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ORIGINAL PAPER

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# Eocene-Pliocene time scale and stratigraphy of the Upper Rhine Graben (URG) and the Swiss Molasse Basin (SMB)

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**Abstract** We present a general stratigraphic synthesis for the Upper Rhine Graben (URG) and the Swiss Molasse Basin (SMB) from Eocene to Pliocene times. The stratigraphic data were compiled both from literature and from research carried out by the authors during the past 6 years ; an index of the stratigraphically most important localitites is provided. We distinguish 14 geographical areas from the Helvetic domain in the South to the Hanau Basin in the North. For each geographical area, we give a synthesis of the biostratigraphy, lithofacies, and chronostratigraphic ranges. The relationships between this stratigraphic record and the global sea-level changes are generally disturbed by the geodynamic (e.g., subsidence) evolution of the basins. However, global sea-level changes probably affected the dynamic of transgression–regression in the URG (e.g., Middle Pechelbronn Beds and Serie Grise corresponding with sea-level rise between Ru1/Ru2 and Ru2/Ru3 sequences, respectively) as well as in the Molasse basin (regression of the UMM corresponding with the sea-level drop at the Ch1 sequence). The URGENT-project (Upper Rhine Graben evolution and neotectonics) provided an unique opportunity to carry out and present this synthesis. Discussions with scientists addressing sedimentology, tectonics, geophysics and geochemistry permitted the comparison of the sedimentary history and stratigraphy of the basin with processes controlling its geodynamic evolution. Data presented here back up the palaeogeographic reconstructions presented in a companion paper by the same authors (see Berger et al. in Int J Earth Sci 2005).

**Keywords** Rhine Graben · Molasse · Paleogene · Neogene · Stratigraphy

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## Introduction

During the last decade, important progresses have been made in Tertiary stratigraphy and correlation. Different synthetic stratigraphic charts have been published (e.g., Berggren et al. 1995; Hardenbol et al. 1998; Steininger 1999). Some recent data slightly modify several boundaries (particularly owing to the extension of astronomically calibrated geological time scales into the Neogene and Paleogene; see Pälike and Shackleton 2003) that will be synthesized probably in 2005 (see Berggren et al. 2003).

A detailed stratigraphic frame is absolutely necessary to constrain geodynamic models. This stratigraphic study could thus be used to evaluate different geodynamic questions such as subsidence rates, uplift of Vogesen–Schwarzwald massifs or correlations between Upper Rhine Graben (URG)-rifting and alpine orogeny.

The charts presented here, for the URG and Western Switzerland, address two basic aspects:

A. The first aspect concerns the time scale, correlating biozones, magnetostratigraphy, sequence stratigraphy, chronostratigraphic units and the absolute time scale (Fig. 1). We present in this chart different correlations proposed by different authors, following the concept published by Berger (1992a). Eight columns have been compiled by the following authors:

| | |
|---|---|
| - Magnetostratigraphy: | Cande and Kent 1992, 1995 |
| - Planktonic foram. zones: | 1. Berggren et al. 1995 |
| | 2. Hardenbol et al. 1998 |
| | 3. Steininger 1999 |
| - Calc. Nannoplankton zones: | 1. Berggren et al. 1995 |
| | 2. Hardenbol et al. 1998 |
| | 3. Steininger 1999 |
| | 4. Odin et al. 1997 |
| - Mammal zones and Swiss mammal levels: | 2. Hardenbol et al. 1998 |
| | 3. Steininger 1999 |
| | 5. Schmidt-kittler et al. 1997 |
| | 6. Bolliger 1997, Engesser and Mödden 1997, Kälin 1997a, Kälin and Kempf 2002, Kempf et al. 1997, 1999, Kempf and Matter 1999, Schlunegger et al. 1993, 1996, 1997a,b, c |
| | 7. Steininger et al. 1996 |
| | 8. Heissig 1997 |
| | 9. Fejfar et al. 1997 |
| | 10. Escarguel et al. 1997, Legendre and Leveque 1997 |
| - Charophyte zones: | 2. Hardenbol et al. 1998 |
| | 11. Riveline et al. 1996 |
| | 12. Berger 1999 |
| - Otolith zones: | 13. Reichenbacher 1999, 2000 |
| - Sequence stratigraphy: | 2. Hardenbol et al. 1998 |
| - Paratethys stages: | 3. Steininger 1999 |
| | 14. Vakarcs et al. 1998 |
| - Mediteranean stages: | 1. Berggren et al. 1995 |
| | 2. Hardenbol et al. 1998 |
| | 7. Steininger et al. 1996 |
| | 15. Odin and Luterbacher 1992 |

Accepted GSSP according to Aguirre and Pasini (1985), Castradori et al. (1998), Hilgen et al. (2000), Premoli Silva and Jenkins (1993), Remane et al. (1999), Rio et al. (1998), Steininger et al. (1997), and van Couvering et al. (1999)
Possible future GSSP according to Odin et al. (1997)

The correlation presented here has to be used carefully as demonstrated in Fig. 2: for instance, if a locality A (continental) is dated by mammals as MP21, and a locality B (marine) is dated by nannoplankton as NP22, the locality A could be older, synchronous or younger than the locality B due to the following factors:

– The boundaries between NP21, NP22 and NP23 are generally based on extinction events. Thus, serious problems may appear due to reworked nannofossils. Therefore, correlations between these boundaries and the absolute time scale are still uncertain.
– The precise age of the boundary between MP21 and MP22 varies from about 33.0 Ma to 32.0 Ma., according to different authors.

These examples explain the difficulties that often appear in correlating different environments (marine, continental). They underline that the quality of the different data has to be checked carefully, before using for other purposes such as paleogeography or paleoclimate changes.

B. The second aspect of our chart presents the lithostratigraphic units of the Swiss Molasse Basin (SMB) and the URG (Figs. 7, 8, 9, 10). The 14 columns for the specific geographical areas (Fig. 3) are listed below :

1. Helvetic domain and Subalpine Molasse
2. Plateau Molasse proximal
3. Plateau Molasse distal
4. Jura Molasse SW (Valserine, Joux, Auberson, Travers, Val de Ruz)
5. Jura Molasse NW (Verrières, Pont de Martel, Locle-Chaux de Fonds)
6. Jura Molasse Centre-S (St. Imier, Pery-Reuchenette, Tramelan-Tavannes, Welschenrohr-Balstahl, Sornetan-Bellelay, Moutier)
7. Jura Molasse Centre-N (Soulce, Delémont, Laufen, Courgenay-Charmoilles, Bressaucourt-Porrentruy, Liesberg, Löwenburg, Movelier
8. Jura Molasse E (Mummliswil, Waldenburg)
9. Southern URG (Basel Horst, Dannemarie Basin, Mulhouse Horst, Mulhouse Basin potassique, Sierentz-Wollschwiller Basin, Rauracian Depression, Lörrach to Freiburg im Br.)
10. S-Middle URG (Colmar, Sélestat, Erstein, Zorn or Strasbourg Basin), Fault area of Saverne, Ribeauvillé & Guebwiller
11. N-Middle URG (Haguenau, Pechelbronn, Rastatt, Karlsruhe, Landau), Fault area of Bruchsal-Wiesloch
12. Northern URG (Heidelberg Basin, Darmstadt, Wetterau, Horloff Graben)

    S-boundary: Neustadt/Weinstraße-Heidelberg / W-boundary: Mainz Basin /
    E-boundary: Hanau Basin

13. Mainz Basin
14. Hanau Basin

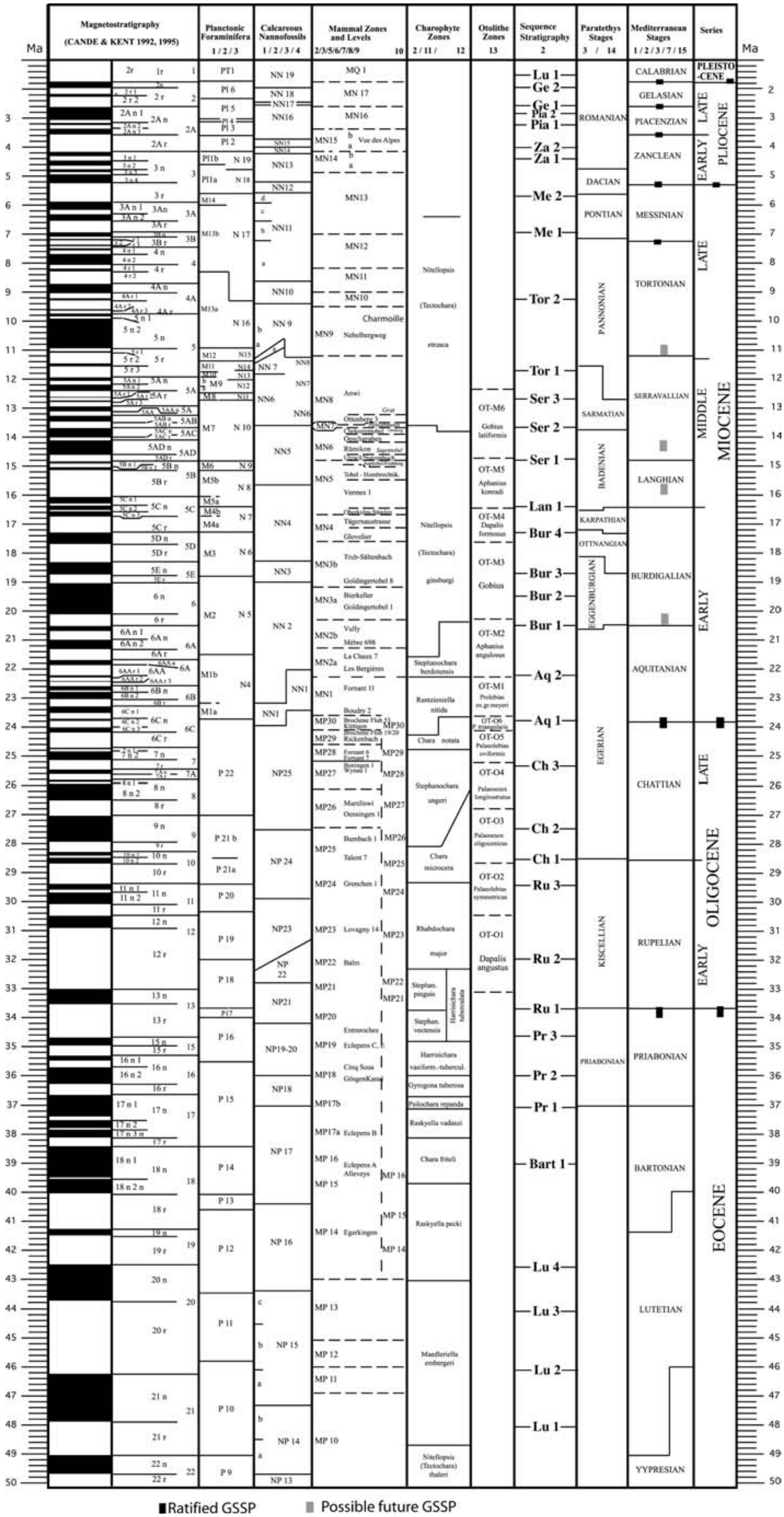


**Fig. 1** Eocene-Pliocene stratigraphic chart

■ Ratified GSSP ■ Possible future GSSP

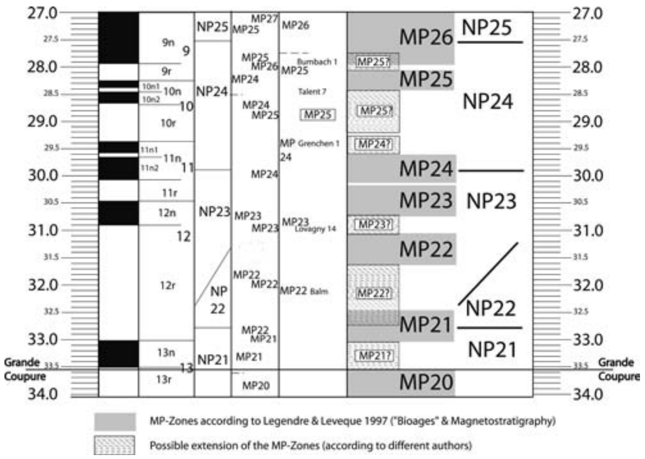



**Fig. 2** Early Oligocene correlation problems between mammals (MP21–25) and calcareous nannoplankton (NP21–25)

The lithostratigraphic units are correlated with the time scale according to stratigraphical data found in outcrops or boreholes. Figures 4 and 5 list the most important localities, which we used for stratigraphic correlations. Figure 6 summarizes the lithostratigraphical units (and their key numbers), which we applied in

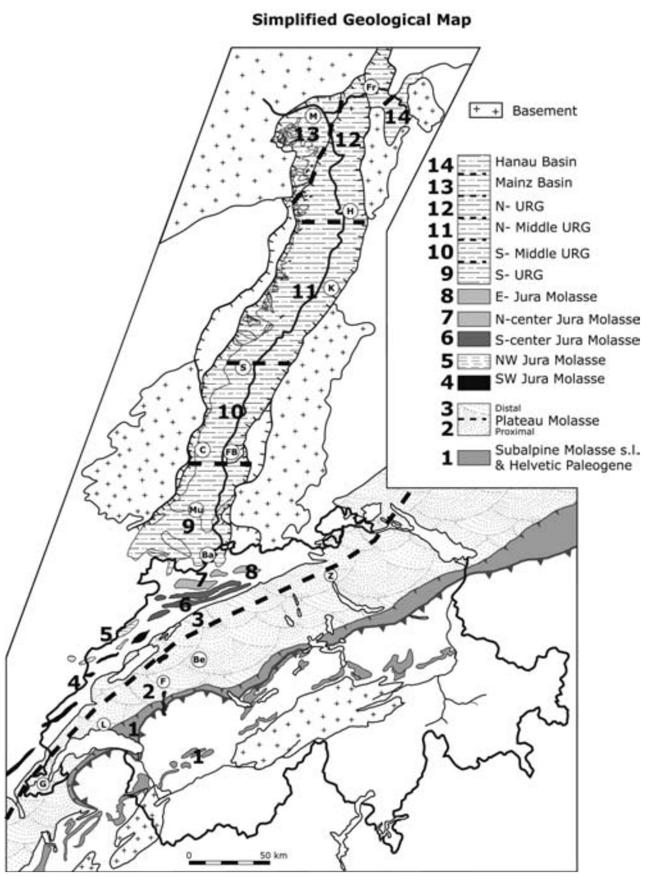



**Fig. 3** Simplified geological map

**Fig. 4** Map of localities (see listing on Fig. 5)

Figs. 7, 8, 9 and 10. To avoid the abundant use of quotation marks in the following discussion, informal lithostratigraphic units, like *Green marls* or *Calcaires et dolomies*, are written in italics.

The Deutsche Stratigraphische Kommission (2002) recently published a stratigraphic synthesis for the German part of the URG. The study of Sissingh (2003) deals with the Rhine Graben system in general, and stresses the correlation of eustatic sea-level changes, rifting phases, palaeogeography, and sedimentary evolution. However, the topic of our study is to present both the stratigraphical frame and the sedimentary evolution for the URG–Western Switzerland system. For this purpose, we took into account a lot of new stratigraphic data.

The relationships between the stratigraphic record presented here and the global sea-level changes are generally disturbed by the geodynamic (subsidence) evolution of the basins. However, global sea-level changes probably affected the dynamic of transgression–regression in the URG as well as in the Molasse basin (see discussion below).

## Helvetic domain subalpine Molasse and Foreland Molasse (Fig. 7)

### Eocene

Deep marine sediments of Lutetian to Priabonian age are present in the Helvetic nappes (Einsiedeln Formation, Steinbach-Gallensis Fm., Bürgen Fm., *Globigerinenmergel*, *Flysch sudhelvétique*, *Marnes à Foraminifères*, Hohgant Fm.). In addition, coastal facies (Klimsenhorn Fm., Wildstrubel Fm.) and brackish environments (*Couches à Cerithes*, *Couches des Diablerets*, Sanetsch Fm.) of the same age are known (Herb 1988; Herb et al. 1984; Menkveld–Gfeller 1994, 1995, 1997; Weidmann et al. 1991).

In the Plateau Molasse, continental deposits, rich in lateritic remains (the so-called *Siderolithic*, with *Bohnerz* and/or *Hupper* = quartz sands), were deposited, some of them dated by mammals (Egerkingen, Eclepens, Gösgen Kanal, see Engesser and Mayo 1987; Engesser and Mödden 1997; Hooker and Weidmann 2000).

### Oligocene

In the Helvetic domain and the subalpine Molasse, marine sedimentation continued with the Lower Marine Molasse (UMM) during the Rupelian. The UMM comprises the *Meletta-shales*, the *Taveyannaz* and *Aldorf sandstones*, the Val d'Illiez Fm. and the Vaulruz Fm. (see

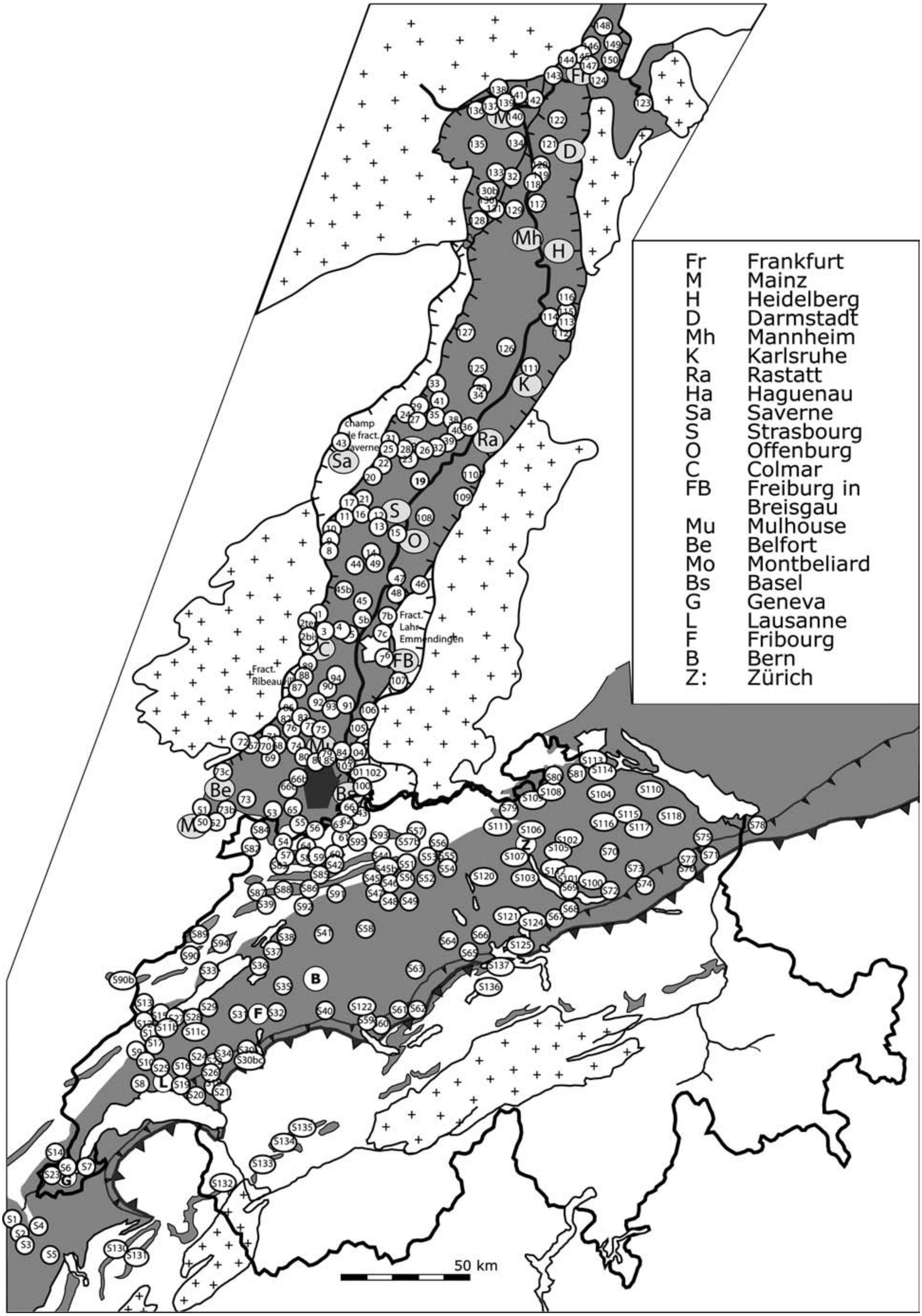

Fr Frankfurt
M Mainz
H Heidelberg
D Darmstadt
Mh Mannheim
K Karlsruhe
Ra Rastatt
Ha Haguenau
Sa Saverne
S Strasbourg
O Offenburg
C Colmar
FB Freiburg in Breisgau
Mu Mulhouse
Be Belfort
Mo Montbeliard
Bs Basel
G Geneva
L Lausanne
F Fribourg
B Bern
Z: Zürich
Fract. Lahr Emmendingen
50 km

**Fig. 5** List of the localities (see map on Fig. 4)

1. Rohrschwihr
2. Sigolsheim
2bis Turkheim, Wintzenheim, Wettolsheim
2ter Bergheim-Mittelwihr
3. Ostheim
4. Illhausern
5. Elsenheim
5b Oehnenheim
6. Eichstätten-Pfaffenthal-Bölzingen
7. Wasenweiler
7b Herbolzheim, Emmendingen
7c Limberg
8. Heiligenstein
9. Obernai, Bischofsheim, Barr
10. Bischoffsheim-Rosheim
11. Ergersheim-Scharrachberg-Wolxheim
12. Entzheim-Hölzhheim
13. Lipsheim
14. Schaeffersheim
15. Eschau
16. Kolbsheim
17 Ittlenheim
18 Truchtersheim-Kelinfrankenheim -Reitwiller
19. Gambsheim-Killstett
20. Kienheim
21. Dossenheim-Wiwenheim-Quatzenheim
22. Schaffhouse-Hochfelden
23. Bischwiller
24. Woerth (+ Diffenbach)
25. Wittersheim
26. Schirrheim
27. Schwabwiller
28. Schweighouse (2) & Ohlungen
29. Merkwiller - Pechelbronn, Lobsann + Soultz s- Forets & Retschwiller
30. Schwabwiller
31. Dauendorf
32. Soufflenheim-Sessenheim
33. Altenstadt-Oberhof , Riedseltz, Wissenbourg
34. Scheibenhard
35. Rittershofen
36. Beinheim
37. Wintzenbach
38. Niederroedern , Hatten, Croetwiller
39 Auenheim
40 Forstfeld
41. Oberseebach
42. Büchelberg
43. Région Bouxwiller-Grand Basberg
44. Westhouse, Osthouse, Uttenheim
45. Sundhouse
45b Ebertsheim
46. Lahr, Dinglingen, Burgheim, Dingten, Mittersheim, Schutterlindenberg
47. Nonnenweiler
48. Mahlberg
49. Erstein-Kraft
50. Allondans, Ste Suzanne, Pezol
51. Bethoncourt
52. Audincourt-Exincourt
53. Rechésy
54. Charmoilles
55. Bouxwiller-Oltingue-Kiffis
56. Wollschwiler
57. Boecourt, Seprais
58. Develier-Delémont
59 Vicques
60. Corban
61. Laufen-Brislach-Breitenbach
62. Oberwil-Therwil-Witterswil
63. Leymen
64. Mettenberg
65. Knoeringue-Durlinsdorf
66 Neuwiller, Allschwil
66b Altkirch, Tagolsheim
66c Dannemarie
67. Sentheim
68. Schweighouse sur Thann
69 Burnhaupt
70. Guewenheim, Mischelbach
71. Cernay
72. Hoelenslheim-Lauw
73. Froidefontaine, Bourogne, Morvillars
73b. Allenjoie
73c. Bethovillers & Roppe
74. Reiningue
75. Wittenheim, Sausheim
76. Staffelfelden, Wittelsheim
77. Schoenensteinbach
78. Rheinweiler
79. Zimmersheim, Rixheim, Riedisheim
80. Brunnstadt, Hochstadt
81. Bruebach
82. Hartmannswiller, Wuenheim
83. Einsisheim, Ungersheim
84. Homburg
85. Habsheim
86. Soultz Haut Rhin
87. Rouffach
88. Pfaffenheim, Hattstadt, Herrlisheim, Gueberschwihr
89. Eguisheim
90. Oberbergheim & Niederbergheim
91. Blodenheim, Fessenheim
92. Meyenheim
93. Hirtzfelden
94. Hettenschlag
100. Tüllingen
101. Istein, Kelinkems
102. Hammerstein, Wolzen, Kandern, Rötteln
103. Sierentz
104 Mühleim-Schiengen
105. Oberweiler, Zienken, Bitzingen, Stauffen
106. Grissheim
107. Pfaffenweiler-Merzhausen
108. Kork
109. Bühl 1
110. Baden-Baden 1 & 2
111. Linkenheim 1
112. Ubstadt
113. Malsch sondages
114. Rott-Malsch
115. Oberhausen 1
116. Wiesloch, Rauenberg
117. Hofheim 3
118. Eich 17
119. Biebesheim 2
120. Stockstadt
121. Dornheim 9
122. Königsstädten
123. Gross Anhaim-Gross Katzenburg
124. Obertshausen
125. WInden 4
126. Rülzheim 1 & 2
127. Landau west 1
128. Göllheim 1 , Kerzenheim, Lautersheim 1
129. Worms 3
130. Alzey 1, 2, Heimersheim, Weinheim
130b. Ufhoffen, Flonheim
131. Galgenberg, Eppelsheim, Westhofen, Gundersheim, Bermersheim, Esselborn
132. Alsheim, Dorn-Dürkheim
133. Gabsheim
134. Oppenheim 1, Nierstein, Bodenheim
135. Sprendlingen 3 , Wissberg 2, Wolfsheim
136. Algesheim, Ingelheim
137. Heidesheim
138. "Rodung Vollrads"
139. Budenheim 1
140. Nackenheim, Weisenau
141. Wiesbaden 1, Hessler, Kostheim
142. Flörsheim 1, Hochheim
143. Niederhöchstadt
144. Bommersheim
145. Beckersheim-Bodenheim
146. Niedererlenbach
147. Fechenheim
148. Rockenberg, Wölfersheim, Echszell
149. Ostheim 1
150. Ravolzhausen (Mn2)

S1. Pyrimont-Challonges, Génissiat
S2. Findreuse 3-27
S3. Chavannes
S4. La Chaude Fontaine, Rte de Serasson, Fornant 6-13
S5. Lovagny
S6. Avanchet
S7. Choulex
S8. Vaux
S9. Veyron 2
S10. Cossonay
S11. Boscéaz, Orbe
S11b Eclepens, Alleveys, Mormont Entreroches
S11c Augine
S12. Rances, Perrée, Valeyres
S13. La Chaux
S14. Sergy (SPM5)
S15. Ruisseau du Bey
S16. Talent 12
S17. Talent 1-19, Cuennet, Bavois
S18. Mt Chesau, Bois de Tey 5-7
S19. Region Lausanne: La Mèbre 630+698, Bois-Genoud, Les Bèrgieres, Les Pierrettes, Rochette, Paudèze 2-15, Flon 2, Le Lendar, Savigny, Chandelar B, Le Marcheret
S20. La Cornalle
S21. Bellières
S22. Les Fontanettes 1-2
S23. La Roulavaz
S24. Broye 555
S25. Petite Chamberonne
S26. Vuibroye F, Moulin de Haut Crêt
S27. Cheseaux-Noréaz
S28. La Maugettaz
S29. Cheyres
S30. Le Gérignoz
S30b Vaulruz
S31. Arbogne 2
S32. Ameismühle, Gottéron 1+6
S33. Boudry
S34. Lieffrens
S35. Schiffenen 4
S36. Vully 1
S37. Brüttelen 2
S38. Mörigen
S39. Cortébert
S40. Seligraben
S41. Messen
S42. Vermes, Corban
S43. Basel-St Jakob
S44. Brochenen Fluh, Waldenburg-Humbel, Breitehöchi, Mümliswil
S45. Oensingen
S45b Egerkingen
S46. Wolfwil, Wynau 1+2
S47. Bannwil
S48. Wischberg
S49. Roggliswil
S50. Boningen
S51. Rickenbach
S52. Bierkeller, Brunngraben, hinterer Bühnenberg, Safenwil
S53. Gösgen-Kanal
S54. Hirschthal
S55. Gränichen-Moorberg
S56. Küttigen
S57. Anwil
S57b Zeglingen
S58. Wyningen-Brittenberg
S59. Schwendibach, Frohberg, Tobel-Hombrechtikon, Hottwil, Chlaustobel, Matt Tébeli, Martinsbrunneli, Tägernaustrasse, Hummelberg
S60. Losenegg 1+2, Marbachsection, Cheistlisteig, Dürrenbach, Pressenrenbach, Thun 1, Eriz
S61. Hombach 3
S62. Bumbach 1, Emme Section, Trub-Sältenbach
S63. Hasenbach 1, Eimattili, Oeschgraben, Schwändigraben, Fontannen Section
S64. Werthenstein-Grabenhüsli
S65. Rümlig 2, Rängg loch 3/8
S66. Löwencenter, Hintersteinbruch, Luzern 10/76
S67. Sparenweid
S68. Feusisberg
S69. Schliffitobel, Bürgistobel B, Tobel +Speerstrasse Hombrechtikon, Matt
S70. Ergeten, Steg, Chlihörnli, Grat, Bärtobel-Hörnli, Goggelswald, Gfell
S71. Sommersberg
S72. Goldingertobel, Lattenbach, Fätzikon
S73. Dorfbachtobel, Wattwil
S74. Ebnat-Kappel, Wintersberg-Trempel, Umfahrungsstrasse+Thur-Krummenau Steintal section
S75. Martinsbrücke
S76. Appenzell-Kaubach
S77. Sägibach
S78. Unter Staudach, Schwarzachtobel
S79. Kaiserstuhl
S80. Benken am Kohlfirst
S81. Schlattingen
S82. Bressaucourt
S83. Glovelier, Neuf Camps
S84. Bonfol
S85. Moutier, Pâturage
S86. Court, Golat
S87. Tramelan
S88. Tavannes
S89. La-Chaux-De-Fonds, Le Locle
S90. Les Ponts de Martel
S90b Les Verrières
S91. Balm
S92. Grenchen 1
S93. Bennwil
S94. Vue Des Alpes
S95. Nebelberg

S100 Ornberg, Schwartz-Rüti, Güntisberg, Hüllistein
S101 Esslingen
S102 Gerstel, Elgg, Schauenberg
S103 Langnau
S.104 Imenberg-Stettfurt, Chräzerentobel
S105 Rümikon
S106 TMC-Glattbruggg
S107 Hirschengrabentunnel Zh
S108 Andelfingen
S109 Buchberg
S110 Hellsigshausen-Fischbach, Ottenberg
S111 Iberg
S112 Küssnacht borehole
S113 Wiesholz
S114 Oeningen
S115 Greuterschberg, Mttelen-Weid
S116 Schauenberg
S117 Utzwil, Nutzenfluh
S118 Lauffenbach

S120 Boswil 1
S121 Hünenberg 1
S122 Linden 1
S123 Fisch 2, Fischenbach section, Entlebuch 1
S124 Höhronen section
S125 Rigi section, Rigi 1 & 2

S130 Dessy
S131 Molettes, Portettes, Lombardes, Palton
S132 Covaye, Platté
S133 Quille, Pierredar, Lizerne, Diablerets
S134 Tzanfleuron
S 135 Fürstli, Schwand, Rothorn, Niesen, Sanetsch, Rawil
S 136 Foribach
S 137 Bürgenstock, Klimsenhorn

1. Steinbach/Gallensis Formation, Bürgen Fm., Klimsenhorn Fm.
2. Globigerinenmergel, Flysch sudhelvétique, Marnes à Foraminifères, Hohgant Formation (base)
3. Klimsenhorn Formation, Wildstrubel Fm.
4. Siderolithic, Eozäner Basiston
5. Calcaires à petites nummulites, Cerithium Beds, Couches à Cérithes, Couches des Diablerets, Sanetsch Fm.
6. UMM Meletta shale, Taveyannaz and Aldorf sandstones, Val d'Illiez Fm.
7. UMM Vaulruz Fm., Grisiger Mergel & Horwer Sandstein
8. UMM Top Baustein Beds
9. USM Molasse rouge, Untere Bunte Mergel and Conglomerates, Mt. Pelerin Fm., Beichlen Fm. and Uerscheli Fm., Homberg Beds, Losenegg Beds, Schwändibach conglomerate, Thun conglomerate, Honegg marls, Gitzischöpf conglomerate
10. USM Molasse à charbon and conglomerates
11. USM Calcaires and Dolomies
12. USM Grès and Marnes grises à gypse (GMGG)
13. USM Molasse grise de Lausanne ( and local conglomerates), Gunten Quartzite, Granitische Molasse
14. OMM (Luzern Fm., St-Gall Fm., Sense Fm., Belpberg Fm.)
15. OSM (conglomerates)
16. Calcaires inférieurs, Krustenkalk
17. Obere Bunte Mergel (and sandstones)
18. OMM-OSM transition, Marnes rouges, Rote Mergel, Helicidenmergel, Graupensandrinne
19. OSM ("Oeningian") and Glimmersand
20. Hegau and Höwenegg series
21. Molasse alsacienne
22. Calcaires delemontiens
23. Calcaires de La Chaux
24. Karst Vue des Alpes
25. Gelberde, Raitsche
26. Fischschiefer, Septarienton, Meeressand, Foraminiferenmergel,
27. Conglomerate de Porrentruy
28. Calcaires de Vermes
29. Anwiler Kalke
30. Juranagelfluh s.l., Vogesensande, Hipparionsande, Dinotheriensande, Bohnerzton, ?Wanderblock Fm. ?, ?Heubergschotter?, Dorn-Dürkheim Beds, Lautersheim Formation
31. Sundgauschotter and Argiles de Bonfol, Weiße Serie
32. URG-conglomerates and breccies ("Steingang")
33. Planorbenkalke, Calcaires d'eau douce "Lutétiens", Bouxwiller Fm.
34. Lymneenmergel, Marnes vertes, Grüne Mergel
35. Melanienkalke
36. Salifère inférieur, Lower Salt Fm.
37. Messel Formation
38. Ältere Eisenberger Tonfolge, Eisenberger Grünton
39. Lower Pechelbronn Beds, Rote Leitschicht, Couches Rouge
40. Zone dolomitique
41. Salifere moyen, Middle Salt Fm.
42. Plattiger Steinmergel, Marnes et calcaires en plaquette, Zone fossilifère
43. Middle Pechelbronn Beds
44. Salifere supérieure, Upper Salt Fm.
45. Haustein
46. Upper Pechelbronn Beds
47. "Serie grise", (Foraminiferenmergel, Fischschiefer, Meletta-Beds, Cyrenenmergel, etc.), Alzey Fm, Bodenheim Fm., Stadecken Fm., Sulzheim Fm. (pars)
48. Freshwater Beds, Niederroedern Beds
49. Tüllinger Kalk
50. Ältere Deckenschotter
51. Arvernensis-Schotter, Klebsand, Weißes Mio-Pliozän, Ältere Weisenauer Sande "Pliocene not differenciated", Pliozän I-III, Jungtertiär II (higher part)
52. Lower Cerithium Beds, Sulzheim Formation (pars)
53. Middle and Upper Cerithium Beds, Landschneckenkalke, Lower Hydrobia Beds, Oberrad Formation, Oppenheim Formation
54. Rüssingen Formation, Inflata-Beds and Wiesbaden Fm, Upper Hydrobia Beds, Landscheckenmergel, Niederrad Formation, Jungtertiär I
55. Praunheim Formation, Staden Fm., Bockenheim Formation, Salzhausen Beds, Main Trapp, Jungtertiär II (lower part)

**Fig. 6** List of lithostratigraphic units

Diem 1986; Kuhlemann and Kempf 2002; Lateltin 1988; Schlunegger et al. 1997). In the western part of the Swiss Molasse Basin (SMB), marine sedimentation stopped earlier (not younger than NP22, Berger 1992b; Berger et al. 1987; Carbonnel 1982) than in the eastern part, where marine sediments are known until NP24 or even NP25 (Doppler et al. 2000; Deutsche Stratigraphische Kommission 2002; Oberhauser et al. 1991). Following the general sea-level drop (corresponding with the Ch1 sequence at 28.5 Ma, see Hardenbol et al. 1998) these deposits are followed by the freshwater deposits of the Lower Freshwater Molasse (USM), which consist of conglomeratic alluvial fan deposits, fluviatile sediments, and palustrine-lacustrine deposits, e.g., the *Molasse à Charbon* (see Berger 1992b, 1998; Engesser et al. 1984; Fasel 1986; Schlunegger et al. 1996, 1997a, b, c).

In the Plateau Molasse, some punctual lacustrine deposits of Rupelian age are known (*Calcaires inférieurs*), which are generally dated by charophytes (Berger 1992b; Weidmann 1984). In the Lower Chattian, fluviatile sediments (*Untere Bunte Mergel*) are present in the whole Foreland Basin. During the Middle and Late Chattian, lacustrine and brackish limestones, dolomites, and gypsiferous marls occurred. In the NEdistal part of the basin, sedimentation probably started not before the middle Chattian (Müller et al. 2002; Schlunegger and Pfiffner 2001). All mentioned units are relatively well dated by mammals, charophytes, otolithes and magnetostratigraphy (Berger 1992b, 1996; Engesser 1990; Engesser and Mödden 1997; Kempf et al. 1999; Kissling 1974; Platt 1992; Reggiani 1989; Reichenbacher and Weidmann 1992; Reichenbacher 1996; Schlunegger et al. 1996, 1997a, b, c; Strunck and Matter 2002).

## Miocene and Pliocene

No Miocene sediments have been recorded in the subalpine Molasse of Western Switzerland. Some conglomeratic fans persist in Eastern Switzerland until the Middle Aquitanian (Schlunegger et al. 1997a, b, c).

In the Plateau Molasse, fluviatile facies characterizes the Aquitanian deposits (*Molasse Grise de Lausanne*, *Obere Bunte Mergel*, *Granitische Molasse*, see Berger 1985; Keller et al. 1990). A marine transgression (partly corresponding to the global sea-level rise following the Bur 1 sequence at 20.5) flooded the Foreland Basin during the late Aquitanian (MN2) and Burdigalian; its typical deposits are the Upper Marine Molasse (OMM) (Berger 1985, 1996; Graf 1991; Homewood and Allen 1981; Keller 1989; Kempf et al. 1997, 1999; Kempf and Matter 1999; Kuhlemann and Kempf 2002; Schaad et al. 1992; Schoepfer 1989; Strunck and Matter 2002).

During the Langhian, marine sediments were confined to the North, with local "Juranagelfluh" in the NE (Graf 1991); whereas fluviatile sediments related to alluvial fans were present in the South (OSM = Upper Freshwater Molasse), and persisted until the Serravallian (MN7, ?MN8) (Bolliger 1992, 1997, 1998; Kälin and Kempf 2002; Kempf et al. 1999).

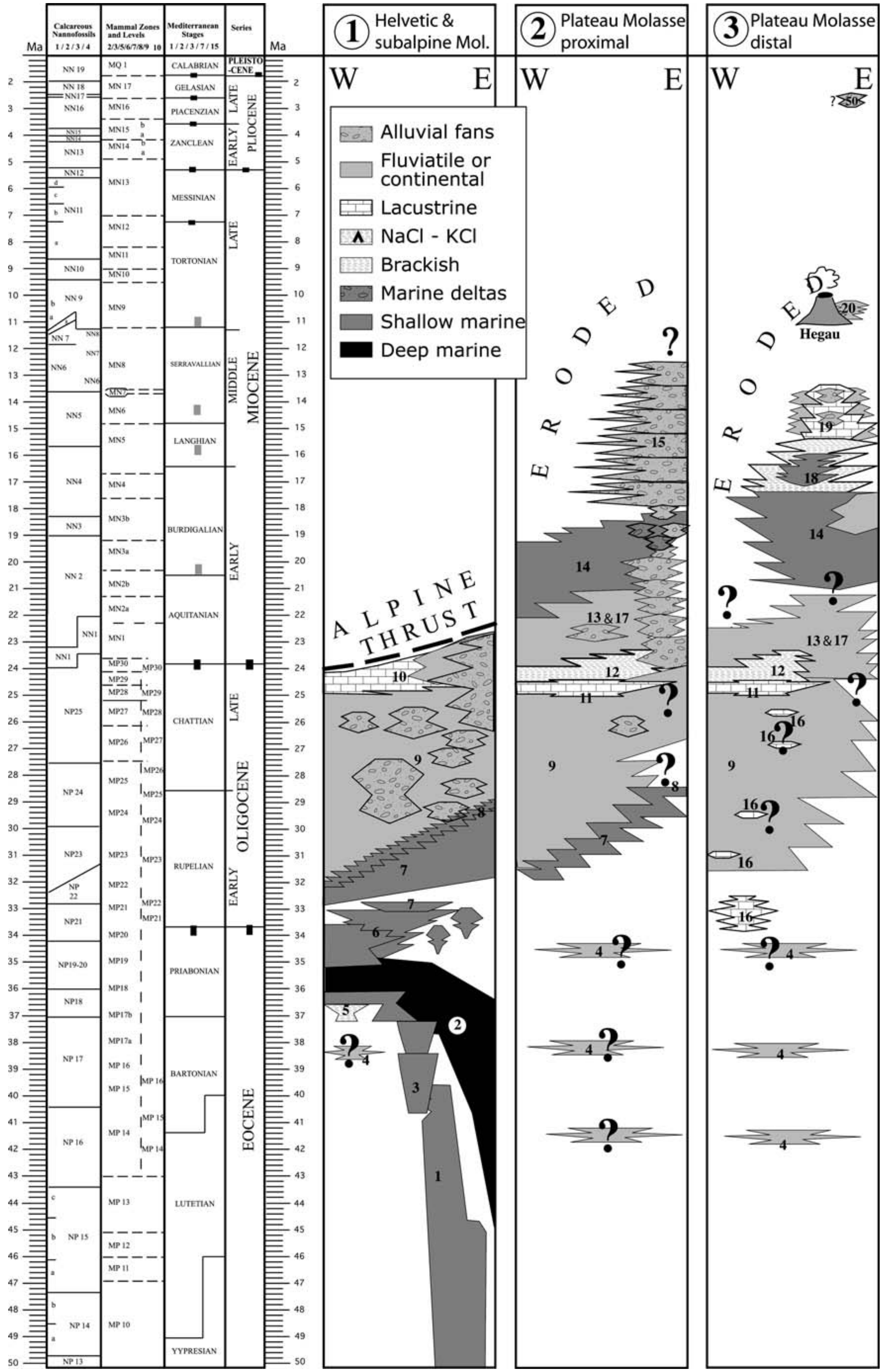
No Late Serravallian, Tortonian and Messinian sediments have been recorded, except in the Northeastern part (Höwenegg, MN9, Tobien 1986). However, several authors suggested an additional 700 m and up to more than 2,000 m were deposited in the Eastern and Western Molasse basin, respectively (see Kuhlemann and Kempf 2002).

The Pliocene is represented only by conglomerates (*\''Altere Deckenschotter*, Graf 1993) in the Northeastern part, with one dated locality (Irchels, MN17, see Bolliger et al. 1996).

## The Molasse of the Jura Mountains (Fig. 8)

In the Jura mountains, Tertiary sediments have been preserved in a number of synclines.

These series were studied in detail by Picot (2002) and Becker (2003).


Calcareous Nannofossils
Mammal Zones and Levels
Mediterranean Stages
Series
Ma
Helvetic & subalpine Mol.
Plateau Molasse proximal
Plateau Molasse distal
W
E
Alluvial fans
Fluviatile or continental
Lacustrine
NaCl - KCl
Brackish
Marine deltas
Shallow marine
Deep marine
ALPINE THRUST
ERODED
Hegau
CALABRIAN
GELASIAN
PIACENZIAN
ZANCLEAN
MESSINIAN
TORTONIAN
SERRAVALLIAN
LANGHIAN
BURDIGALIAN
AQUITANIAN
CHATTIAN
RUPELIAN
PRIABONIAN
BARTONIAN
LUTETIAN
YPRESIAN
PLEISTO-CENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
EARLY
MIDDLE
LATE

◀

**Fig. 7** Stratigraphy of the Helvetic domain, Subalpine and Plateau Molasse

### Eocene

Eocene deposits are represented by the *Siderolithic*. Even though it was never precisely dated, its Lutetian, Bartonian and Priabonian age is suggested owing to correlation with other siderolithic localities (see Chap 2.1)

### Oligocene

During the Oligocene, the different synclines experienced a diversified sedimentary history.

In the Southwest (Fig. 8, column 4), some lacustrine limestones (*Calcaires inférieurs*) appear, which, so far, have not yet been precisely dated. These are overlain by fluviatile sediments, probably of Rupelian to Chattian age (*Untere Bunte Mergel*), and finally by calcareous limestones and gypsiferous marls of Late Chattian to Early Aquitanian age (Berger 1996; Mojon et al. 1985).

In the Northwest (Fig. 8 column 5), no deposits are known from that time.

In the central part, the conditions vary from South to North:

- in the South (Fig. 8 column 6), lacustrine limestones are present that range in age from Early Rupelian (dated by charophytes of the *tuberculata* zone in the Moutier syncline, see Reichenbacher et al. 1996) to Early Chattian (mammals in Oensingen, Wynau or Soulce, see Engesser and Möedden 1997). They are overlain by the fluviatile *Molasse alsacienne* with a possible marine horizon, but a reworking of marine alpine material cannot be excluded (Reichenbacher et al. 1996). In the Late Chattian, lacustrine limestones (*Calcaires delémontiens*) and gypsiferous marls were common and persisted until the Early Aquitanian.
- in the North (Fig. 8 column 7), Tertiary started in the Priabonian with lacustrine-brackish deposits (*Gelberde*, *Raitsche*) in the Delsberg Basin, and with the *Porrentruy conglomerates* near the French border (see also Clement and Berger 1999; Picot et al. 2004). These deposits are overlain by marine Late Rupelian sediments (*Foraminiferenmergel*, *Fischschiefer*, *Septarienton*), which additionally build up the base of the Tertiary deposits in the Laufen Basin (NP22 and 23). Then follow fluviatile sediments (*Molasse alsacienne*), which are dated as MP23 to MP26, depending on the presence or absence of the marine sediments (Clement and Berger 1999). During the Late Chattian and Early Aquitanian, the *Calcaires delémontiens* indicated lacustrine sedimentation (Picot et al. 1999).

In the eastern Jura (Fig. 8 column 8), we find again the succession of the *Calcaires inférieurs*, the *Molasse alsacienne*, and the *Calcaires delémontiens*. The latter are well dated (from MP29 to MN1) in the Brochene Fluh section (Engesser and Mayo 1987; Becker et al. 2001).

### Miocene and Pliocene

In the Southwest (Fig. 8 column 4), the Aquitanian is only represented by the uppermost part of gypsiferous marls (dated as MN1), and the *Calcaires de La Chaux*, which is a famous fossil locality belonging to MN2 (Engesser and Mödden 1997). The following discordant transgression of the OMM is probably of Burdigalian age. Younger sediments are not known in this area.

In the Northwest (Fig. 8 column 5), Tertiary sedimentation started with the OMM. The overlying brackish-marine *Marnes rouges* are dated as NN4-5. Then follows the lacustrine *Oeningian* facies (MN6-7, see Kälin et al. 2001).

In the central part (Fig. 8 column 6 and 7), there is a time gap between the Early Aquitanian (MN1, top of *Calcaires delémontiens*) and the overlying transgressive OMM, which in the Tavannes area belongs to the Burdigalian (MN3, De Beaumont et al. 1984) and in Glovelier to the late Burdigalian (MN4, Hug et al. 1997). Thus, the Middle and Late Aquitanian, and perhaps the earliest Burdigalian sediments are missing. The OMM is overlain by the lacustrine *Oeningian* facies (MN6-7) or the *Calcaires de Vermes* (MN5, Kälin 1993; Kälin and Kempf 2002). Then follow conglomerates and sands (*Jura Nagelfluh*, *Hipparion*- and *Vogesensande*, Bois de Raube Formation), which have been dated by mammals to MN6 up to MN9 (Kälin 1993, 1997b; Kälin and Engesser 2001). The so-called *Wanderblock* Formation probably was deposited during this time (Kemna and Becker-Haumann 2003).

In the Eastern part (Fig. 8 column 8), the OMM is generally followed by the brackish complex of the *Marnes rouges*, and then by the fluviatile "Glimmersandschüttung". During the Burdigalian, the "Graupensandrinne", an estuarine system running along the distal border of the German part of the Foreland Basin, was active (Reichenbacher et al. 1998).

The only Late Miocene or Pliocene deposits in this area are the karstic filling of the Vue des Alpes (which is dated as MN15 and is posterior to the main Jura folding, see Bolliger et al. 1993), and the Höhere Deckenschotter from Irchels (Bolliger et al. 1996).

## The South and Middle Upper Rhine Graben (URG) (Fig. 9)

### Eocene

Eocene sedimentation generally began with the rarely dated Siderolithic (Pharisat 1982, MP19) that can be attributed to the Middle to Late Eocene in comparison

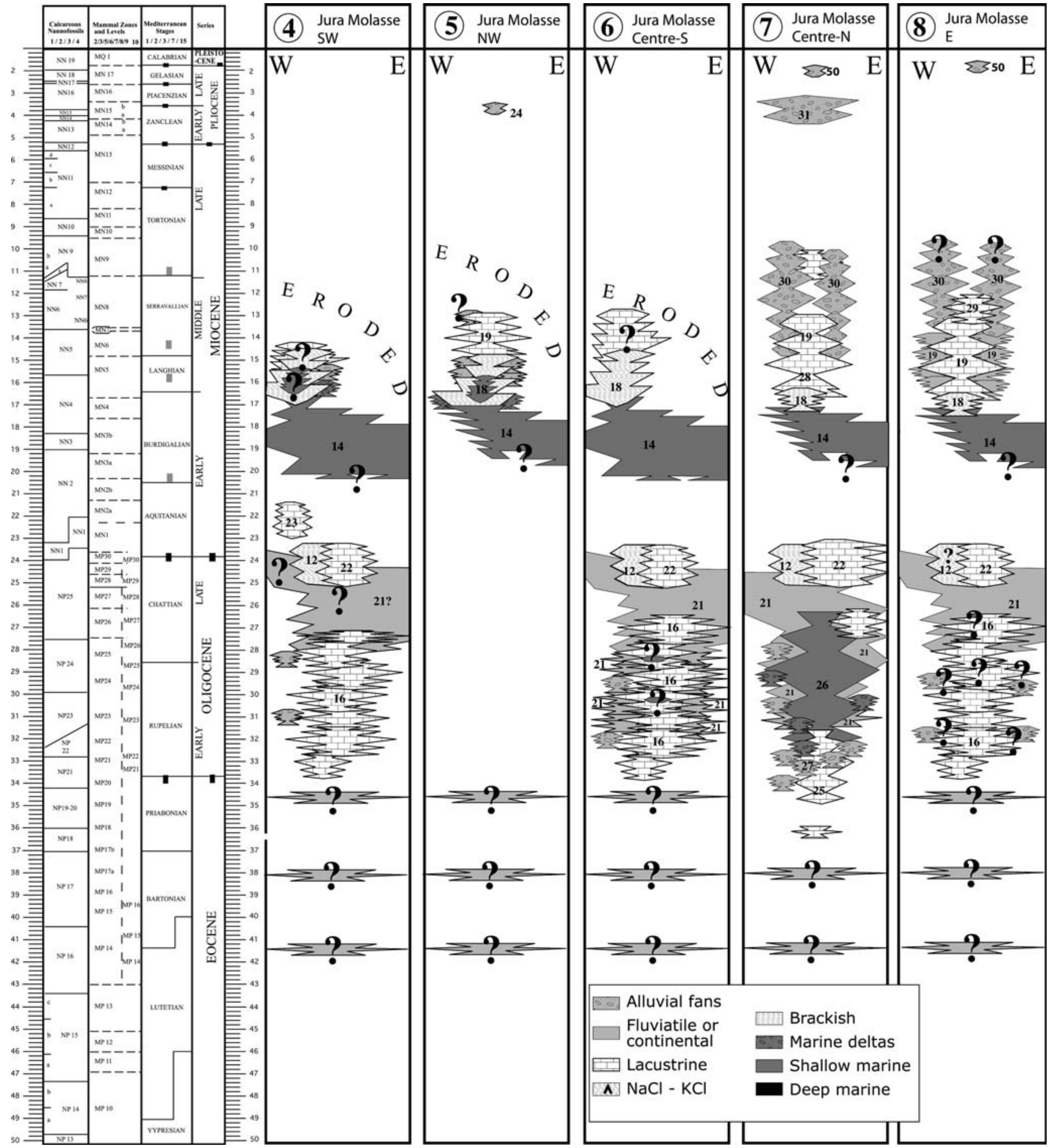



**Fig. 8** Stratigraphy of the Jura Molasse

with adjacent areas. It is followed by various sedimentary facies depending on the syntectonic processes in the URG at that time.

In its Southern part (Fig. 9 column 9), the URG is tectonically subdivided W to E into the following four major areas, the Dannemarie Basin, Mulhouse Horst (with Altkirch- and Sierentz blocs), Sierentz Basin, and the Basel Horst (Förster 1905; van Werveke 1908; Wittmann 1949; Doebl 1970; Lutz and Cleintuar 1999; Sittler 1965, 1972, 1992; Sittler and Schuler 1988):

– In the Dannemarie Basin, important accumulation of brackish sediments (*Lymnaeenmergel*) and salt (Lower Salt Formation) is known. Their ages span probably from the Lutetian to the Priabonian, possibly from NP12 to NP17 (see Chateauneuf 1983; Sittler 1965;

Schuler 1983, 1988, 1990). However, it is not clear if sedimentation was continuous, or a gap corresponds to the Bartonian, as postulated by Sissingh (1998). In the western part, some undated conglomerates are tentatively assigned to the Lutetian and the Priabonian (Duringer 1988).

- On the Mulhouse Horst, brackish marls and lacustrine limestones are present, probably ranging from Lutetian to Priabonian. The *Melanienkalke* are clearly dated to the Priabonian (MP18) at Brunstatt (Schwarz 1997; Tobien 1949, 1968, 1987, 1988a).
- In the Sierentz Basin, the *Lymnaea marls* (also called *Green marls*), lacustrine limestones and the Lower Salt Formation (but without salt!) were deposited (Sittler 1965). In the eastern part, some conglomerates probably accumulated during the Priabonian. At the locality Pfaffenweiler, they could be dated by mammals to MP18 (Tobien 1968, 1987, 1988b).
- In the northern part of the Basel horst, a condensed sequence is present, which is very similar to that of the Mulhouse horst. In the southern part, Eocene sediments are absent (Doebl 1970).

In the middle part (Fig. 9 column 10) we recognize a similar situation from W to E, with lacustrine limestones, *Lymnaea marls* and Salt formation (especially developed in the Western part). A brackish complex (*Zone dolomitique*) generally overlies these deposits, but is not dated. Conglomeratic facies is present at both borders (particulary from the Priabonian onwards).

Toward the north, the Lower Pechelbronn Beds are partly dated by mammals as Priabonian (MP 20, Tobien 1987, 1988).

In the northern part (Fig. 9 column 11) a Lutetian age of the lacustrine limestones at Bouxwiller is documented by charophytes and mammals attributed to the MP13b zone (Jaeger 1971; Schmidt-Kittler et al. 1997; BiochroM'97 1997). Also the *Lymnaea marls* (or *Zone de marnes à anhydrite*) could be correlated by charophytes with the Lutetian (*embergeri* zone, Breuer and Feist 1986; Riveline 1985). An undated brackish complex (*Zone de marnes dolomitique*) generally overlies these deposits. The *Zone de marnes à anhydrite* and the *Zone de marnes dolomitique* are combined by Schnaebele (1948) to the *Zone dolomitique* (or *Green Marls*), which underlie the Lower Pechelbronn Beds in the Pechelbronn Basin). Conglomerates are also present on both sides of the graben.

## Oligocene

In the southern part (Fig. 9 column 9), the Early Rupelian sedimentation is represented by

- the Middle and Upper Salt Formation (Dannemarie Basin)
- the *Zone fossilifère* and the *Streifige Mergel* (= *Marnes en plaquettes*) as well as the *Haustein*. The latter is dated as NP21-22 (Schuler 1988, 1990) and MP21 (Altkirch, see Storni 2002, Mulhouse Horst)
- the conglomeratic facies at both borders.

The *Zone fossilifère* represents the first Rupelian transgression from the North Sea (partly corresponding with the global sea-level rise following the Ru 1 sequence at 33 Ma, see Harednbol et al. 1998) and separates the Middle from the Upper Salt Formation.

In the Middle Rupelian, the most important marine transgression, second marine Rupelian transgression from the North Sea, corresponding to the global sea-level rise between sequences Ru2 and Ru3, see Hardenbol et al 1998) flooded the whole basin, with the classical succession: *Foraminiferenmergel—Fischschiefer—Meletta—Schichten* (partly). These sediments range from NP23 to NP24 (Grimm 2002a; Müller 1988; Pharisat 1991). They are combined with the Late Rupelian brackish-marine *Cyrenenmergel* to the so-called *Graue Serie* (= *Série grise*) and represent an important marker on seismic lines.

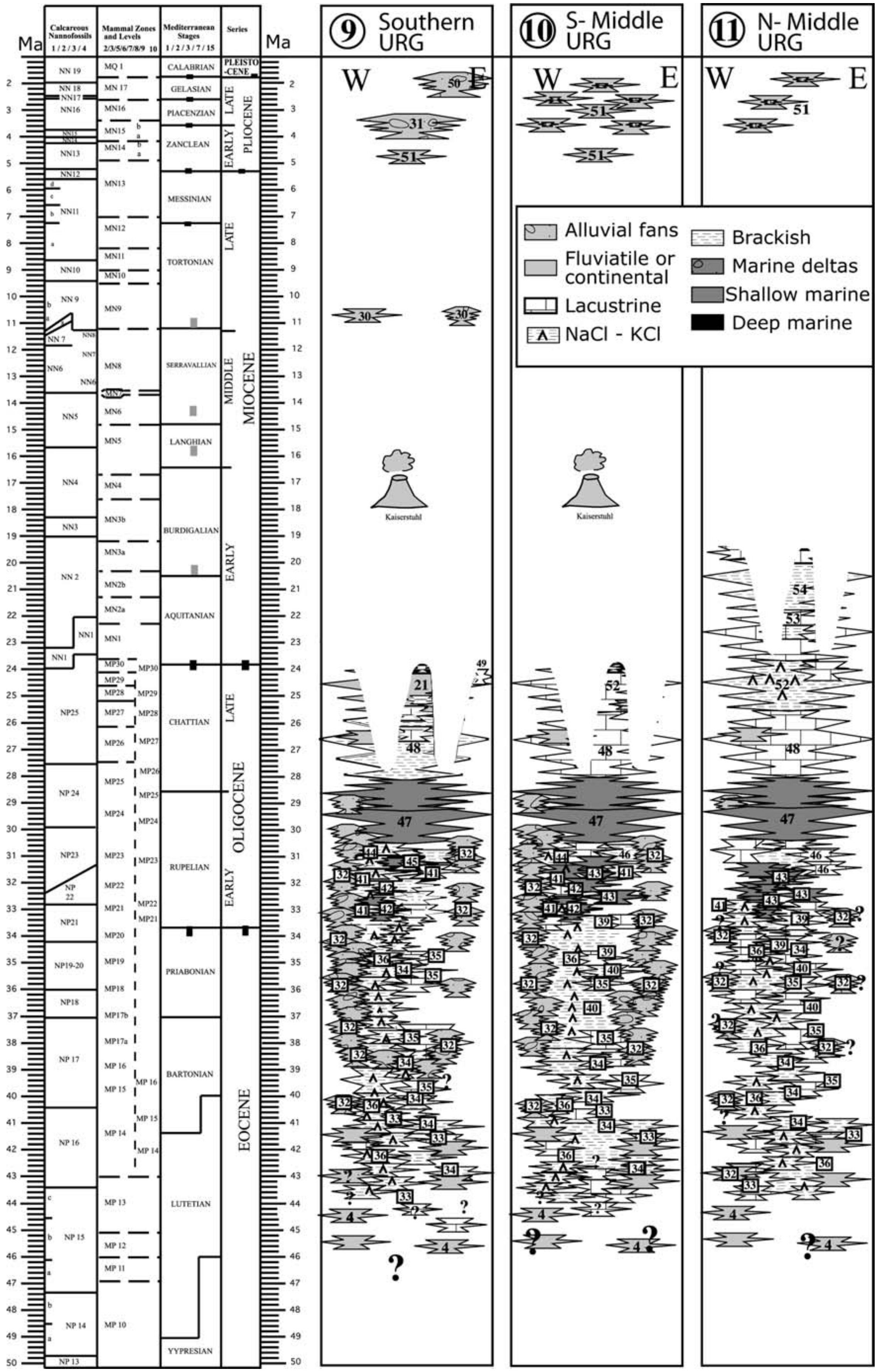
During the Early Chattian, the fluviatile sediments of the *Molasse alsacienne* interfingered to the north (Tüllinger Berg) with lacustrine or brackish marls (*Gipsmergel*, see Wurz 1912). During the Middle and Late Chattian, the lacustrine limestones of the *Calcaires delémontiens* and the *Tüllinger Kalk* were deposited. The *Calcaires delémontiens* are well dated as MP29 to MN1 in the Jura Molasse (Becker 2003; Picot 2002), and the *Tüllinger Kalk* can be correlated by charophytes to the Middle Chattian *Stephanochara ungeri* Zone (Nötzold 1962).

In the middle part, the Middle Salt Formation and the brackish-marine Middle Pechelbronn Beds are present. Even though their correlation is not fully solved, they probably belong to the NP22 and MP21 zones (Martini 1973; Griessemer 1998, 2002; Storni 2002; Derer 2003 and discussion on Fig. 2).

The overlying Upper Salt Formation and the Upper Pechelbronn Beds can be assigned to MP21 and MP22 (= ? NP22 and NP23, Schwarz and Griessemer 1992).

The marine-brackish Middle to Late Rupelian *Serie grise* covers these units, and is itself overlain by the fluvio-lacustrine Niederroedern Beds and the brackish-lacustrine Cerithium Beds (Doebl and Geissert 1971; Doebl et al. 1976). In some localities, these freshwater sediments are also referred to as *Molasse alsacienne*.

In the northern part (Fig. 9 column 10 and 11), the Early Rupelian sedimentation is represented by the Middle Pechelbronn Beds, followed by the Upper Pechelbronn Beds, the *Série grise* and the Niederroedern Beds. Based on lithostratigraphic correlations with the Süßwasserschichten of the Mainz Basin, the Niederroedern Beds belong to the Middle to Upper Chattian. The overlying Lower and Middle Cerithium Beds, and the lowermost part of the Upper Cerithium Beds are of Upper Chattian age (Martini 1978; Reichenbacher 2000).


Ma
Calcareous Nannofossils 1/2/3/4
Mammal Zones and Levels 2/3/5/6/7/8/9 10
Mediterranean Stages 1/2/3/7/15
Series
Ma
9 Southern URG
10 S- Middle URG
11 N- Middle URG
W
E
Alluvial fans
Fluviatile or continental
Lacustrine
NaCl - KCl
Brackish
Marine deltas
Shallow marine
Deep marine
Kaiserstuhl
CALABRIAN
GELASIAN
PIACENZIAN
ZANCLEAN
MESSINIAN
TORTONIAN
SERRAVALLIAN
LANGHIAN
BURDIGALIAN
AQUITANIAN
CHATTIAN
RUPELIAN
PRIABONIAN
BARTONIAN
LUTETIAN
YYPRESIAN
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
EARLY
MIDDLE
LATE

◀
**Fig. 9** Stratigraphy of the South and Middle URG

Miocene and Pliocene

From the Aquitanian onwards, the southern and middle parts of the URG were subjected to erosion. Sediments may have been deposited until uplift of the Vosges and Schwarzwald (Burdigalian), or the nondeposition already commenced during the Middle and Late Aquitanian, as proposed for the Jura molasse (see Picot 2002; Becker 2003).

Sedimentation rescued only locally during the Early Tortonian, with the deposition of the *Dinotherium* and *Hipparion sands* (dated by mammals as MN9, Tobien 1986a, 1988b).

No Messinian sediments are known. The last sedimentary event is represented by the *Sundgau Schotter*, which could be attributed to the Middle Pliocene (MN15 to 16) in comparison with the Bresse Graben mammal localities (Petit et al. 1996). The *arvernensis Schotter* is also punctually represented and dated as MN14–MN16 (Tobien 1988b). Pliocene deposits (dated by spores and pollens) are also known in the vicinity of Colmar and Strasburg.

In the northern part (Fig. 9 column 11), sedimentation continues in the Aquitanian with the brackish Upper Cerithium Beds, which are overlain by the Inflata Beds (now Rüssingen Formation, see chapter Miocene and Pliocene), which are followed by the Lower Hydrobia Beds (now Wiesbaden-Formation, see chapter Miocene and Pliocene). This sequence seems to belong to the Aquitanian, according to its correlation with the Mainz Basin (MN1 and MN2, see Reichenbacher 2000). The Upper Hydrobia Beds are still present, and may be attributed to the Early Burdigalian (MN3) by correlation with the Hanau Basin (see chapter Miocene and Pliocene). After an important gap (Burdigalian to Messinian), the sedimentation rescued again during the Pliocene, as known in the Haguenau area.

## The northern URG, the Mainz Basin and the Hanau Basin (Fig. 10)

Eocene

During the Eocene and Early Oligocene the northern part of the URG was not yet developed. Instead of this the main structures were influenced by preTertiary tectonism. From north to south the following prerift structures are recognized, namely the Rüsselsheim Basin, Palatinat-Stockstadt Ridge and Marnheim Bay (Grimm and Grimm 2003).

In the Rüsselheim Basin, the Marnheim Bay and the southward connected northern URG sedimentation began with the terrestrial *Eozäner Basiston* and *Basissand* (Sonne 1968; Schäfer 1996, 2000). On the Palastinat-Stockstadt Ridge, especially on its eastern part (the so-called Sprendlingen Horst), the Messel Formation accumulated in a maar-lake (Harms et al. 2000, 2001; Jacoby et al. 2000). These sediments are dated by mammals as MP11 (Tobien 1988b).

The Priabonian Lower Pechelbronn Beds overlay Eocene basal sediments in the Rüsselheim Basin. In the Marnheim Bay and in the URG, these basal sediments are overlain by the lacustrine to brackish deposits of the *Green marls*, the *Rote Leitschicht*, and the *Eisenberg clays* (Schäfer 2000; Grimm and Grimm 2003). The latter can be correlated to the Middle Lutetian by pollens and spores (Hottenrott 2000, 2002). The *Green marls* correlate to the Lutetian *embergeri* zone and the Priabonian *vectensis* zone by charophytes (Schwarz 1997). Generally, the Lower Pechelbronn Beds are dated as MP 20 (Derer 2003; Gad et al. 1990; Gaupp and Nickel 2001; Schwarz 1993, 1997; Schwarz and Griessemer 1994, Tobien 1949, 1968, 1987).

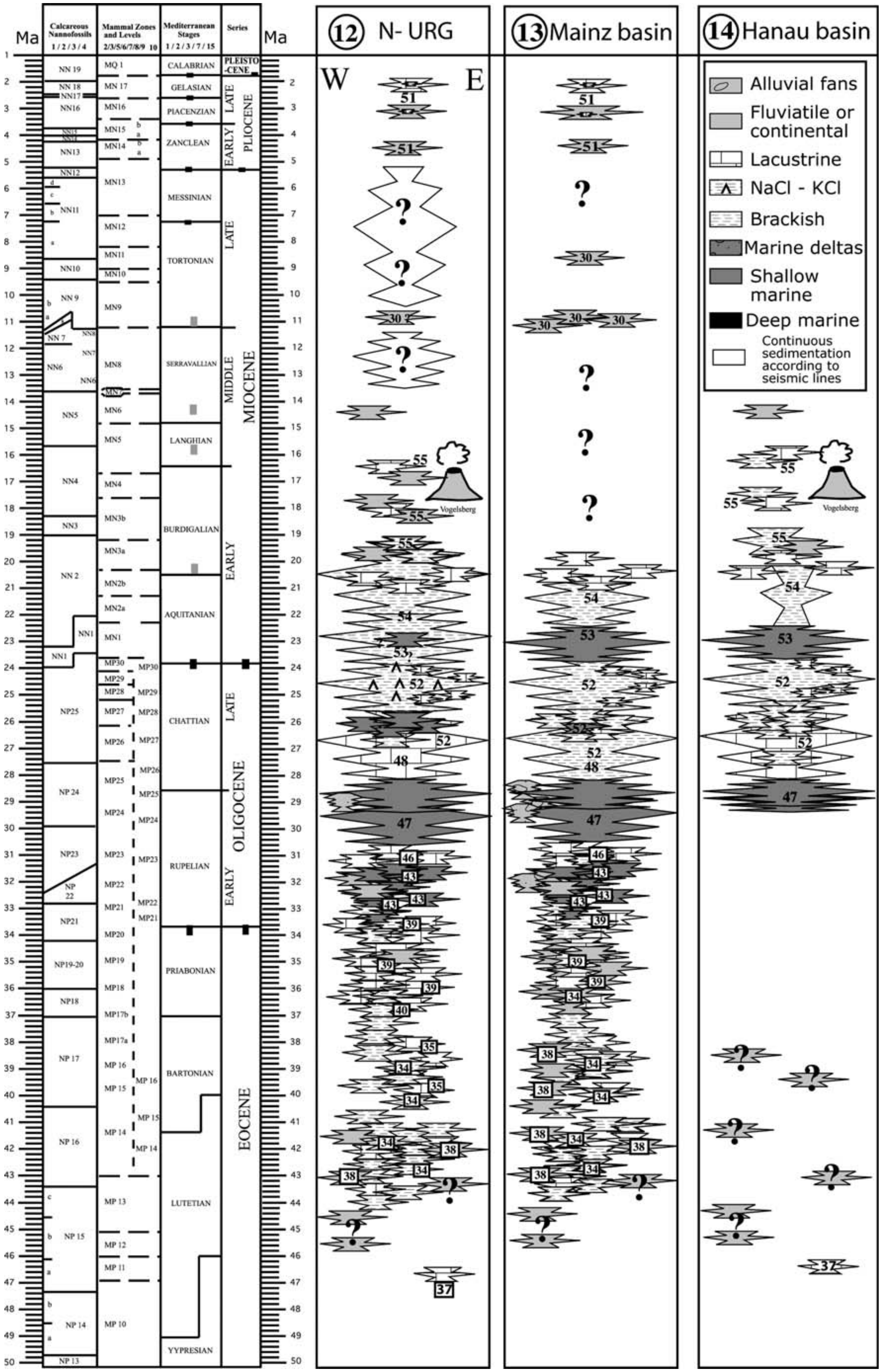
Along the border of these basins, terrestrial alluvial fan deposits of the ‘‘Steingang’’ accumulated during the Lutetian to Early Rupelian (Grimm and Grimm 2003). Eocene sediments are absent in the Hanau Basin.

Oligocene

The Middle Pechelbronn Beds have been correlated with the first brackish-marine Rupelian transgression (Sissingh 2003). The Palatinat-Stockstadt Ridge was partly flooded, and the Rüsselheim Basin was connected to the URG (Grimm and Grimm 2003). The Middle Pechelbronn Beds are well dated by nannoplankton (NP 22 according to Martini 1973, 1982, 1990; Martini and Reichenbacher 2004) and foraminifers (NSR 7a according to Grimm 2002b; Grimm et al. 2005). In the central parts of these basins, the Middle Pechelbronn Beds are overlain by the fluviatile Upper Pechelbronn Beds. The Pechelbronn-Group was not deposited in the Hanau Basin (Hottenrott 1988).

The second and third Rupelian marine ingressions, which invaded the whole area (corressponding to sea-level highstands between Ru2/R3, and Ru3/Ru4 respectively) are dated to the top of NP23 up to NP24 (Doebl and Sonne 1974; Doebl et al. 1980; Grimm 1998, 2002a; Grimm et al. 2002; Grimm and Grimm 2003; Hottenrott 1988; Martini 1982; Müller 1988; Pross 1997; Tobien 1987). Several formations have been recently introduced for these sediments (Alzey-, Bodenheim-, Stadecken-, Sulzheim Formation, Grimm et al. 2000). At this time the URG transected the older structures and reconfigurated the investigated area into the western Mainz Basin, the central URG and the eastern Hanau Basin. The Hanau Basin was first flooded during the deposition of the upper part of the Bodenheim Formation (= Oberer Rupelton).

Following regression of the sea (corresponding to the sea-level drop at the sequence Ch1 and/or Ch2, see Hardenbol et al. 1998), brackish to fluviolacustrine sediments dominated the area (Niederroedern Schichten,


Ma
Calcareous Nannofossils
Mammal Zones and Levels
Mediterranean Stages
Series
12 N- URG
13 Mainz basin
14 Hanau basin
W
E
Alluvial fans
Fluviatile or continental
Lacustrine
NaCl - KCl
Brackish
Marine deltas
Shallow marine
Deep marine
Continuous sedimentation according to seismic lines
Vogelsberg
CALABRIAN
GELASIAN
PIACENZIAN
ZANCLEAN
MESSINIAN
TORTONIAN
SERRAVALLIAN
LANGHIAN
BURDIGALIAN
AQUITANIAN
CHATTIAN
RUPELIAN
PRIABONIAN
BARTONIAN
LUTETIAN
YYPRESIAN
PLEISTO-CENE
PLIOCENE
MIOCENE
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EARLY
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**Fig. 10** Stratigraphy of the North URG, Mainz- and Hanau basins

Süsswasserschichten = Sulzheim Formation pars), dated to MP24 (Mödden et al. 2000; Reichenbacher 2000). These are overlain by (or pass laterally to) the brackish Lower Cerithium Beds, which have been correlated to the second Chattian transgression (Schäfer 1996, Sissingh 2003). At the same time alluvial fan deposits of the Budenheim Formation accumulated along the south-western border of the Rhenish Slate Mountains (Schäfer and Kadolsky 1998). The Lower Cerithium Beds are overlain by (or pass laterally to) the brackish-marine sequence of the *Landschneckenkalk*, the Middle Cerithium Beds and the lowermost part of the Upper Cerithium Beds. This sequence still belongs to the Late Chattian (Martini 1978; Kadolsky 19881988; Reichenbacher 2000; Schäfer 1988).

Miocene and Pliocene

During the sedimentation of carbonate platform and lagoonal sediments in the border areas of the URG (= Mainz Group according to Grimm and Grimm 2003) a basin facies was formed in the URG (e.g., Rothausen and Sonne 1984; Sissingh 2003).

The Upper Cerithium Beds span the Chattian–Aquitanian boundary. The brackish-lagoonal sediments of the Oberrad Formation (= upper part of the Upper Cerithium Beds, see Schäfer and Kadolsky 2002) correlate, owing to mammals and otoliths, with the Aquitanian (MN1, MN2; Engesser et al. 1993; Mödden 1996; Schäfer and Kadolsky 2002; Försterling et al. 2002; Försterling and Reichenbacher 2002).

The overlying brackish-lacustrine marls and limestones of the Rüssingen Formation (= *Inflata*-Beds) still belong to the Aquitanian (MN2a, Engesser et al. 1993). In the uppermost part of the Rüssingen Formation, biota indicates a further brackish-marine ingression from the south (Schäfer 1984; Reichenbacher 2000; Sissingh 2003), which is again followed by an ingression from the North Sea (Martini 1981, 2000). This ingression (probably corresponding with the major sea-level highstand following the Aq 1 sequence) characterizes the base of the Wiesbaden-Formation (= Lower Hydrobia Beds, see Reichenbacher and Keller 2002), which consists of mainly bituminous marls and limestones and is of Aquitanian age, except perhaps its uppermost part.

During the Burdigalian, brackish sedimentation was progressively reduced, and replaced by lacustrine and fluviatile deposits. In the Hanau Basin, the Upper Hydrobia Beds, the Niederrad Formation (= *Landschneckenmergel*), and the Praunheim-Formation (= *Prosothenia-Beds*) were deposited (Grimm and Hottenrott 2002; Hottenrott 1988; Radtke and Kümmerle 2005; Reichenbacher 2000). In the URG the "Jungtertiär I" was formed. The Niederrad Formation was correlated to MN3 by Stephan-Hartl (1972) and Tobien (1987).

During the Langhian and the Early Serravallian, sedimentation was essentially continental, brackish or lacustrine in the northern URG and the Hanau Basin (Staden Formation, Bockenheim Fm., lower part of the "Jung Tertiär II", see Grimm and Hottenrott 2002; Hottenrott 1988) A plateau-basalt layer ("Maintrapp"), which has a radiometric age of 16.3 Ma, interfingers between the Staden Formation and Bockenheim Formation (Fuhrmann and Lippolt 1987; Grimm and Hottenrott 2005). There is no sedimentation known in the Mainz Basin from Late Burdigalian to Late Serravallian. Dated Middle and Late Serravallian sediments are unknown in the whole area.

The presence of limno-fluviatile Tortonian deposits is attested by the Lautersheim Formation, the *Dinotherium sands* and the Dorn-Dürkheim Formation, which are dated at several localities of the Mainz Basin to MN9 and MN11 (Franzen 1997, 2000; Franzen and Storch 1975, Grimm and Grimm 2003; Lutz et al. 2003; Rothausen and Sonne 1984; Schäfer 2000; Tobien 1980, 1988b, 1986b).

Uppermost Miocene to Pliocene sediments are known from some areas in the Mainz Basin and the western part of the northern URG and are represented by the "White Mio-Pliocene" and Bohnerz-clays (Rothausen and Sonne 1984; Grimm and Grimm 2003).

Piacenzian fluviatile sediments are represented by the *Arvernensis-gravels* and *Weisenau sands* of the northernmost URG and the Mainz Basin and dated by magnetostratigraphy and heavy mineral associations (Fromm 1986; Semmel 1983). The late Pliocene probably exists at least in the Heidelberg and Frankfurt area (Hottenrott et al. 1995).

The presence of several unconformities (between early Serravallian and Tortonian, between Tortonian and Lower Messinian and below the Piacencian *arvernensis*-gravels) is still subject to controversy: field and borehole observations indicate three breaks in sedimentation (this study), whereas the new river seismic lines do not show any unconformity during the Mio-Pliocene in the northern part of the URG (Dèzes et al. 2004).

## Conclusion

The present study gives a general stratigraphic frame for the Swiss Molasse and the URG deposits. However, several points are still hypothetic and have to be clarified in the future:

- precise dating of Eocene to Early Oligocene deposits is still unclear, particularly concerning the Salt Formation, the *Green marls* and the Pechelbronn Group; better data probably will be accessible in the near future due to the study of boreholes material from the Pechelbronn and Colmar areas, which are still available thanks to the BRGM.
- the stratigraphic relationships between the Middle Pechelbronn Beds, the *Streifige Mergel—Hau-*

*stein*complex, the Jura Molasse and the eastern distal Molasse Basin have to be clarified.
- the problems of unconformities (Bartonian, Burdigalian in the southern part, Middle to Late Serravallian and Lower Messinian for the whole basin) have to be checked by comparing new (and old) seismic lines.
- the precise dating of the Pliocene sediments is still unclear, particularly in the Middle and Northwestern URG.

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