, the distinctive and abrupt warming inferred for early Miocene time appears to coincide with the onset of playa deposition (Fig. 10).

6. Conclusions

Two new magnetostratigraphic chronologies permit a detailed temporal calibration of the depositional and faunal record of the Lower Freshwater Molasse in Haute-Savoie. Because the studied sections contain the most extensive and best studied mammalian faunal record in the western Molasse basin, the new dates provide important time limits on previously poorly dated biozonations. The Oligocene-Miocene boundary is placed here at 24.15–24.25 Ma. Assemblage zones are seen to vary in duration by at least 3-fold and may be as brief as 200–300 Kyr.

One long-term depositional cycle dominates the 4-Myr-long duration of the Lower Freshwater Molasse. Two intervals of accelerated subsidence (ca. 26 and 24 Ma) punctu-

ate the record and suggest that significant changes in loading, sediment supply, and/or base level occurred at ca. 1-Myr intervals. Due to the limited spatial distribution of the data, few reliable tectonic inferences can be drawn, and whereas it appears that some depositional changes may coincide with inferred climatic changes, the absence of clear correspondence for other changes suggests that non-climatic forcing controlled much of the depositional record.

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