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A REVISED PALAEOGENE LITHOSTRATIGRAPHIC FRAMEWORK FOR THE NORTHERN SWISS JURA AND THE SOUTHERN UPPER RHINE GRABEN AND ITS RELATIONSHIP TO THE NORTH ALPINE FORELAND BASIN

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*Abstract***.** The Palaeogene deposits in the Swiss Molasse Basin, the intermediate Swiss Jura and the adjacent southern Upper Rhine Graben represent an excellent case study for interbasinal sedimentary and palaeogeographic relationships. The topographic and geologic complexity of the area led to an accumulation of local stratigraphic terms during nearly 200 years of research activity, necessitating a simplification of the lithostratigraphic framework. Additionally, the extension of the investigated area over two historically shifting language areas and the absence of a standardised supraregional lithostratigraphy adds to complexity of the situation.

In revising and grouping around 200 multilingual Palaeogene lithostratigraphic terms and spellings from the northern Jura and the southern Upper Rhine Graben that accumulated since 1821 we propose a concise standardised framework of 10 formations (6 new and/or emended) and 6 new members. It avoids the confusing multitude of historic "formation" names and stratigraphic ambiguity like the "Septarienton", "Molasse alsacienne" or the "Cyrenenmergel". The new formations include the Turckheim Formation (formerly "Steingang", "Conglomérats côtiers"), the Rossemaison Formation (formerly "Terre jaune", "Gelberde"), the Pulversheim Formation (formerly "Melettaschichten") and the Wahlebach Formation (formerly "Cyrenenmergel", partim "Molasse alsacienne"). The Wallau and Hochberg subformations are emended and elevated to formation status. For all discussed units except the Sidérolithique new reference and/or type sections are provided and illustrated. This new framework is put in context to recent stratigraphic schemes from adjacent areas in the Upper Rhine Graben, proposing status changes and emendations for existing units (e.g. Wallau-Subformation emended to Wallau Formation). To illustrate the former complexity and the proposed standardisation in the larger area, we applied the lithostratigraphic context to 9 palaeogeographic maps.

New heavy mineral data from the Delémont Basin complements the scarce regional information and is discussed in relation to Palaeogene tectonosedimentary context of the North Alpine Foreland Basin and the southern Upper Rhine Graben.

1 Introduction

During the last two decades the study of the Cenozoic deposits of the so-called "Jura-Molasse" re-intensified due to the construction of motorway A16 in northwestern Switzerland, stimulating more complex interpretations of the regional palaeogeography linked to lateral facies changes. These deposits represent the interface of two major tectonic units: the Upper Rhine Graben (URG) and the North Alpine Foreland Basin (NAFB, "Molasse Basin"; Fig. 1, 43), hence leading to a complex palaeogeographic history and an alternating provenance of regional sediments. The tectonic evolution (folding and thrusting of the Jura mountains) of the studied area led to the erosion of formerly more widespread sedimentary units to relics preserved in topographically separated synclines. The palaeogeographic complexity also led to the deposition of locally confined facies or condensed lateral equivalents of well-developed sedimentary successions in the adjacent main basins. During nearly 200 years of local and regional research activity this consequently resulted in the accumulation of numerous, partly overlapping or substituting stratigraphic terms (Fig. 3-7). Despite the elaboration of detailed summaries of the known lithostratigraphic units (e.g. Sittler 1965; Doebl 1970; Picot 2002; Becker 2003; Berger et al. 2005a), no

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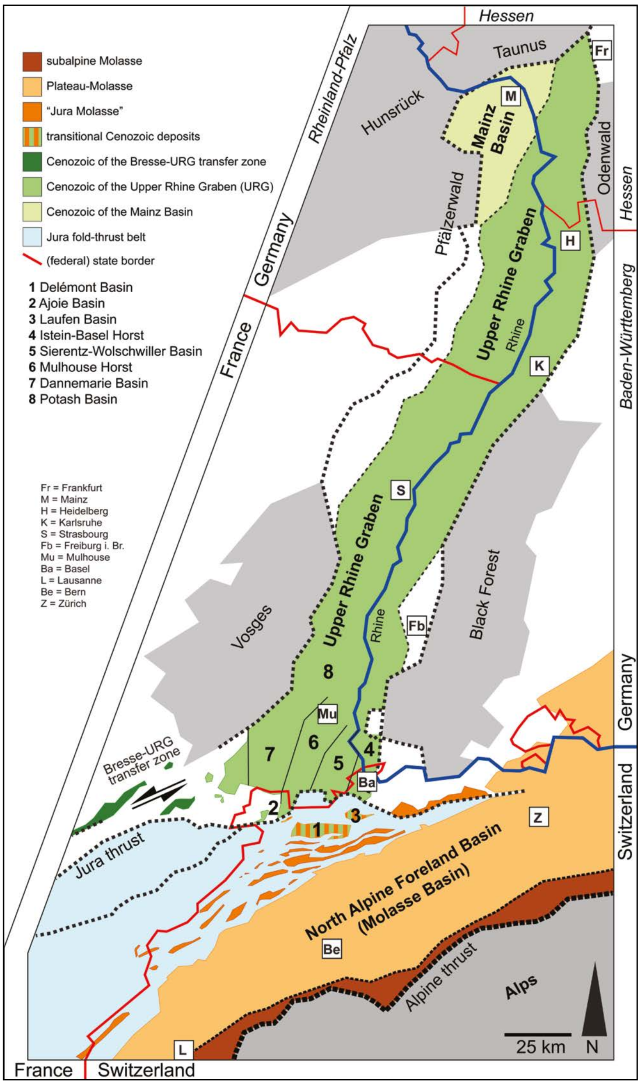


Fig. 1 - Geographic overview and subdivision of Cenozoic basins (German federal states in italics; adapted from Berger et al. 2005a).

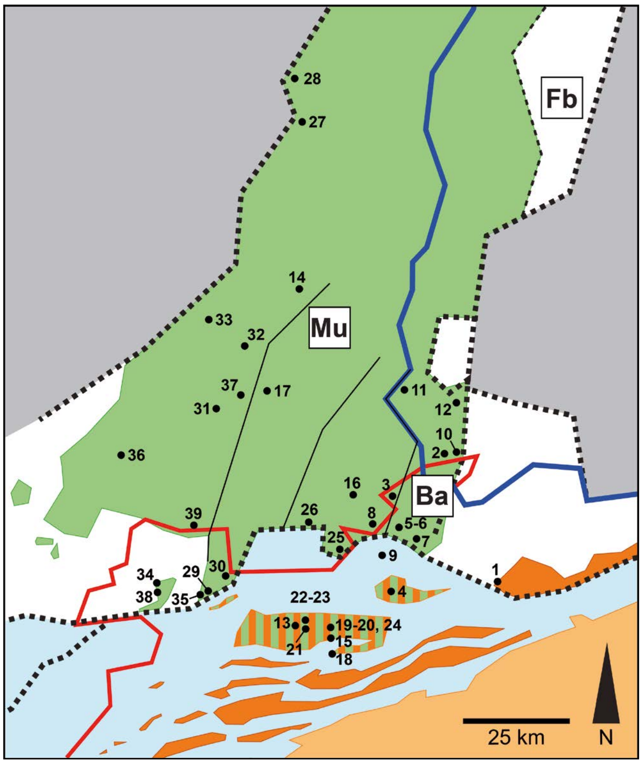


Fig. 2 - Geographic distribution of analysed sections (for basin subdivision see Fig. 1): 1 Brochene Fluh, 2 Logs Tüllingen Hill, 3 drilling Allschwil-2, 4 Laufen, 5 Fichtenrain (Therwil), 6 Stutzweg (Therwil), 7 Dornachbrugg - River Birse, 8 Biel-Benken & Leymen, 9 Blauen-3, 10 Lörrach logs, 11 Rheinweiler, 12 Kandern area logs, 13 drilling COM-F5, 14 drilling DP-202, 15 drillings HRT-F8 & 9, 16 Folgensburg, 17 Heidwiller, 18 CRD-VRR (La Verrerie), 19 CRD-POI C-142 & CRD-PRC C-5, 20 Courroux - River Birse, 21 DEL-BEE C-19, 22 Près-Roses mine shaft, 23 River Sorne bed, 24 River Scheulte & Birse bed, 25 Burg-Biederthal, 26 Bouxwiller-Oltingue, 27 Eguisheim, 28 Turckheim, 29 drilling RNA-F1 & 2, 30 drilling CHM-F4, 31 Retzwiller, 32 Burnhaupt-Le-Haut, 33 Güwenheim, 34 drilling ETA-F2, 35 drilling CLJ-F1, 36 Froidefontaine, 37 Hagenbach, 38 POR-OIP C-4, 39 Réchésy.

comprehensive formal definition of formations and designations of concise names took place.

New stratigraphic and micropalaeontological data from the southern URG (e.g. Roussé 2006; Picot et al. 2008; Pirkenseer & Berger 2011) including the Delémont, Laufen and Ajoie subbasins as well as the elaboration of homogenized lithostratigraphies (e.g. Grimm et al. 2011b; LGRB 2011) for adjacent areas needed to be integrated to achieve a better understanding of the larger stratigraphic context of the individual formations. The choice of type localities and names outside the Delémont, Ajoie and Laufen subbasins proved necessary since for the Oligocene the local deposits represent condensed marginal extensions of formations closer to the depositional centre(s) of the southern URG. Since the evolution of tectonic events was triggered by respective phases of the alpine orogeny, progressing along a comparatively similar timeline throughout the (southern) Upper Rhine Graben, supraregional lithostratigraphic units should be homogenized. A large tectonic feature as the Upper Rhine Graben extending over three countries and two language areas greatly benefits from common formation names based on geographic terms, and not as is the case up to now on predominantly descriptive, ambiguous, partly vaguely or inconsistently defined terms that need to be translated (e.g., Marnes à Cyrènes, Cyrenenmergel, Cyrena Marls = Hagenbach, Retzwiller and Courroux Members).

As clarified below only one lithostratigraphic unit will keep its historical name (Sidérolithique), whereas for others new names will be proposed (e.g.

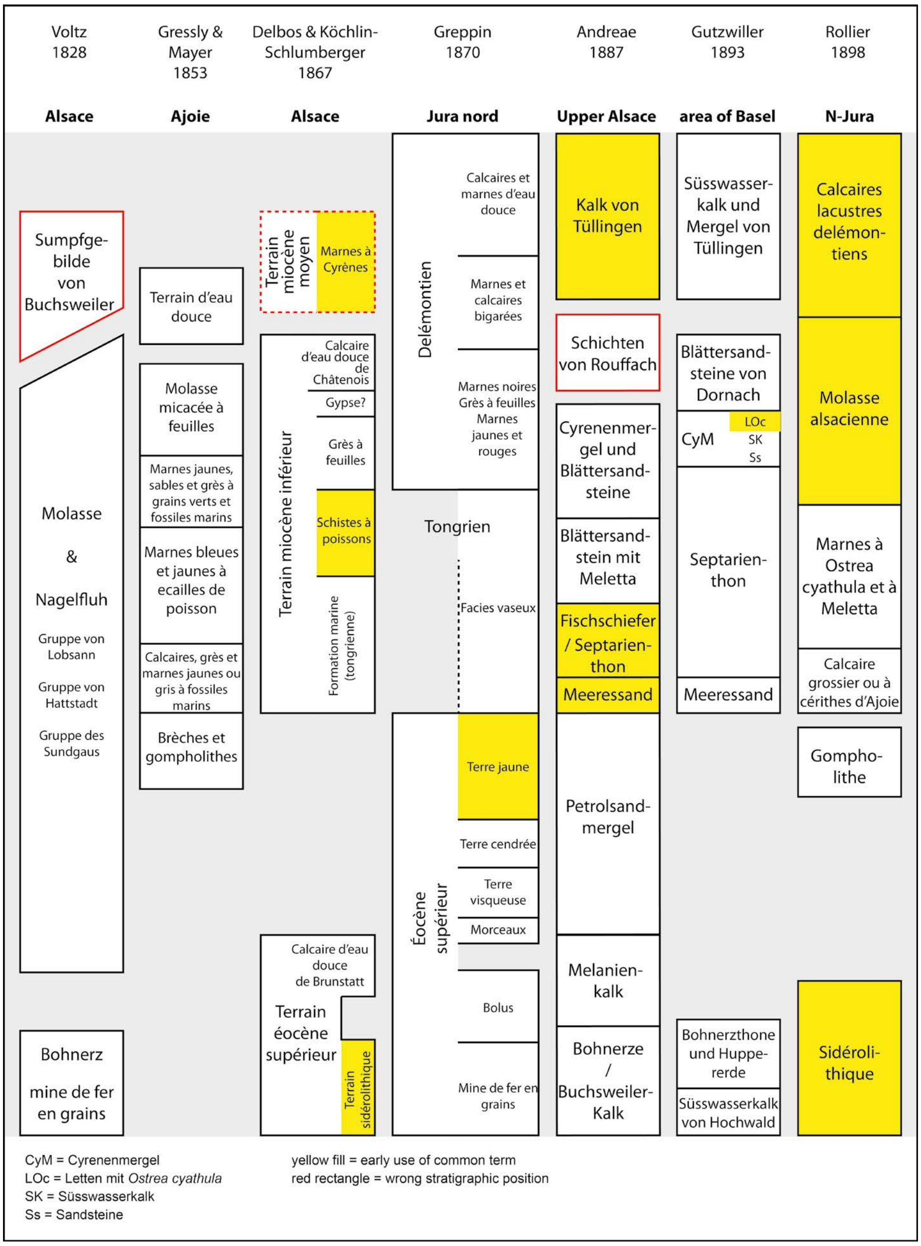


Fig. 3 - Correlation of past lithostratigraphic concepts in chronological order (part 1).

Steingang, Conglomérates côtiers = Turckheim Fm) or adapted from already well-defined formations from adjacent areas. Some units are subject to status changes (e.g. Cyrenenmergel as member of the [new] Wahlebach Fm; Fig. 40, 44).

Abbreviations: URG = Upper Rhine Graben, NAFB = North Alpine Foreland Basin, USM = Untere Süsswassermolasse, UMM = Untere Meeresmolasse, OSM = Obere Süsswassermolasse, OMM = Obere Meeresmolasse, Fm = formation, Mb = member

2 Previous stratigraphic work

During the initial phase from the 1820ies to 1870 geognostic investigations often concerned the larger area of the French Departments Bas/Haut-Rhin (e.g. Voltz 1828; Daubrée 1852; Delbos & Köchlin-Schlumberger 1867) (Fig. 3). While Daubrée (1852) described many Cenozoic deposits in detail (e.g. "Couches de Bechelbronn"), their stratigraphic position remained ambiguous. A first ordered lithostratigraphy was presented in Delbos & Köchlin-Schlumberger (1867), introducing amongst others the later common terms "Schiste à poissons", "Tongrien", "Grès à feuilles" and "Marne à Cyrènes" for selected Rupelian deposits. Merian (1821) and Greppin (1870) dealt explicitly with the geology of the Jura mountains, though Merian (1821) was somewhat hampered being the first to discuss also the Cenozoic deposits, their description remaining rather vague. Greppin (1870) went much more in detail describing the succession

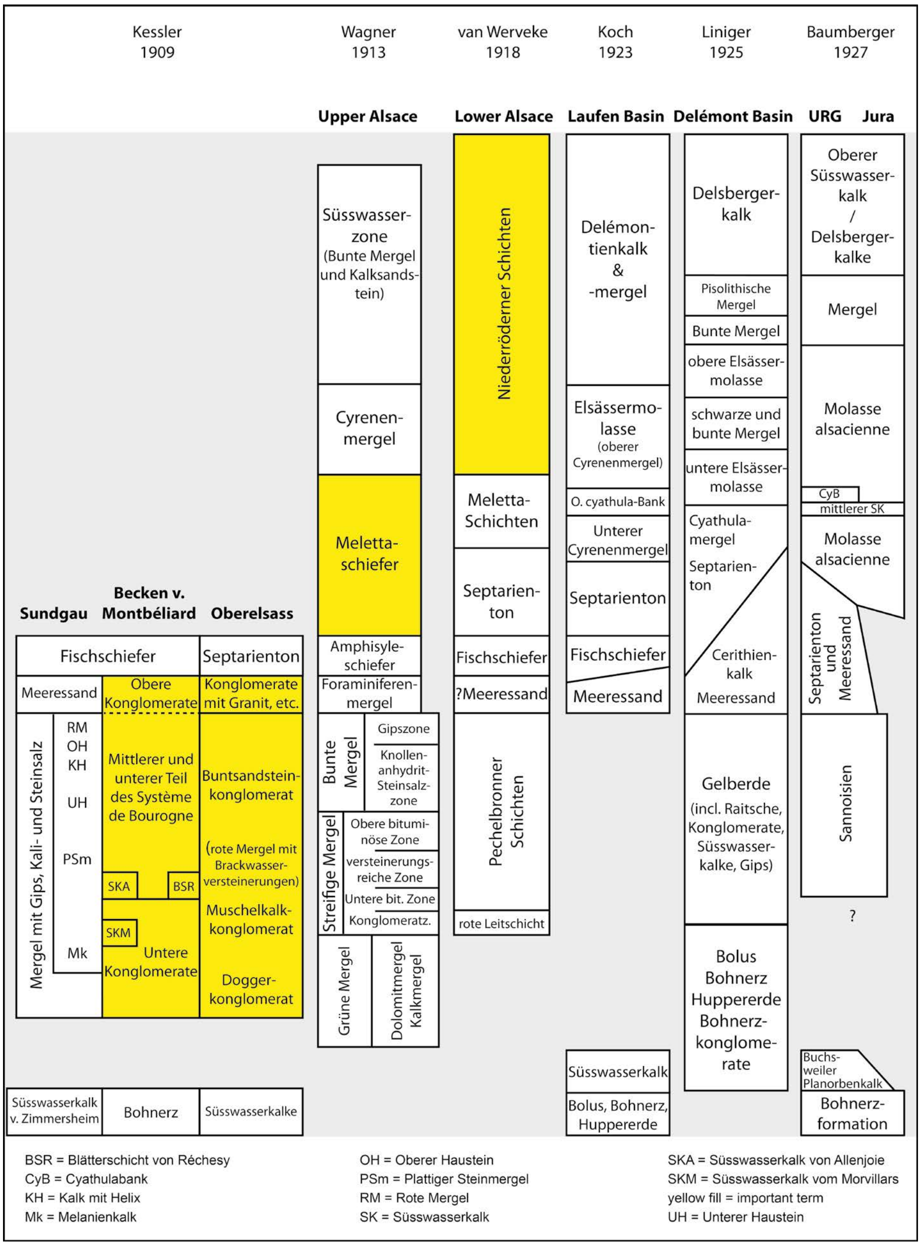


Fig. 4 - Correlation of past lithostratigraphic concepts in chronological order (part 2).

of each syncline in a stratigraphic order and presenting a first comprehensive lithostratigraphic synthesis (introducing e.g. the "Terre jaune", "Delémontien") with correlations to adjacent basins (Fig. 3).

Following a short hiatus Andreae (1884) and Kilian (1884) proposed extended lithostratigraphies for the southern and middle upper Rhine Graben, establishing the "modern" pattern that has been refined since (Fig. 3). The few still erroneously positioned deposits concern parts of the widely distributed conglomerates and sands along the borders of the URG, which remained notoriously difficult to attribute. These problems were only finally solved by the extensive analysis of the entire conglomeratic complex by Duringer (1988).

The following years brought a refinement on a regional scale with the establishment of the initial geological maps of the Jura area and more specialized analyses of selected stratigraphic units (e.g. Rollier 1893a, b, 1898, 1910; Gutzwiller 1893; Förster 1888, 1892; Kessler 1909; Wurz 1912). The bimodal naming of lithostratigraphic units based on French and German terms gets established around that time.

The following years were characterised by a first emendation / completion of geological maps of NW Switzerland (e.g. Koch 1923; Liniger 1925; Buxtorf & Christ 1936) and an important NW-SE correlation of Rupelian sediments between the southernmost URG and the Swiss "Molasse Basin" (Baumberger 1927).

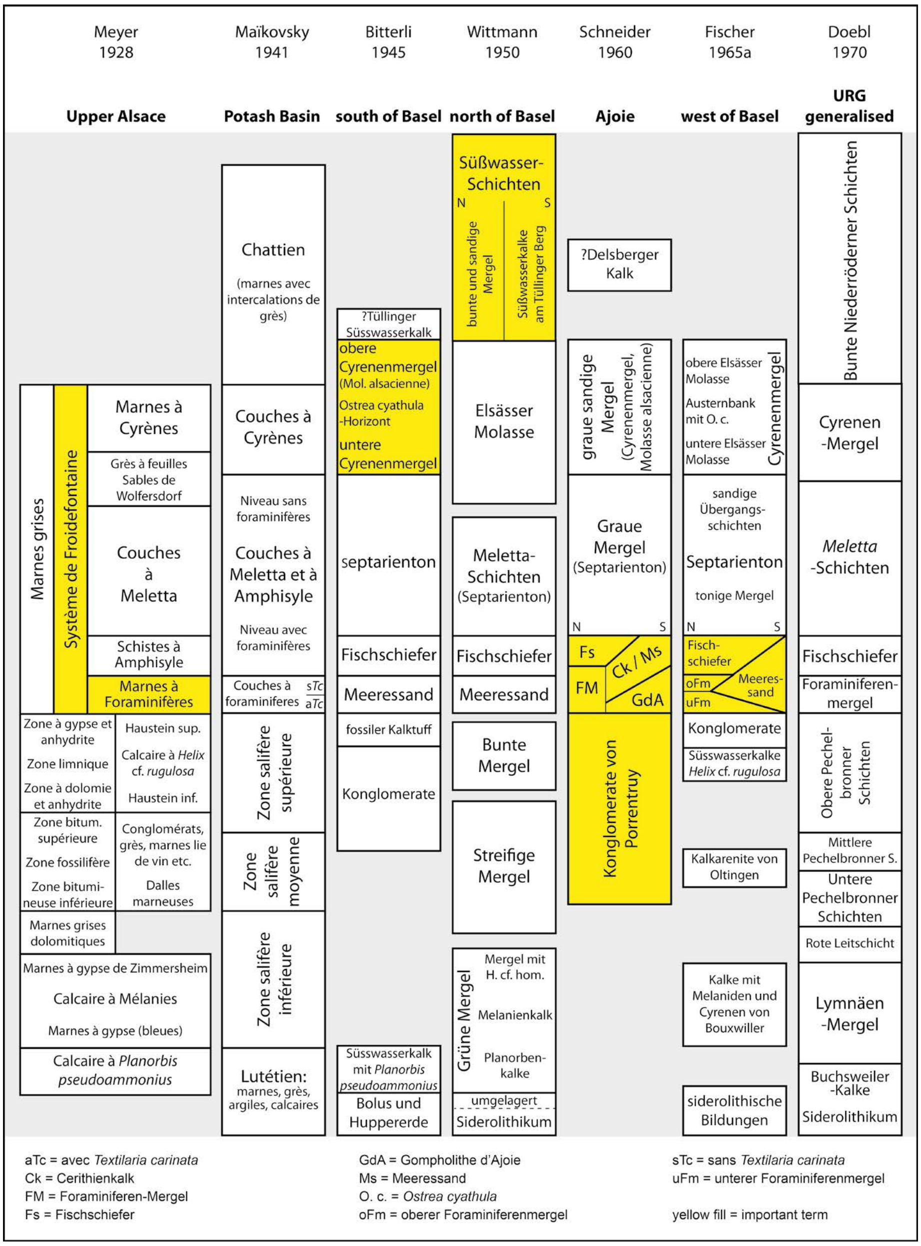


Fig. 5 - Correlation of past lithostratigraphic concepts in chronological order (part 3).

Further interest in the southern URG was spurred by the discovery of large Cenozoic salt deposits at the end of the 19th century and renewed interest in the oil reservoir of the Pechelbronn area at the beginning of the 20th century, leading to vastly increased drilling activity and investigation of cored material (e.g. Förster 1909b; van Werveke 1918; Christ 1924; Meyer 1928; Barbier 1938; Maïkovsky 1941; Vonderschmitt 1942; Schnaebele 1948), adding more precision to the data formerly obtained mainly from outcrops and clarifying the stratigraphic situation in the basin centre.

Stratigraphic research in the southern URG and the Jura increased due to the intensified mapping activity to complete / emend geological maps in NW Switzerland (Diebold 1960; Schneider 1960; Tschopp 1960; Fischer 1965a; Fig. 5) and (renewed) interest in old and not exhaustingly treated topics (e.g. clay mineralogy, palaeoclimatology and stratigraphy, Sittler 1965; "Meeressand", Wittmann 1967). This trend continued more or less in the 80ies and early 90ies (e.g. marginal URG conglomerates, Duringer 1988; "Schistes à poissons" fish assemblages, Pharisat 1991a; geological maps of NW Switzerland, Fischer et al. 1971; Bitterli-Brunner & Fischer 1988). A pivotal lithostratigraphic summary of the southern URG comparing different subbasins was elaborated by Sittler (1965), incorporating much of the previously available information in a complete chart (Fig. 6).

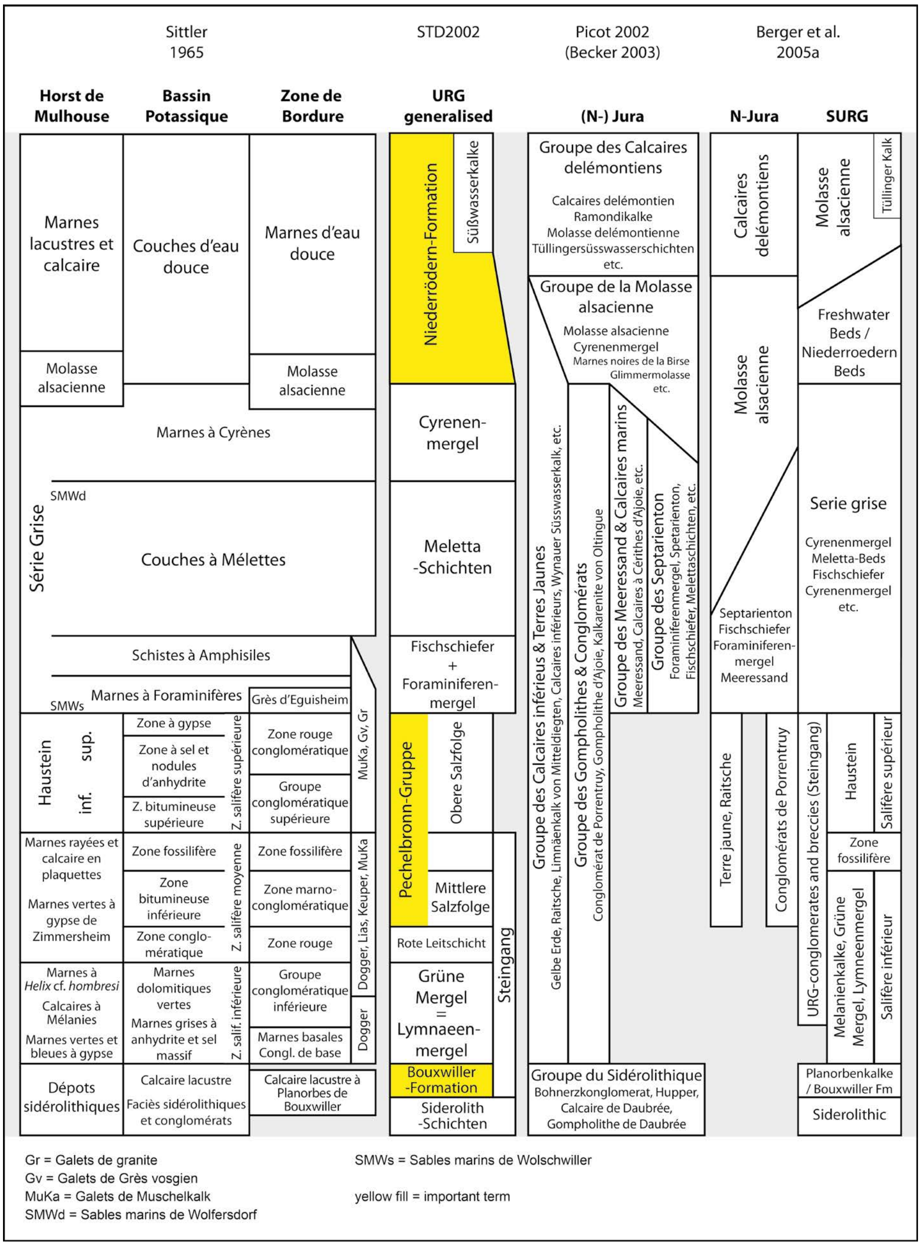


Fig. 6 - Correlation of past lithostratigraphic concepts in chronological order (part 4).

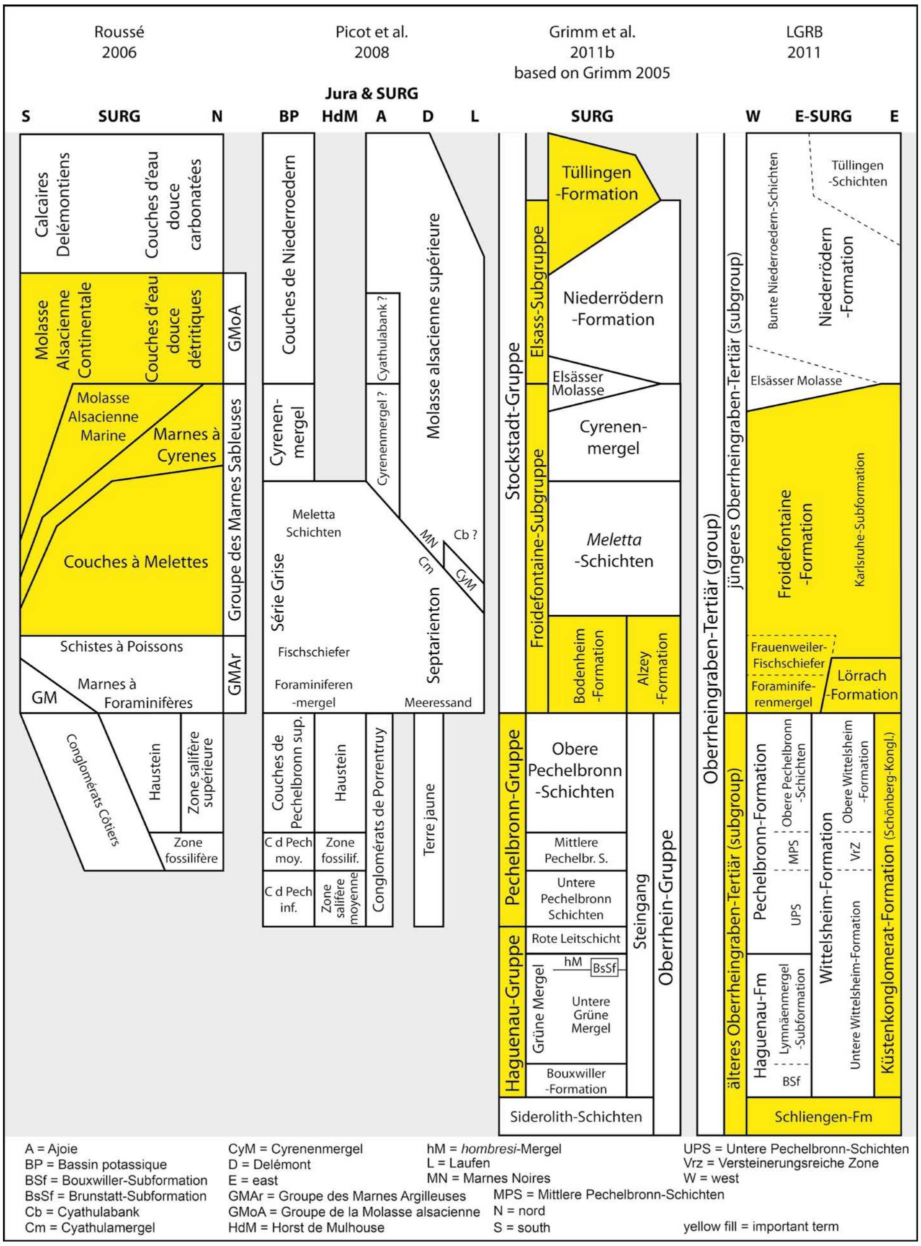
From the second half of the 90ies until recently increasing numbers of theses and publications dealing with the “Jura Molasse” and the southern URG were owed to research projects initiated in Switzerland (Universities of Basel, Bern, Fribourg and Zürich) and France (University of Strasbourg), partly in the framework of the transnational EUCOR-URGENT project (Behrmann et al. 2005). These publications provided fresh insights and global summaries on palaeontologic, palaeogeographic, geochemic and biostratigraphic aspects (e.g. Schlunegger et al. 1996; Kälin 1997; Clément & Berger 1999; Picot 2002; Storni 2002; Becker 2003; Hinsken 2003; Berger et al. 2005a,b; Roussé 2006; Picot et al. 2008; Le Metayer 2007; Pirkenseer 2007; Fig. 6-7).

The most recent comprehensive lithostratigraphic summaries treat either the entire URG (Grimm et al. 2011b) or the part lying within the federal state Baden-Württemberg (LGRB 2011). Unfortunately both references were published only in German.

3 Geologic context

The URG represents the 300 km long, roughly N-S trending central part of the European Continental rift system (ECRIS, Ziegler 1992) extending between Wiesbaden (Germany) and Basel (Switzerland) (Fig. 1). Several hundred to over thou-

Fig. 7 - Correlation of past lithostratigraphic concepts in chronological order (part 5).



sand meters of Palaeogene southern URG basin sediments are mostly covered by Quaternary deposits of the Rhine River. The crystalline basement and the Triassic "Buntsandstein" cover of the Vosges and Black Forest mountains bordering the URG to the east and the west (e.g. Sittler 1992). Outcrops of Cenozoic sediments are generally distributed along river valleys and near the graben margins. Near the latter conglomerates containing medium to large-size gravels of different origin (Duringer 1988) or coastal marine sands (Roussé 2006) are dominant. Towards the centre of the basin grain sizes get progressively finer. The basin fill consists mainly of lacustrine to marine sands, marls and massive evaporitic deposits ("Potash Basin" north of Mulhouse, Dannemarie Basin). Neogene deposits are nearly absent in the region south of Strasbourg, but are well-documented in the Delémont and Ajoie subbasins (Liniger 1925; Kälin 1997; Becker 2003).

Based on the sedimentary history rifting started in the mid-Eocene (e.g. Sittler 1992; Sissingh 1998; Berger et al. 2005 a,b) due to the build-up of a N-S directed stress regime after the closure of the Valais Ocean and the accretion of the Briançonnais terrane (Stampfli et al. 1998; Ziegler & Dèzes 2005). This induced a strike slip motion along reactivated WSW-ENE trending late Palaeozoic fault lines (Schumacher 2002), separating the URG into several subbasins. South of Mulhouse the URG is further subdivided by north-south trending faults into the

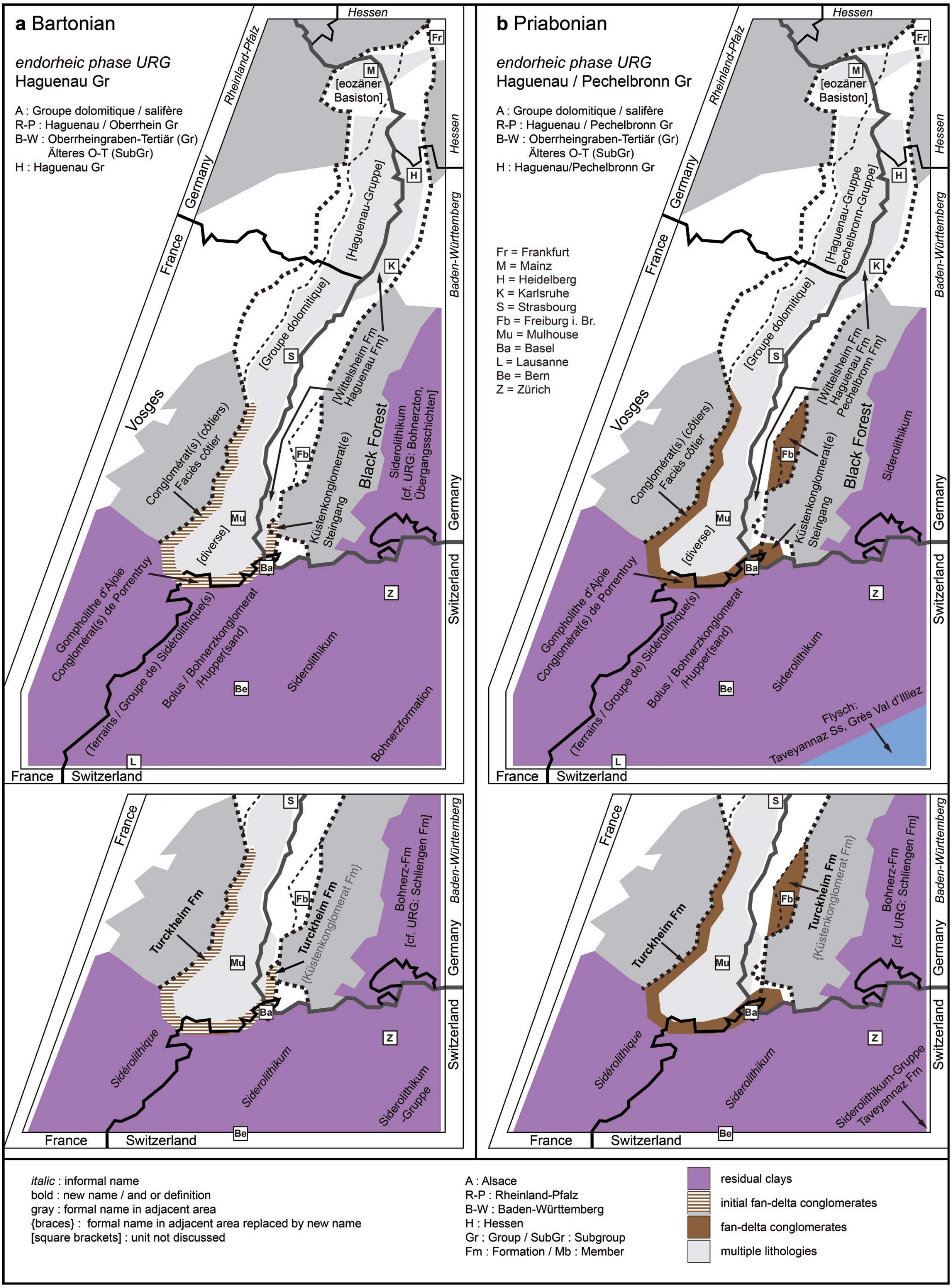


Fig. 8 - Palaeogeographic representation of major facies and regional lithostratigraphic terms (updated from and based on maps in Berger et al. 2005b). Top of the figure represents the formerly used most common terms, lower part the status after revision and simplification. 8a Map for the Bartonian, 8b Map for the Priabonian.

Dannemarie Basin in the west, the Mulhouse Horst and several half-grabens in the east (e.g. Rotstein et al. 2005). The tabular and folded Jura Mountains (Mesozoic) frame the rift valley to the south. In this area Cenozoic deposits are found in the synclines of the folded Jura as well as the Delémont, Laufen and Ajoie subbasins (e.g. Becker 2003), which are tectonically related to the main URG rift (e.g. Picot et al. 2005) but have been overprinted by the Jura folding since the late Miocene.

The Jura Mountains are themselves bordered by the North Alpine Foreland Basin (NAFB) to the southeast (Fig. 1), emphasising the important palaeogeographic role of this intermediate area and its Cenozoic sedimentary and tectonic history for interpreting interbasinal relationships.

4 Larger Palaeogene stratigraphic evolution

The oldest common synrift deposits (excluding the Sidérolithique) related to the initial rifting phase (Sittler 1992; Sissingh 1998; Berger et al 2005a,b) in the southern URG date from the Lutetian, whereas in the Ajoie and Delémont subbasins they are younger (latest Priabonian, early Rupelian) (Liniger 1925; Berger et al. 2005a,b; Picot et al. 2008) (Fig. 8b, 13a, 43), and are younger still in the Laufen subbasin (late Rupelian). Highly fragmentary terrestrial to lacustrine sediments (e.g. Koch 1923; Liniger 1925) in the individual subbasins probably indicate tentative tectonic influence related to the URG rifting in the area. Depending on their geographic position the residual clays of the underlying Sidérolithique are accordingly of strongly varying ages (Lutetian-Priabonian; Becker et al. 2013b) (Fig. 8).

The deposition of hundreds of metres (max. over 2000 m) of predominantly lacustrine marls, limestones, conglomerates and evaporites (berger et al. 2005a,b; Grimm 2005; Grimm et al. 2011b) indicates the acceleration of the rifting during the late Lutetian to the early Rupelian (e.g. Sissingh 2006).

In the basal Rupelian a first marine ingression (“Zone fossilifère”, “Mittlere Pechelbronn-Schichten”) invades the URG basin from the North via the Hessian depression. This transgression-regression cycle is evidenced by microfossil assemblages (Grießemer et al. 2007; Grimm et al. 2007; Lavoyer 2013; Pirkenseer & Berger 2011). It reaches southwards into the Wolschwiller halfgraben (Pirkenseer & Berger 2011) and the Ajoie subbasin (Picot et al. 2005, 2008), but not the Laufen and Delémont subbasins.

A second, more pronounced late Rupelian transgression-regression cycle affected the entire URG and reached the Ajoie, Delémont and Laufen subbasins (Clément & Berger 1999; Picot et al. 2008) (Fig. 13b, 23). In the URG this led to the deposition of a several hundred meters thick marine series (“Série grise”, “Froidefontaine Subgruppe”; Berger et al 2005 a, b; Grimm et al. 2011b), which came gradually under influence of detrital sedimentation of alpine provenance after the overfill of the NAFB, indicated by the northwards directed progradation of a delta system in the research area (Roussé 2006; Pirkenseer et al. 2011) (see 8 and Fig. 23b, 28a, 43). The presence or absence of individual members and formations subdividing these marine to deltaic sediments in the regional subbasins is discussed in this paper.

During the latest Rupelian and Chattian fluvio-lacustrine conditions became established (Niederroedern Fm, “Molasse alsacienne”) as northwards directed branch of the axial drainage system of the NAFB (“Genfersee-Schüttung”, e.g. Füchtbauer 1964) (Fig. 28). The Palaeogene sedimentation culminated in the deposition of the Tüllingen Fm with predominant freshwater limestones (e.g. Picot 2002; Berger et al. 2005a, b; Grimm et al. 2011b) (Fig. 28).

5 Methods

Synonymy lists are comprehensive and may include some references not dealing directly with stratigraphic issues (e.g. Schumacher 2002). They illustrate the confusing variety of lithostratigraphic terms and translations used throughout the literature. Individual authors may have applied more than one term or translation to an individual lithostratigraphic unit (e.g. Delbos & Köchlin-Schlumberger 1866; Sissingh 1998).

The lithostratigraphic terms ante-revision applied to the palaeogeographic maps (Figs 8, 13, 23, 28, 39) are derived from the historically most commonly used names in the corresponding areas. Adapted or not modified terms post-revision

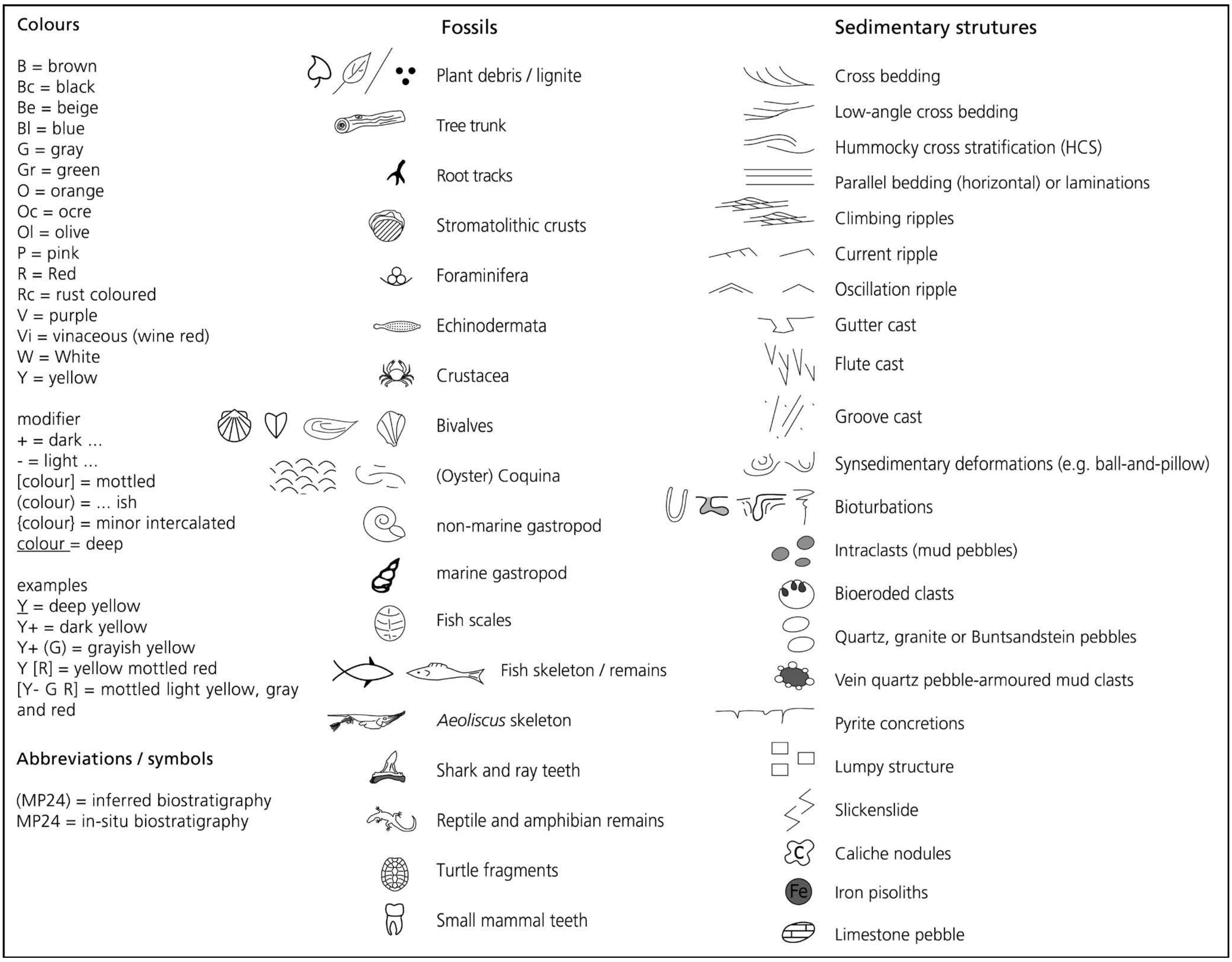


Fig. 9 - Abbreviations and symbols.

are based on the most recent available stratigraphic overviews in the respective areas (e.g. Roussé 2006; LGRB 2011; Grimm et al. 2011b; LLS 2014).

The naming of formations follows the guidelines advanced by the International Commission on Stratigraphy (http://www.stratigraphy.org).

Coordinates of indicative localities are as precise as possible, but may be positioned in the middle of a group of outcrops or in the close vicinity when based on descriptions in older literature. The approximate geographical positions of localities are indicated in Fig. 2, their relative stratigraphical position in Fig. 45.

To achieve a better understanding of the larger lithostratigraphic context the available outcrops are combined with selected drill cores. Granulometric classifications are based on estimates, which are substituted by selected control measurements. The granulometric classification follows Blair & McPherson (1998). Lithofacies denominators follow a custom scheme (see Roussé 2006).

To attain a continuous stratigraphical record of heavy mineral suites data was obtained from two cores drilled near the southern Delémont Basin margin southeast of the village Courrendlin. While drilling HRT-F8 (47.33602° N / 7.38169° E) covers the lithostratigraphical units from the Sidérolithique to the Niederroedern Fm (Eocene to Chattian), drilling HRT-F4 (47.33962° N / 7.38097° E) supplements the range from the Niederroedern Fm to the Bois-de-Raube Fm (Chattian to Burdigalian). Selected outcrops complement data for the Heidwiller Mb (PRC004-41, POI007-229) and Sidérolithique karst pockets (VRR005-69).

Heavy mineral analyses were carried out in the Laboratories for Applied Organic Petrology (LAOP) in Lauta (Germany). Depending on grain size sample weights between 200-400 gr were chosen for analysis. For disaggregation samples were soaked in H_2O_2 and treated subsequently in ultrasound baths. Acetic acid was used to dissolve carbonate cement. After wet-sieving the grain sizes 63-100 μm and 100-200 μm were chosen for gravity separation. The separation liquid applied was sodium polytungstate solution with a density of 3 gr/cm³. Mineral grains were embedded in meltmount with refraction index of 1.662. During optical analysis 300 grains per fraction were determined by band count on a scanning stage.

6 Synonymy, definition and description of formations and groups

6.1 Sidérolithique / Siderolithikum (Fig. 8)

6.1.1 Synonomy and generalities

- Eisenstein (Merian 1821)
- Bohnerz, Bohnerzton, Bohnerzformation (Bolus) (Voltz 1828, Rollier 1904, Buxtorf & Christ 1936, Gander 2013)
- Terrain(s) sidérolithique(s) (Thurmann 1836, Gressly 1841, Delbos & Köchlin-Schlumberger 1867, Greppin 1870, Rollier 1893a,b)
- Minerai de fer sidérolithique (Kilian 1884)
- Sidérolithique (Rollier 1893a,b, Fleury 1909, Meyer 1928, Sittler 1965, Clément & Berger 1999, Berger 2011, LLS 2014)
- ?Calcaires / Gompholithes de Daubrée (Fleury 1909, Liniger 1925, Buxtorf & Christ 1936, Sittler 1965)
- Bolus und Tonerz, Huppererde, Bohnerzkonglomerate (Liniger 1925; Fischer 1965a)
- Siderolithikum (Buxtorf & Christ 1936, Fischer 1965a, 1969, Doebl 1970, Bitterli-Brunner & Fischer 1988, Gander 2013)
- Sidérolithic, Siderolithic (Duringer 1988, Sissingh 1998, 2006, Berger et al. 2005a)
- Groupe du Sidérolithique (Picot 2002, Becker 2003)
- Siderolith-Schichten (Grimm et al. 2011b, for additional older synonymy therein, DSK 2016)
- Bohnerz-Formation, Schliengen-Formation (LGRB 2011, DSK 2016)

The traditional (e.g. Thurmann 1836) name will remain unchanged due to the widespread occurrence of the formation and the absence of an applicable type section. The newer name "Siderolith-Schichten" in Grimm et al. (2011b) is misleading, since the Sidérolithique generally does not occur in well-defined beds, as indicated by the German term "Schichten". Older authors name the formation after its most important (economic) aspect, namely the pisolitic iron ore ("Bohnerz", "fer pisolithique"; Merian 1821; Voltz 1828; Daubrée 1852).

Picot (2002) considers the Sidérolithique itself as a group, but the grouped units (e.g. "Bohnerzkonglomerat", "Hupper") are of a too minor extent to merit a formation status. LGRB (2011) groups all residual sediments (Palaeogene and Neogene) as "tertiäre Residuallehme", whereas for the URG the Sidérolithique is treated as discrete, but lithologically similar Schliengen-Formation (see also GeORG 2013).

6.1.2 Definition, distribution and thickness

The Sidérolithique consists of residual clays of often reddish and yellowish colours, deposited in karst fissures or directly on underlying Jurassic limestones in erosional depressions. The latter are probably a result of relief due to large-scale crustal flexuring / buckling in the Palaeocene to late Eocene (e.g. Bourgeois et al. 2007; Dèzes et al. 2004).

Iron pisoliths are generally present, either distributed throughout the sediment or enriched in "pockets". Sizes range from sub-millimetric to cm-large irregular specimens and aggregations. The secondary nature of the accumulation of iron pisoliths in minable ore deposits through reworking has been discussed in Wittmann (1955). Locally quartz-rich sands may be intercalated, known as "Huppersand/-erde" / "sables silicieux vitrifiables" (Greppin 1870; Fleury 1909; Christ 1924). Primarily eroded from crystalline rocks of the Massif Central in the Cretaceous, they have been regionally reworked and accumulated due to fluviatile processes in the Eocene (Aubert & Le Ribault 1974). These sands may potentially be classified as a disjunct member, since Christ (1924) indicates maximal thicknesses of more than 10 m. Rare limestones and conglomerates ("gompholithes de Daubrée") have been attributed to the Sidérolithique s.l. (Picot 2002), their stratigraphic relationships however remain ambigous.

Considering the residual state of the deposits, karst infills represent the most common occurrences (e.g. site Courrendlin-Verrerie; 47.31606° N / 7.39325° E) that are scattered over the entire research area. Karst infills overlain by horizontal Sidérolithique deposits can be observed in drill cores (COM-F5, HRT-F9; Fig. 10-12). Karst fissures may descend more than 10 m into the underlying substratum (e.g. drilling HRT-F9; Fig. 11), and even down to about 100 m near Seehof (Canton of Berne, Switzerland; Bläsi et al. 2015).

The Sidérolithique was partially eroded in the early Oligocene. This is born out by reworked Sidérolithique in the basal Rossemaison Fm (see 6.2). In the Laufen subbasin the marine Pulversheim Fm was partly deposited directly on the bio-eroded

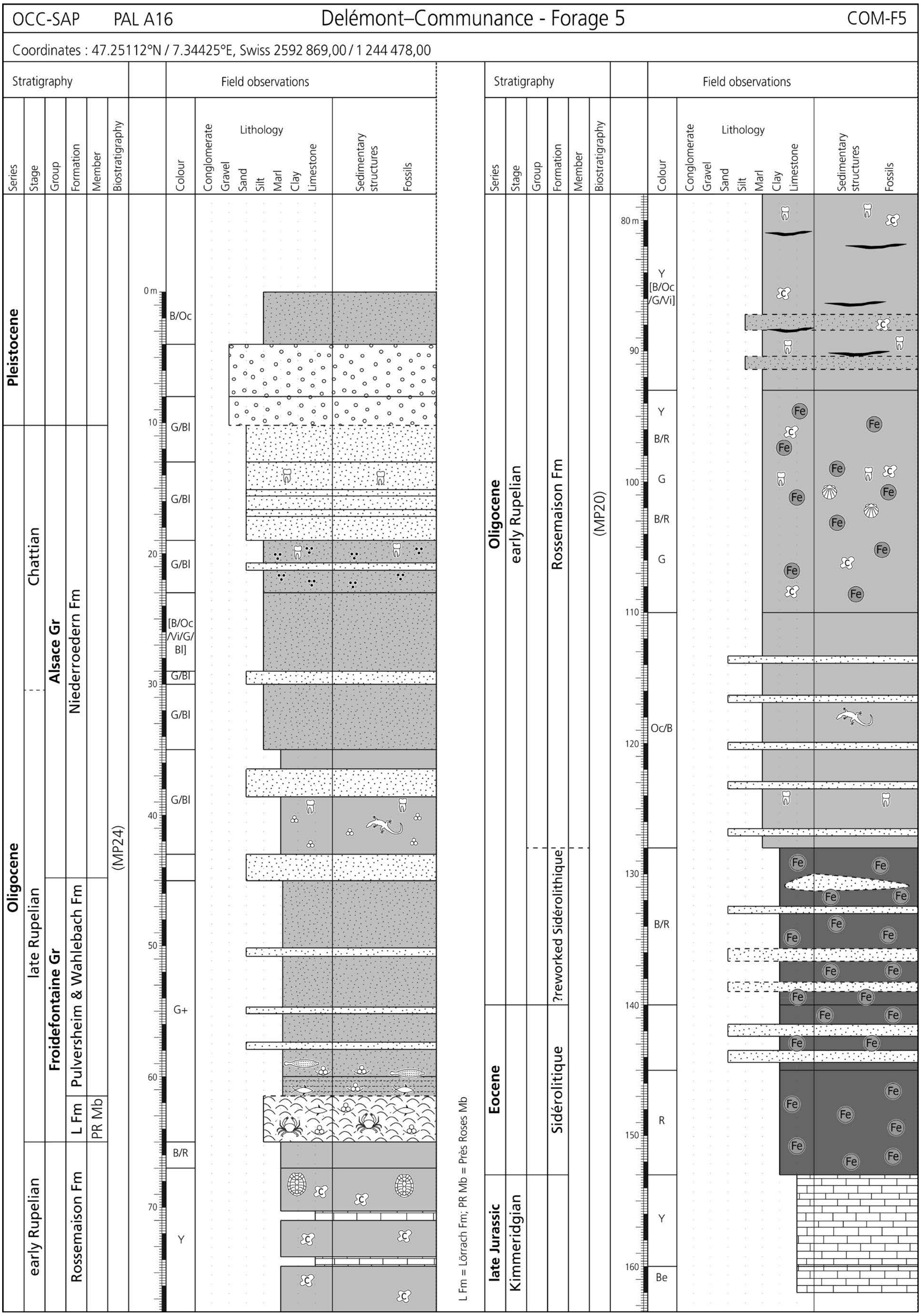


Fig. 10 - Log of the drilling Delémont-Communance (COM-F5) from the Delémont subbasin centre, showing a near complete though condensed succession of Cenozoic sediments (Switzerland).

Jurassic substratum (see logs in Roussé 2006; Picot et al. 2008), with a cm-thick reddish clay layer at the base hinting at the presence of an erosional remnant of Sidérolithique.

Thicknesses in the Delémont area range from around 20 cm (HRT-F8) at the margin of the subbasin to around 18 m (COM-F5) in the centre. Grimm et al. (2011b) indicate a maximum thickness of 64 m in the southern Upper Rhine Graben in drill cores.

Clay minerals of the Sidérolithique are dominated by kaolinite with illite being scarce (Sittler 1970). Interestingly the clay mineral assemblage of the so-called "Calcaires / Gompholithes de Daubrée" is markedly different with abundant illite and low to moderate contents of kaolinite and chlorite in the conglomerates ("gompholithes"), and a high content of palygorskite in the limestones (Sittler 1965).

6.1.3 Type, reference and classic localities

So far no type locality has been assigned, since no outcrop section showing both karst pockets and layered deposits exists. A generalized section of the Sidérolithique in the Delémont Basin has been proposed by Fleury (1909) based on cumulative observations in mine shafts. The exemplary section from the Delémont Basin margin in drilling COM-F5 (153.0 to 140 m, Fig. 10) may be considered as a type section, though the observed thickness does not come close to the maximum thickness in the URG cited by Grimm et al. (2011b).

6.1.4 Differentiation from other units

The underlying Jurassic limestones can always clearly be separated from the Sidérolithique, whereas the transition to the overlying yellowish marly Rossemaison Fm deposits (see 6.2) in the Delémont subbasin is rather gradual, with a redeposition and mixing of Sidérolithique sediments. In areas outside the Delémont Basin other clearly distinct lithostratigraphic units may be deposited directly on or include eroded Sidérolithique at the base (e.g. conglomeratic Turckheim Fm, sandy Wahlebach Fm).

Insufficiently documented local limestones and conglomerates termed "Calcaires de Daubrée" and "Gompholithes de Daubrée / Bohnerzkonglomerat" have been attributed to the Sidérolithique (Fleury 1909; Liniger 1925; Buxtorf & Christ 1936; Picot 2002), based on the proximity of "true" Sidérolithique deposits and a certain content of ferruginous cement and pisoliths. Since (bio)stratigraphic evidence is lacking, a definitive correlation with either the Sidérolithique, the basal conglomerates of the Turckheim Fm (see 6.3) or the limestones of the Bouxwiller Fm (Grimm et al. 2011b) remains difficult. A similarity of clay mineral assemblages of the Bouxwiller Fm and the "Calcaires de Daubrée" (Sittler 1965) probably indicates a comparable depositional environment.

These scattered conglomerates and lacustrine limestones may have been deposited simultaneously with the Sidérolithique in areas with a stronger local relief.

6.1.5 Age and fossil content

The Sidérolithique has scarcely been dated. Outside the research area in the Swiss Molasse Basin the biostratigraphic age ranges from MP14-19 (late Lutetian to late Priabonian; see listing in Becker 2003). In the research area the fossil-rich site Courrendlin-Verrerie was recently correlated with small mammal zone MP16 (Bartonian; Becker et al. 2013b). To the north in the Upper Rhine Graben no autochthonous age has been documented so far (see Grimm et al. 2011b), but the Sidérolithique should be older than the overlying Bouxwiller Fm attributed to small mammal zone MP13b (Jaeger 1971), thus distinctly precedes the Sidérolithique at Courrendlin-Verrerie.

The assemblage from the Courrendlin-Verrerie karst pockets (Becker et al. 2013b) consists of numerous mammal teeth (e.g. *Elfomys engesseri*, *Mixtotherium lavergnense*), crocodile teeth and abundant bone fragments. Many other localities of the research area are barren of fossils, except for reworked Mesozoic biota. An early faunal overview of the Sidérolithique has been provided in Fleury (1909).

6.2 Rossemaison Fm (ex Terre jaune, Gelberde) (Fig. 13a)

6.2.1 Synonomy and generalities

- Terre(s) jaune(s) (Greppin 1870, Fleury 1909, Liniger 1925, Fischer 1965a, Clément & Berger 1999, Picot 2002, Becker 2003, Roussé 2006, SKS 2014)
- Argiles jaunes ou rougeatres, A. jaunes avec gypse, Marnes jaunes ou bigarrées, Terre jaune ou rouge, Raiche, and others (Rollier 1893a,b, 1898)
- Gelberde, Raitsche (Liniger 1925, Fischer 1965a, Berger et al. 2005a, Gander 2013)
- USM I (Berger 2011)

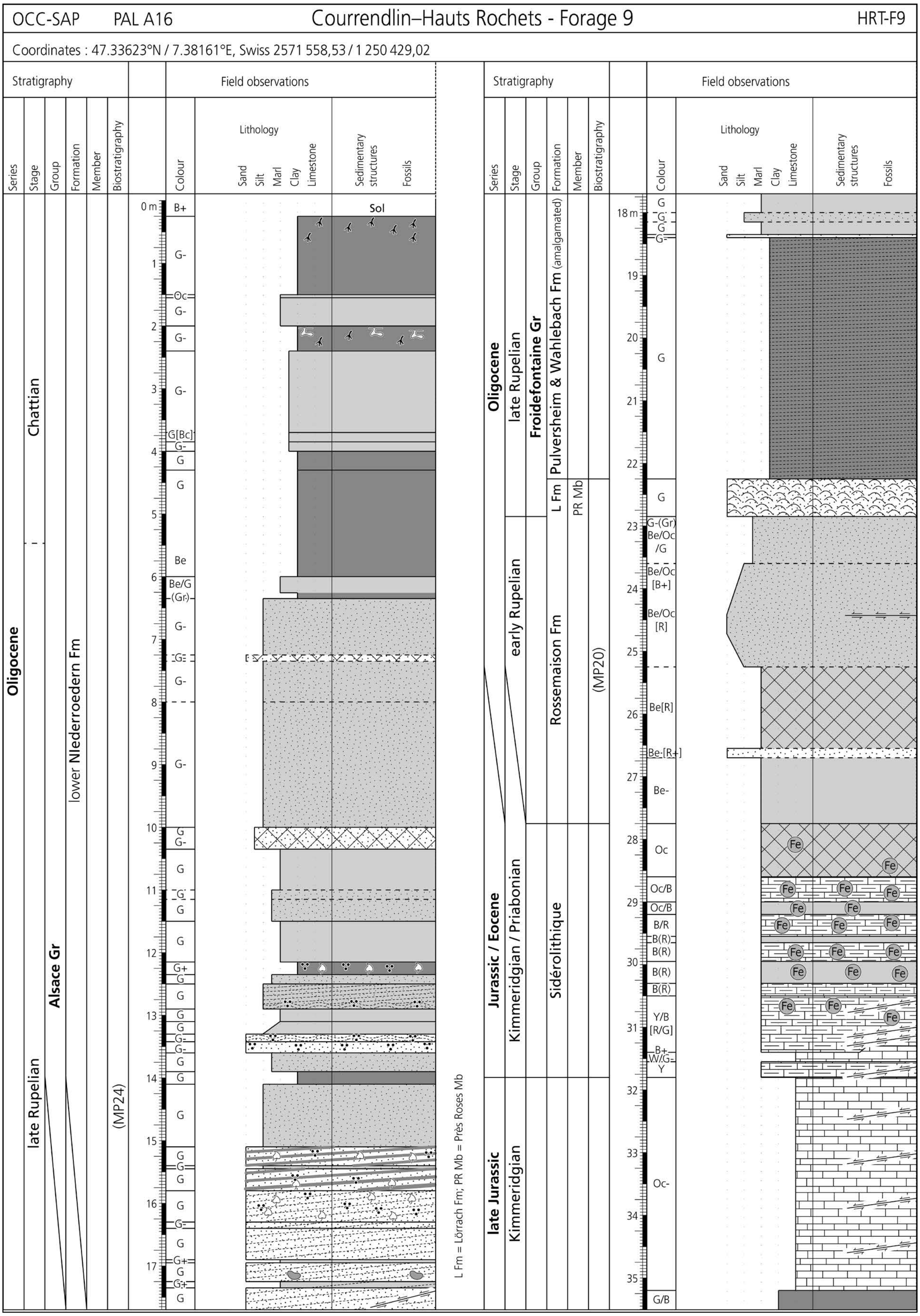


Fig. 11 - Partial log of the drilling Courrendlin-Hauts Rochets 9 (HRT-F9) from the southern Delémont subbasin margin, showing an extremely condensed succession of Cenozoic sediments (Switzerland).

The Rossemaison Fm represents a lithological unit largely restricted to the central Delémont Basin. It may be attributed as a coeval formation to the tripartite Pechelbronn Group (Grimm et al. 2011a, b) (see 7 and Fig. 40). The former term "Gelberde" should be avoided due to its application to other not coeval yellow deposits of varying provenance (e.g. "Gelberde" underlying Lutetian limestones in Wittmann 1950).

6.2.2 Definition, distribution and thickness

Generally yellow to red marls with variable sand content and reworked Sidérolithique components that are limited to the central Delémont subbasin (Liniger 1925). Locally evaporites (gypsum), lacustrine limestones ("Raiche, Raitsche") and conglomerates are intercalated (e.g. Rollier 1910), thus hinting at a fluvio-lacustrine, probably endorheic environment. The Rossemaison Fm has been historically (mining) subdivided in four units (see Liniger 1925), which however cannot be followed throughout the subbasin.

The Rossemaison Fm pinches out towards the southern basin margin, with a variable maximum thickness of 70 m (drilling COM-F5; 128.0 to 65.0 m, Fig. 10) to more than 140 m near Delémont (abandoned mine Près Grebis; Liniger 1925). At the subbasin margin the thickness ranges between 10 m (Châtillon; Gander 2013) and 4-5 m (drilling HRT-F8; 21.9 to 19.2 m, Fig. 12).

6.2.3 Type, reference and classic localities

Historically the Rossemaison Fm was well exposed in now inaccessible numerous mine shafts and exploratory drillings (e.g. Rollier 1898; Liniger 1925). Surface outcrops are rare and small, for example near Courroux on the banks of the River Birse (47.35977° N/7.37023° E) and Scheulte (Raitsche limestones; 47.36346° N/7.38621° E) and near Châtillon (47.32255° N/7.34115° E). More recently the Rossemaison Fm was drilled near the centre and the southern margin of the Delémont Basin (COM-F5 and HRT-F8/9 respectively). On the basis of log descriptions (Meury Flury Rieben SA 1990; Weidmann 1990, formalised in Mojon et al. in print) drilling COM-F5 (Fig. 10) has been designated as type section for the Rossemaison Fm. The logs of drilling HRT-F8/9 act as reference sections (Fig. 11-12).

6.2.4 Differentiation from other units

The transition from the underlying Sidérolithique is generally gradual, with reworked Sidérolithique mixed with autochthonous sediment for several meters, and sometimes higher up in the section. The subsequent marine deposits (either a quartz-rich oyster coquina or dark grey marls) of the Froidefontaine Group (see 6.4) are clearly distinct and show a sharp boundary at their base, partly bioeroding the topmost Rossemaison Fm marls (e.g. drilling HRT-F8; Fig. 12).

The sediments from the Pechelbronn Group in the URG differ in a much more varied sedimentology and sediment colour, with the coeval Rossemaison Fm likely being deposited in an isolated (during the early Rupelian) subbasin linked to the southern URG tectonic evolution.

Yellowish brown marls of 1 m thickness containing abundant blocks and pebbles of upper Jurassic origin that are overlain by sediments of the Lörrach and subsequent formations have been documented (Fischer 1965a) from a trial well near Löwenburg (Movelier; 47.43327° N / 7.31265° E) and possibly represent the northeastern pinchout of the Rossemaison Fm. Other similar sediments are not documented north of the Delémont subbasin.

6.2.5 Age and fossil content

The Rossemaison Fm near Châtillon (Delémont subbasin) was correlated to small mammal zone MP20 (Eocene-Oligocene transition) and near Les Abues to MP21 based on charophyte oogonia (Gander 2013, Mojon et al. in revision). A possible attribution of the "middle" Rossemaison Fm to small mammal zone MP21 (earliest Rupelian) has been cited in Picot et al. (2008).

The Rossemaison Fm is generally not known for abundant fossil content. Greppin (1870) mentions charophyte oogonia, freshwater molluscs and crocodile remains.

6.3 Turckheim Fm (ex Steingang, Conglomérat de Porrentruy) (Fig. 8b, 13a)

6.3.1 Synonomy (selection) and generalities

- partim dépôt de galets calcaires (Daubrée 1852)
- poudinge tertiaire, conglomerát tertiaire, conglomérat ou nagelfluh (Delbos & Köchlin-Schlumberger 1867)

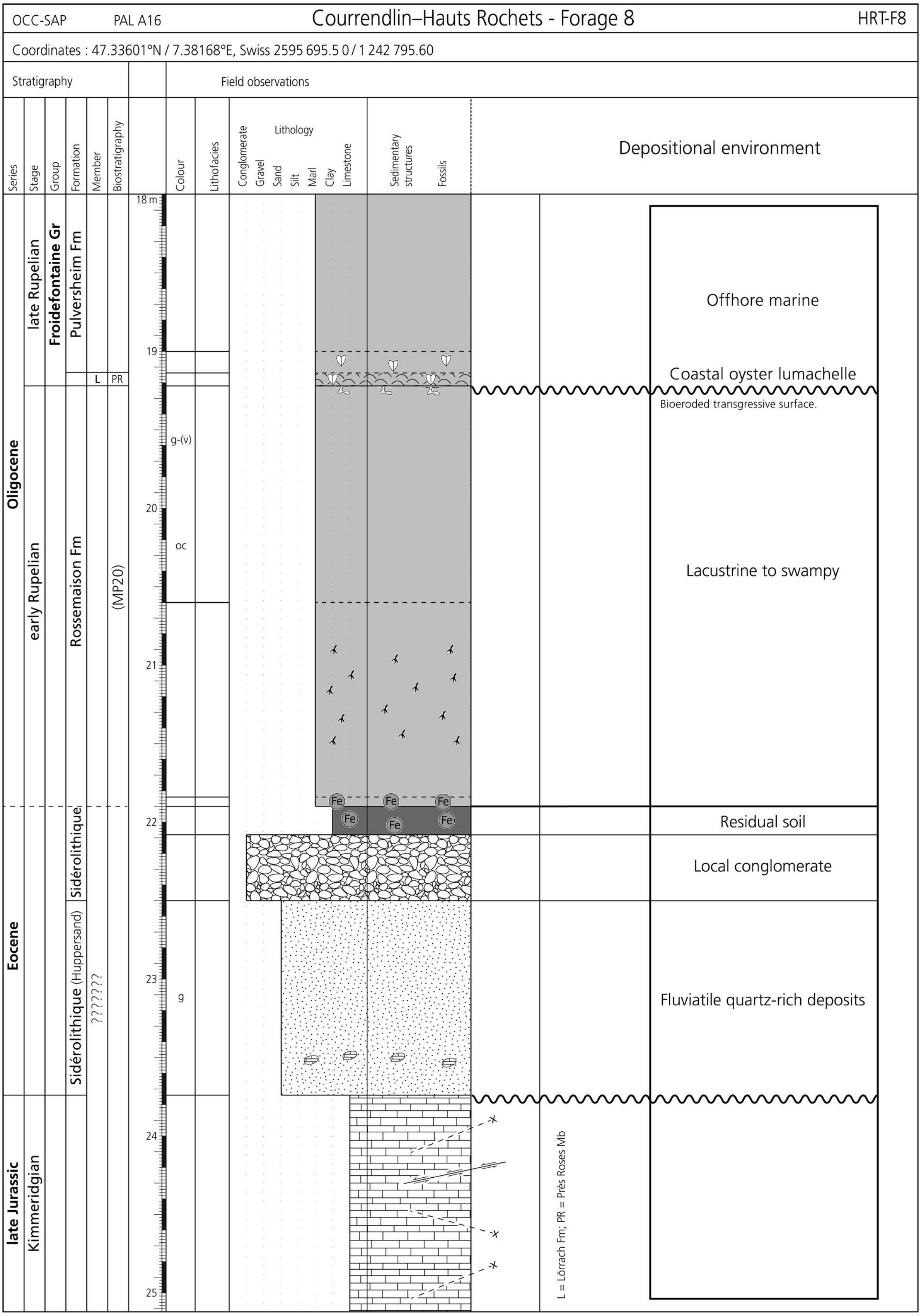


Fig. 12 - Partial log (Niederroedern Fm omitted) of the drilling Courrendlin-Hauts Rochets 8 (HRT-F8) from the southern Delémont subbasin margin (Switzerland).

- Conglomérats (littoraux) (Kilian 1884)
- Schichten von Rouffach, oligocäne Conglomerate (Andreae 1884)
- (partim) Gompholithe (d'Ajoie) (Rollier 1893a,b, 1898, 1910, Tschopp 1960)
- (partim) Küstenkonglomerat(e) (Kessler 1909, Wagner 1955, Tschopp 1960)
- partim Oligozänkonglomerat (Wurz 1912)
- partim Gompholithe d'Ajoie (Rollier 1910, non Liniger 1925, Picot 2002)
- partim Système de Bourogne: faciès côtier (Meyer 1928, Sittler 1965)
- Conglomérat(s) côtier(s) (Gillet & Schnéegans 1935, Duringer 1988, Roussé 2006, GeORG 2013)
- Konglomerate von Porrentruy (Schneider 1960)
- Kalkarenite und Konglomerate von Oltingue (Fischer 1965a)
- Zone / Groupe conglomératique (infériere / supérieur) (Sittler 1965)
- Streifige Mergel: Konglomeratzone (Fischer 1969)
- Conglomérat(s) de Porrentruy (Picot 2002, Becker 2003, Picot et al. 2008)
- Porrentruy conglomerates, conglomeratic facies (Berger et al. 2005a)
- Küstenkonglomerat-Formation (LGRB 2011, DSK 2016)
- Steingang (DSK 2002, Grimm 2005, Grimm et al. 2011b, for additional older synonymy therein)

"Steingang" (DSK 2002; Grimm 2005; Grimm et al. 2011b) represents a common term formerly used as mining terminology and denotes indiscriminately different lithological units (of comparable lithologies) and should thus be avoided (see discussion in Wittmann 1955). "Küstenkonglomerat-Fm" (LGRB 2011; DSK 2016) describes a specific palaeogeographic setting ("coastal conglomerates") that does not hold true for the majority of the depositional context.

6.3.2 Definition, distribution and thickness

The Turckheim Fm represents sediments related to moderate to high relief in the hinterland, resulting in grain sizes ranging from m-scale blocks (proximal) to arenites (distal) with occasional red to yellow clay and marl intercalations. The grain type ranges from unsorted irregular blocks to near-equally sized, well-rounded pebbles and sands. Pebbles and blocks may be encrusted by stromatolithic carbonates (Duringer 1988) or bound by biomineralisations (fig. 15). These conditions led to local deposits of lacustrine limestone nodules and "lenses" within the conglomerates (e.g. in the Ajoie; Schneider 1960). On the eastern and southern URG margin the conglomerates consist of middle and upper Jurassic components, whereas on the western URG shoulder either lower and middle Triassic or middle and upper Jurassic source rocks are dominant, partly including components of the Vosgian crystalline basement (Duringer 1988).

Palaeocurrents were directed basinwards, except during transgressive phases. Several (lacustrine) transgressive-regressive cycles based on the repetitive changes in sedimentology were deduced (ibid.). The conical shape of larger sediment bodies along the western and eastern graben shoulders represents fan-deltas (ibid., Hinsken et al. 2007), whereas the more uniform deposits in the south (including the research area) indicate a less steep gradient, with smaller scaled conglomeratic fans distally merging into a large-scale deltaic-fluviatile to lacustrine or lagoonal system (see discussions in Duringer 1988; Storni 2002; Hinsken 2003; Picot et al. 2005).

The formation is exposed mainly along the rift shoulders, thus representing the most commonly encountered formation in the field (Berger et al. 2005b). It is however absent from the Delémont subbasin, except for the somewhat difficult to attribute "Gompholithe d'Ajoie" of Liniger (1925) (see 6.3.4). The maximal thickness of the formation remains difficult to estimate, since individual outcrops range from 5 to about 60 m height, but probably reaches about 150 m near Britzingen (Duringer 1988). The composite thickness approaches 200-300 m (ibid.).

Clay minerals are characterised by a high and stratigraphically increasing content of illite and a subordinate, decreasing content of kaolinite (Sittler 1965, 1970). In the lower part of the formation illite-montmorillonite alternation occurs, whereas in the upper part montmorillonite occurs independently (ibid.).

6.3.3 Type, reference and classic localities

A host of well-exposed outcrops in the southern URG are described in Kessler (1909), Duringer (1988) and Hinsken (2007, 2010), including Réchésy, Rouffach, Turckheim and Kandern. For the research area detailed sections of the former "Conglomérats de Porrentruy" exist for the outcrops Bressaucourt-Bois Carré and Oiselier-Passage / Crât (Picot et al. 2005; Fig. 15). Turckheim I-Les carrières (Duringer 1988, p. 23, Fig. 23) has been designated as type locality due to the availability of detailed logs (Fig. 14) documenting most facies types, including the short-term intercalation of the Ru1 transgression of the "Mittlere Pechelbronn-Schichten" and stromatolithic encrustations of pebbles.

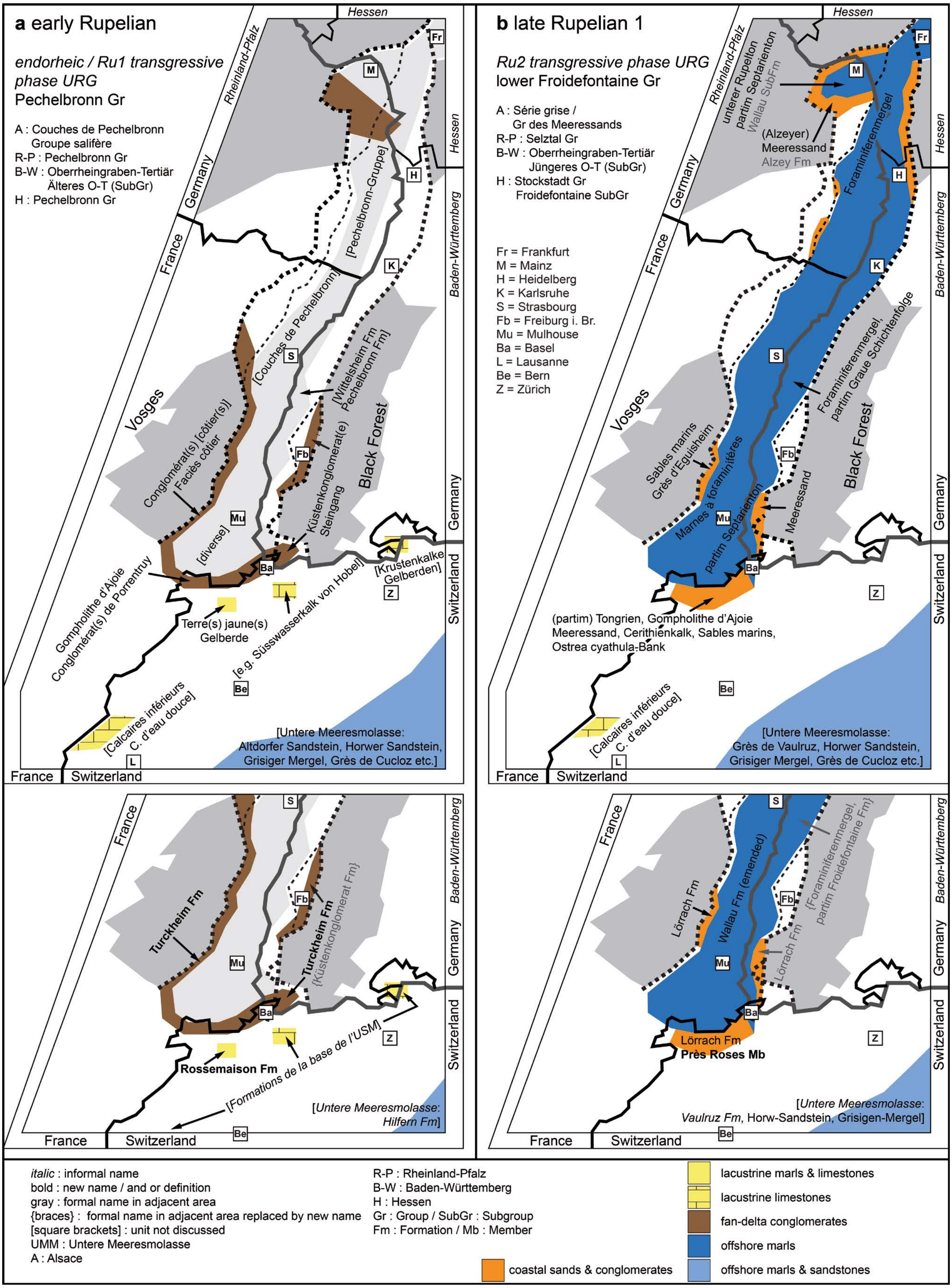


Fig. 13 - Palaeogeographic representation of major facies and regional lithostratigraphic terms (updated from and based on maps in Berger et al. 2005b). Top of the figure represents the formerly used most common terms, lower part the status after revision and simplification. 13a Map for the early Rupelian, 13b Map for the late Rupelian (part 1).

6.3.4 Differentiation from other units

The formation merges basinwards gradually with coeval sediments of the Pechelbronn Group / Formation and the Haguenau Group / Wittelsheim & Haguenau Formation (e.g. Grimm et al. 2011b / LGRB 2011 and DSK 2016 respectively, see discussion in 7). During maximal sedimentary discharge (regression, increased sedimentation rates) conglomeratic beds prograde into basinal facies. Inversely basinal facies may be intercalated in the conglomerats, like the so-called "freshwater limestones containing *Helix rugulosa*" (e.g. Fischer 1965a). Fossil-rich marine marls of the global Ru1-transgression (Pirkenseer & Berger 2011), termed "Mittlere Pechelbronn-Schichten" (Grimm et al. 2011b, LGRB 2011) or "Zone fossilifère" (e.g. Duringer 1988), intercalate as (a) thin bed(s) in the outcrops Strangenberg, Turckheim, Oltingue and Kleinkems (Fischer 1965a; Duringer 1988; Hinsken 2003; Pirkenseer & Berger 2011). This transgression may even have reached the Ajoie subbasin (see below). Lithologically these marine marls cannot be separated from other intercalated marls within the conglomeratic sections.

Part of the "Gompholithe d'Ajoie" sensu Rollier (1910) belongs to the Turckheim Fm Picot (2002) discussed the extent of the "Gompholithe d'Ajoie" and grouped it with the "Conglomérat de Porrentruy" as a stratigraphic equivalent outside the Ajoie subbasin. The stratigraphic attribution of the southernmost occurrences near Châtelat remains uncertain. The "Gompholithe d'Ajoie" from the Delémont subbasin sensu Liniger (1925) indeed resembles the conglomerates of the Turckheim Fm, however represents a coarse-grained marginal equivalent of the Lörrach Fm (see 6.5).

Except for the coastal conglomerates of the Lörrach Fm (see 6.5.2/4), all other formations of the Haguenau, Pechelbronn and Froidefontaine Groups can readily be distinguished from the Turckheim Fm due to a different lithology (clay, marl, limestone) and colour (red to yellowish against predominantly green, gray and black).

6.3.5 Age and fossil content

The locality Fessevillers represents the only available autochthonous biostratigraphic age (Aufranc et al. 2016; Mojon et al. in print) and has been correlated to small mammal zone MP21. Relative ages are derived from correlations to coe-

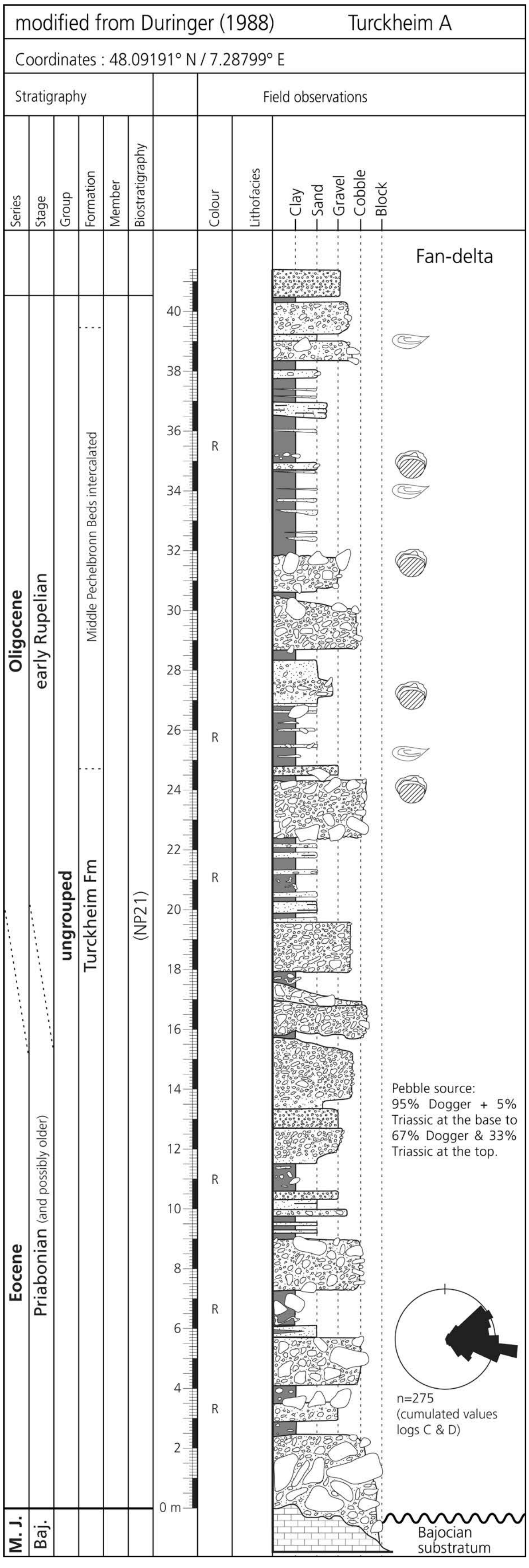


Fig. 14 - Type section of the conglomeratic Turckheim Fm (modified from Duringer 1988) near Colmar (France). For additional logs at the same locality consult reference.

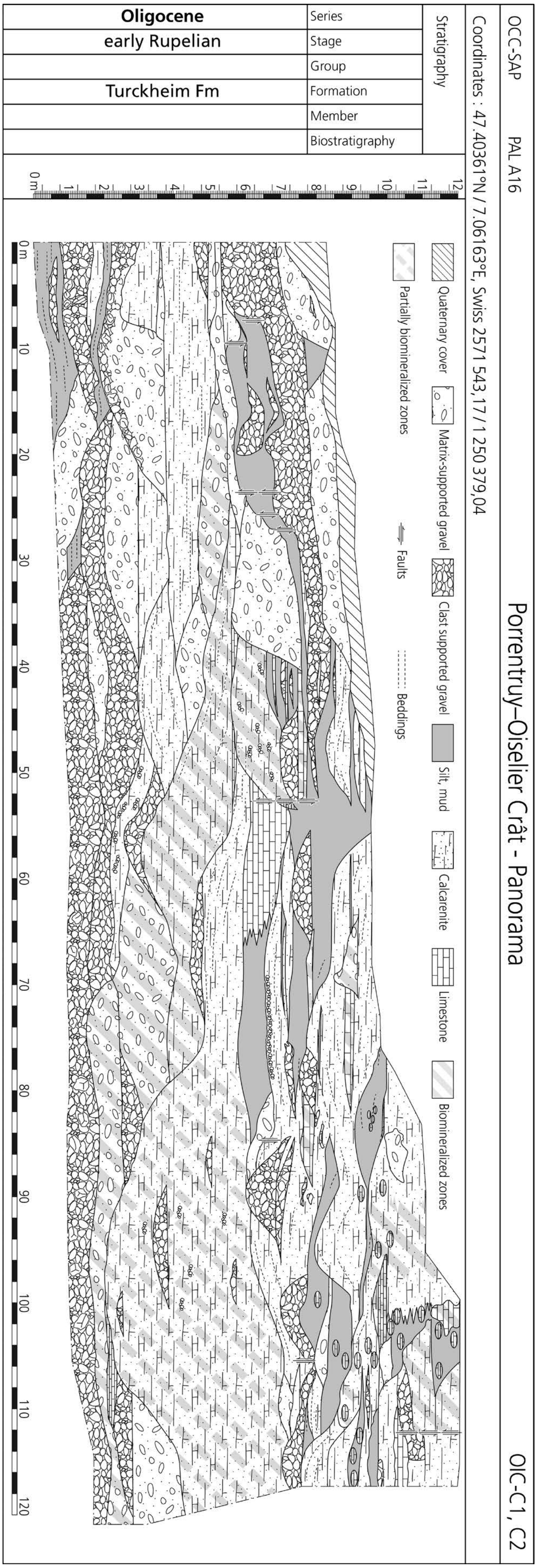


Fig. 15 - Lateral reference section of the Turckheim Fm near Porrentruy (Switzerland) in the Ajoie subbasin. Note the development of stacked channels with fills of varying granulometric composition as well as intercalated limestone lenses.

val basinal sediments. The locality Pfaffenweiler (intermediate between Turckheim Fm and the basinal Untere Grüne Mergel), correlated with the middle part of the Turckheim Fm (Duringer 1988), has been attributed to small mammal zone MP18 (Priabonian) (e.g. Tobien 1988).

The "Mittlere Pechelbronn-Schichten" (see above) represent a basinwide subformation that has been correlated to the global Ru1 transgression-regression cycle (e.g. Martini & Radtke 2007; Pirkenseer & Berger 2011) at the base of the Rupelian. The "Mittlere Pechelbronn Schichten" have been attributed to calcareous nannoplankton zone NP21 (Eocene-Oligocene transition; Lavoyer 2013), to zones NP19-21 according to Storni (2002) and to NP22 in the Mainz Basin in Martini & Reichenbacher (2007).

Accordingly the middle to upper Turckheim Fm corresponds to a Priabonian to "middle" Rupelian age. The age of the lower part of the formation is difficult to estimate, since the conglomerates reside discordantly on either the (Mesozoic) substratum or other formations (e.g. Bouxwiller Fm, small mammal zone MP13b).

Due to the generally coarse-grained nature of the Turckheim Fm macrofossils are scarce, with the mussel *Mytilus* and Bryozoa representing by far the most common (e.g. Schnaebele 1948). The basinal "Mittlere Pechelbronn Schichten" are microfossil-rich in the entire URG (e.g. Grießemer et al. 2007; Grimm et al. 2007; Lavoyer 2013). At the outcrop Strangenberg several fully marine ostracod taxa have been documented (e.g. *Grinioneis* ex gr. *triebeli*, *Hornibrookella macropora*; Pirkenseer & Berger 2011) and thus probably document the highstand of the Ru1 transgression when flooding the entire width of the URG. The presence of few benthic Foraminifera in marly intercalations within the former "Conglomérats de Porrentruy" (Picot et al. 2008) indicates the southernmost extension of the early Rupelian sea.

6.4 Froidefontaine Group (ex Série grise, Graue Schichtenfolge)

6.4.1 Synonomy

- partim Molasses marines (Gressly 1841)
- Kalksandstein und blaue Mergel von Lörrach etc. (Sandberger 1863)
- Système de Froidefontaine, partim Système de Bourogne: faciès côtier (Meyer 1920, 1928, Duringer 1988)
- Blaue Tone oder Letten (Liniger 1925)
- marines Stampien (Baumberger 1927)
- Unterstampien (Wittmann 1952)
- Untere Meeresmolasse (Fischer 1969)
- partim Graue Schichtenfolge (Doebl 1970)
- Rupel Clay (Sissingh 1998, 2006)
- Groupe des Meeressand & Calcaires marins, Groupe des Septarienton, UMM rhénane (Picot 2002)
- partim Grey Marl Formation (Schumacher 2002)
- partim Graue Mergel (Vonderschmitt 1942), Graue Mergel-Formation (LGRB 2005)
- partim lower marine molasse [Delémont Basin] (Sissingh 2006)
- UMM (Clément & Berger 1999), UMM rhénane (Picot et al. 2008), UMM Jura (SKS 2014), UMM III (Berger 2011)
- Série grise (Schnaebele 1948, Sittler 1965, 1992, Duringer 1988, Berger et al. 2005a, b, Roussé 2006, Le Metayer 2007, Picot et al. 2008, Pirkenseer & Berger 2011)
- Froidefontaine-Subgruppe (Grimm 2005, Grimm et al. 2011b, Schäfer 2013)
- Froidefontaine Fm (LGRB 2011, GeORG 2013, DSK 2016)

6.4.2 Definition and distribution

The name of the group is derived from the term “Système de Froidefontaine” (Meyer 1920, 1928), a marine late Rupelian transgressive-regressive sedimentary succession that has been observed in a historical outcrop near the village of Froidefontaine (Territoire de Belfort, France). In this section the normally several hundreds of meters thick Froidefontaine Group is greatly reduced and comprises of relatively uniform greenish-yellowish to grey, partly finely laminated marls and silt to sandstones of the former “Foraminiferenmergel”, “Fischschiefer”, “Melettaschichten” and “Cyrenenmergel” formations.

If fully developed the transgressive-regressive-deltaic Froidefontaine Group is characterized by a clear, historically well recognized quadripartite subdivision in the Wallau, Hochberg, Pulversheim and Wahlebach Formations, accompanied by the coeval coarse clastic coastal Lörrach Fm (former “Meeressand”). In some marginal areas (including the Delémont, Laufen and Ajoie subbasins) this subdivision may not be recognizable due to the amalgamation or absence of individual formations.

Grimm (2005) erected the Froidefontaine Subgroup as part of the Stockstadt Group. However due to the pronounced lithological heterogeneity within the latter and based on the common traits of the four combined formations of the former we raise it to group status, rendering the Stockstadt Group redundant. Furthermore we emend the internal subdivision of the former Froidefontaine Subgroup sensu Grimm (2005) and Grimm et al. (2011b), since the therein-denominated formations were either not consistently based on lithology, or were defined in the somewhat more regional context of the Mainz Basin (see individual formations below).

The Froidefontaine Fm sensu LGRB (2011) is in its lower part (“Foraminiferenmergel” and “Hochberg-Fischschiefer” Subfms) equivalent to the Froidefontaine Group. The overlying Karlsruhe Subfm however deviates strongly in its lithology (and fauna) from the “classic” basinal “Melettaschichten” (which it replaces; now Pulversheim Fm; see 6.9), and should hence be considered as a coeval (sub)Fm of the latter, and/or attributed as basal unit to the subsequent Niederrödern Fm (see 6.16). Interestingly, even though GeORG (2013) state that the Wallau and Hochberg Fms are recognisable as distinct seismic reflectors, the subdivision in formations has not been recognised by LGRB (2011), hence relegating them to subformation status.

Biostratigraphically there are few good indications for the entire group. Many boundaries are or appear to be diachronous due to the ambiguity of the data (e.g. Picot 2002) or a true diachronous development (e.g. Roussé 2006) of facies boundaries (e.g. varying extension of marine sediments between initial flooding and maximum flooding/highstand; progradation of a deltaic system gradually pushing back marine facies).

The Froidefontaine Group is characterised by a gradual increase in the clay mineral montmorillonite (which is absent in older formations) and a simultaneous reduction of the illite and kaolinite content (Sittler 1965). Sandstone intercalations supplied by ex-URG sources (see 8) start to ouccur in the Pulversheim Fm. They become increasingly frequent in the subsequent Wahlebach Fm and Heidwiller MB with simultaneously increasing grain-sizes. The main sandstone components consist of quartz and muscovite.

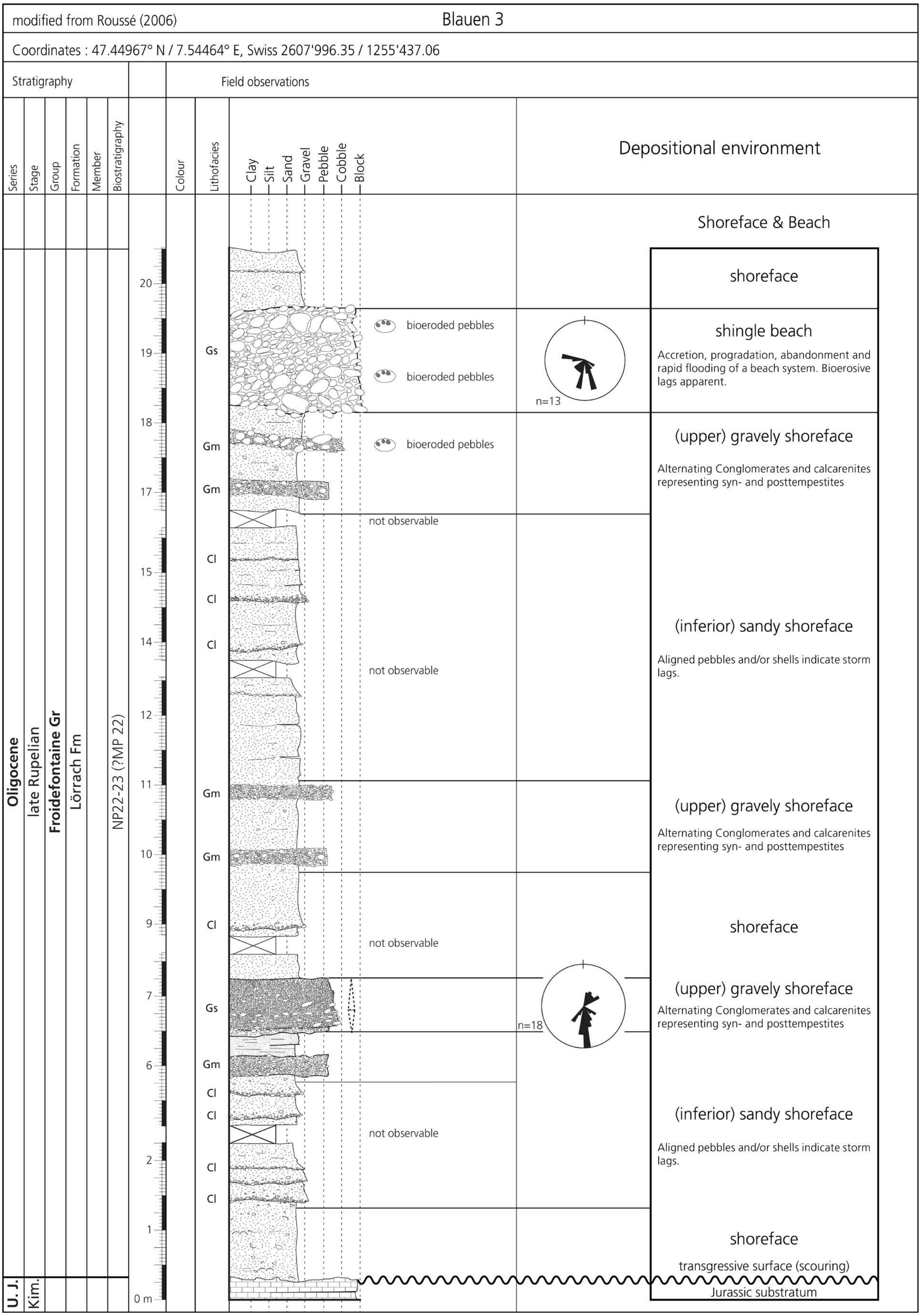


Fig. 16 - Reference log of the coastal Lörrach Fm from the Blauen anticline north of Laufen (Switzerland), representing the finer grained facies.

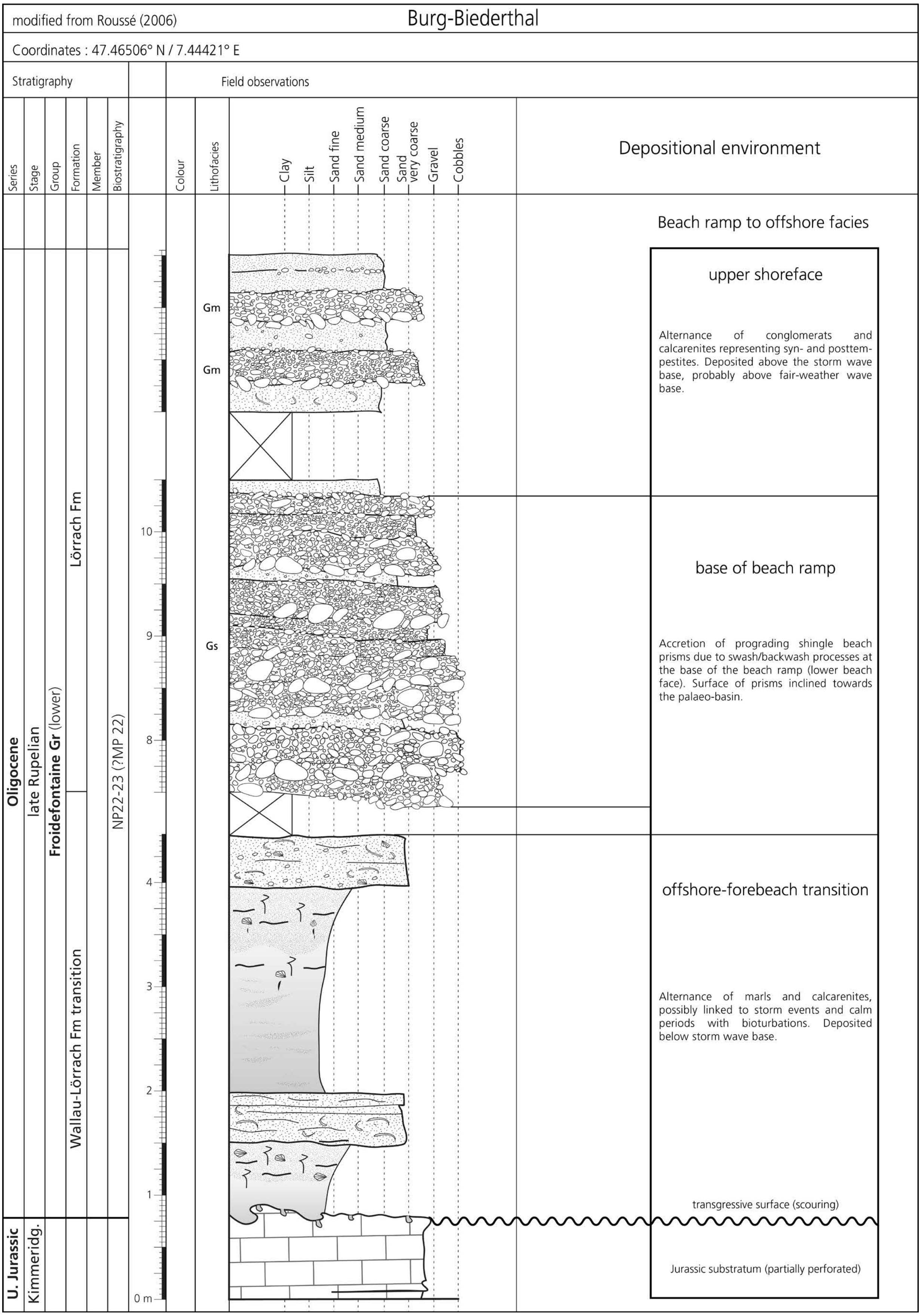


Fig. 17 - Reference log of the Lörrach Fm north of the Blauen anticline near Biederthal (France), representing the conglomeratic beach facies in the upper section, and the transition from the offshore Wallau Fm in the lower part.

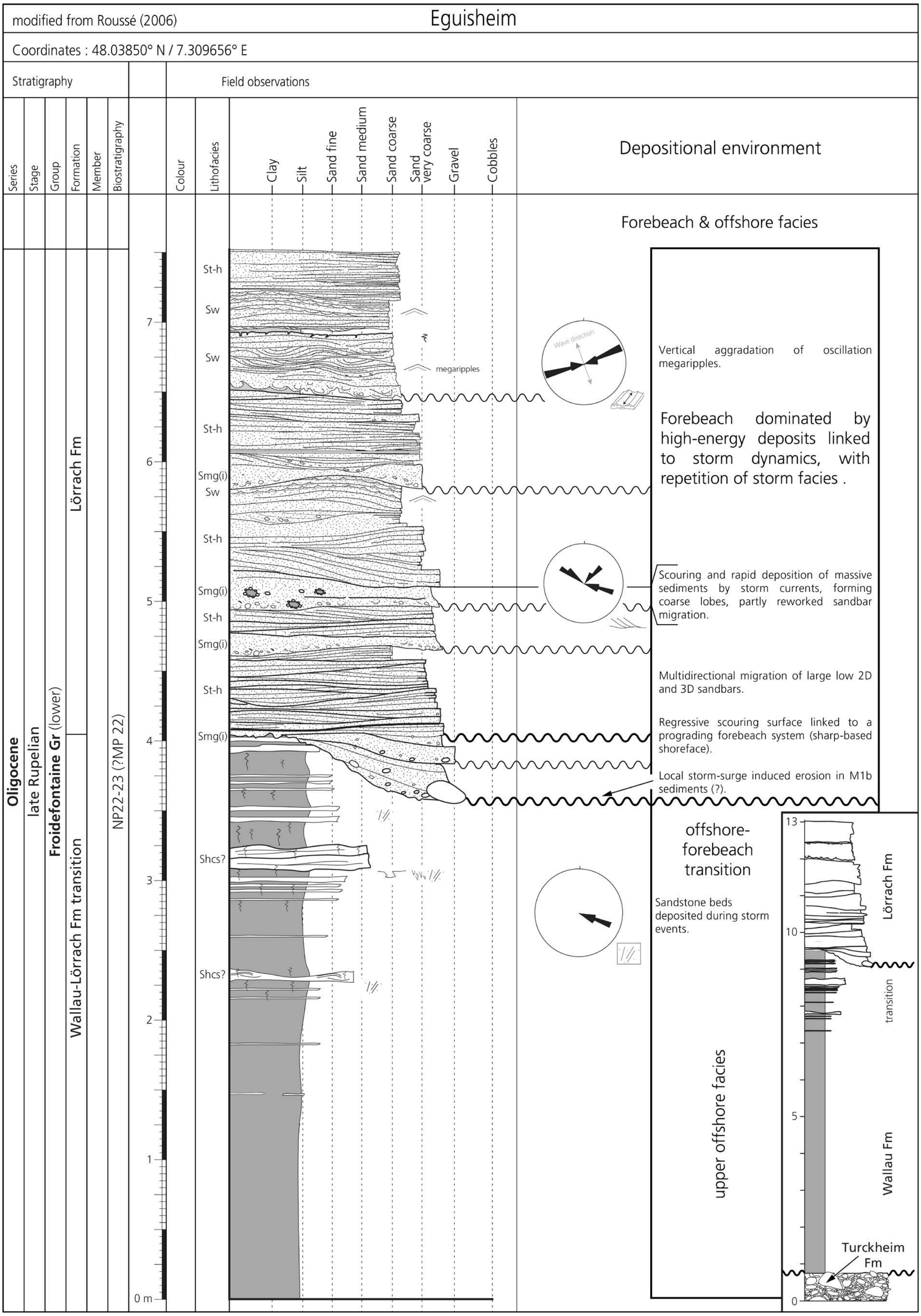


Fig. 18 - Reference log of the Lörrach Fm near Eguisheim (France), representing the sandy forebeach facies in the upper section, and the transition from the offshore Wallau Fm in the lower part. The formerly observable transgression of the offshore marls on the conglomeratic Turckheim Fm is illustrated in the inset in the lower right corner.

6.5 Lörrach Fm (ex-Meeressand) (Fig. 13b)

6.5.1 Synonomy and generalities

- Calcaires, grès et marnes jaunes à fossiles marins (Gressly & Mayer 1853)
- partim gelbe Breisgauer Molasse (Sandberger 1858)
- Terrain tertiaire marin: tongrien, grès jaune grossier (e.g. at Éguisheim; Delbos & Köchlin-Schlumberger 1866)
- Tongrien: facies littoral (Greppin 1870)
- partim sables et marnes de Dannemarie (Kilian 1884)
- partim Gompholithe (d'Ajoie) (Rollier 1893, 1898, 1910)
- Meeressand / Meeres-Sand (Sandberger 1863, Andreae 1884, 1888, Gutzwiller 1893, 1914, Renevier 1897, Rollier 1893a, Kissling 1896, Koch 1923, Liniger 1925, Buxtorf & Christ 1936, Vonderschmitt 1941, Bitterli 1945, Wittmann 1950, 1951, 1952, 1967, Oertli 1956, Schneider 1960, Fischer 1965a, 1969, Fischer et al. 1971, Bitterli-Brunner & Fischer 1988, Picot 2002, SKS 2014)
- Sables et marnes de Dannemarie, Calcaire marin et gompholithe (Rollier 1893a)
- Brislacherkalk, Brislacher-Kalk (Kissling 1896, Renevier 1897)
- Calcaire à cérithes d'Ajoie / Cerithienkalk (Rollier 1898, 1910, Diebold 1960, Schneider 1960, Tschopp 1960)
- Mergel mit Ostreen, Glaukonit-Quarzsand, Meeressand, ?partim Foraminiferenmergel (Förster 1909a)
- partim Küstenkonglomerate (Meeressande therein; Kessler 1909)
- (partim) Gompholithe d'Ajoie (Liniger 1925, Diebold 1960, Schneider 1960)
- Kalksandstein (Tschopp 1960)
- ?Sables marins de Wolschwiller (Sittler 1965, 1992, Duringer 1988)
- Sables marins, Groupe des Meeressands (Roussé 2006)
- Lörrach-Formation (LGRB 2011, GeORG 2013, DSK 2016)
- Grès d'Eguisheim ou/et Gompholithes d'Ajoie (Sittler 1965, GeORG 2013)

The former term "Meeressand" has also been applied to similar, partly not coeval and/or co-geographic deposits like the Chattian "Kasseler Meeressand" (e.g. Faupel 1975). Recent names linked to geographic terms such as the Lörrach or Alzey Fm have since been provided.

The Alzey Fm sensu Grimm et al. (2000), Grimm (2005), Grimm (2006) and Grimm et al. (2011a, b) has been defined in the Mainz Basin for coeval sediments sharing lithological characteristics of the Lörrach Fm. However, since a large geographic gap of occurrences is evident in the middle URG (see documentation in Kessler 1909; Roussé 2006; Fig. 13b), and the definition is not entirely consistent, we decided to adapt the term Lörrach Fm sensu LGRB 2011 for the southern URG outcrops.

6.5.2 Definition, distribution and thickness

Blocks, conglomerates and coarse calcarenitic sands in a coastal shallow marine context (shoreface, beach ramp), with the stratification mostly related to storm events and accretion of beach systems (Wittmann 1951, 1967; Roussé 2006). The generally yellowish sediments are partly bioturbated. Individual sandstone beds may show gravelly lag deposits at their base, the top of conglomerate beds possibly contains abundant bioeroded pebbles (Roussé 2006). Occasionally marls are intercalated, which may either represent periods of low water energy, or the deposition of more basinal offshore sediments (see below and 6.7). Blocks, pebbles and gravel mainly consist of eroded underlying Jurassic limestones. Sands may be indurated due to carbonate cement, usually in context with abundant mollusc fossils (e.g. "Brislacherkalk"). These occurrences represent small-scaled lateral facies variations in areas with lower water energy and do not merit the distinction as members. The calcitic cement of the sandstones and conglomerates has been interpreted to be derived from the diagenetic dissolution of mollusc shells, leaving voids as evidence (Wittmann 1952).

The Lörrach Fm and the coeval basinal Wallau Fm represent the initial transgressive deposits of the Froidefontaine Group and are linked to the ingression of the sea into the URG due to the global sea-level rise of the Ru2 sequence (e.g. Berger et al. 2005a; Roussé 2006; Grimm et al. 2011b). The depositional environment of the Lörrach Fm is interpreted as a highly structured cliff coast consisting of tectonically separated bays (e.g. "Gulf of Basel"; see Roussé 2006).

Similar to the conglomeratic Turckheim Fm the Lörrach Fm was deposited along the southern URG margins. Occurrences are much more scattered though, with outcrops near Eguisheim (Alsace) and from the Ajoie (Switzerland) to Lörrach (Germany). A thickness of at least 20 m is reached in the Blauen 3 section (Roussé 2006; Fig. 16). Wittmann (1949) and Fischer (1965a) report a thickness of maximal 30 m for the area of Lörrach and Wolschwiller.

6.5.3 Type, reference and classic localities

In Baden-Württemberg equivalent sediments have been designated as Lörrach Fm (LGRB 2011;

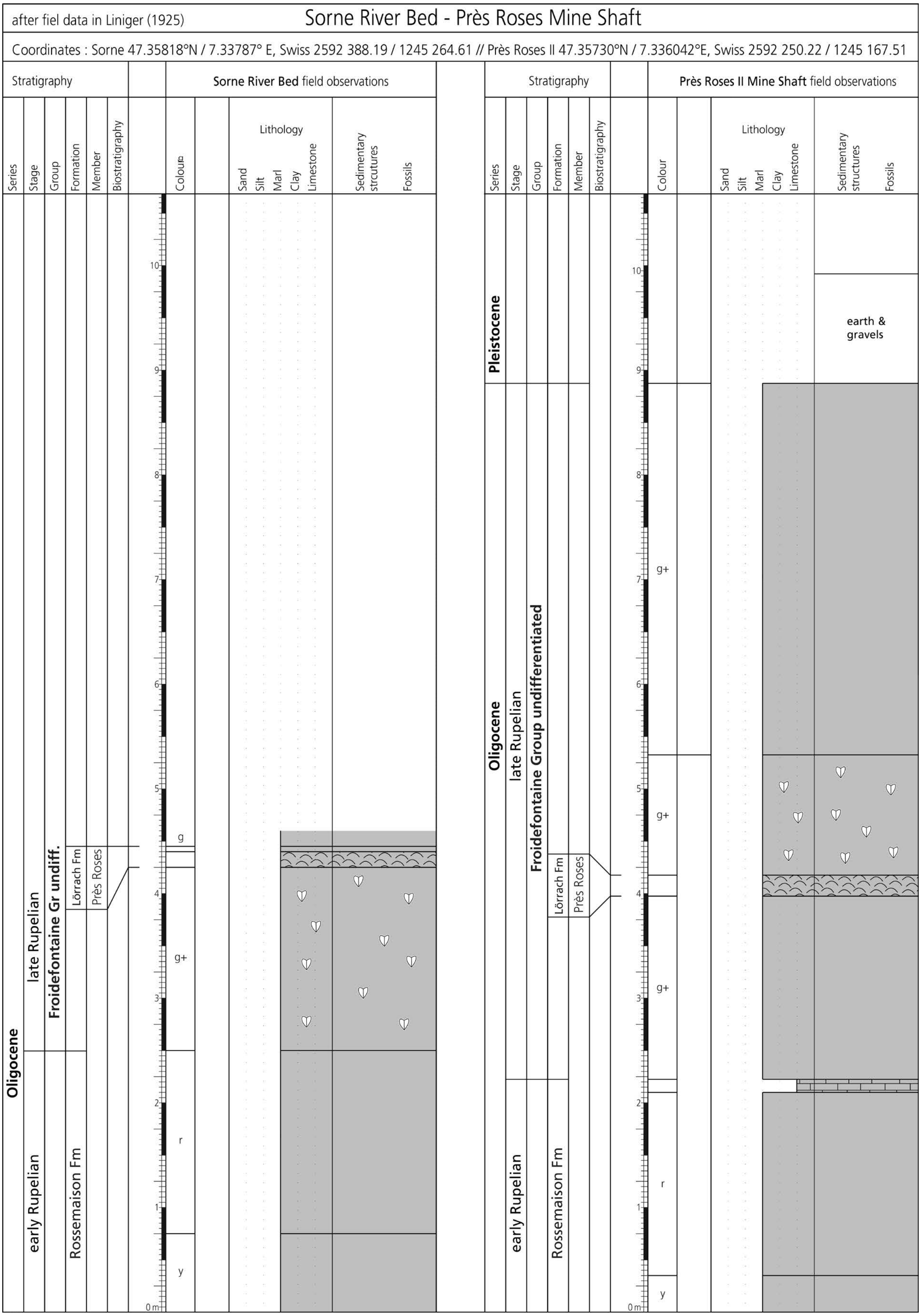


Fig. 19 - Type section of the Près Roses Mb near Delémont (Switzerland) based on historical outcrops in Liniger (1925). For other occurrences of the member see Fig. 10-12.

GeORG 2013), with well-documented localities concentrated around Lörrach (Wittmann 1951; 1952, 1967; Fischer et al. 1971). Though a formal type section is still being evaluated, we adapt this lithostratigraphic term and provide reference profiles.

In the research area Bitterli (1945) investigated the former Kleinblauen quarry section in detail, including an extensive fossil list. Roussé (2006) carried out an exhaustive sedimentary analysis (p. 111-146) of outcrops in the Dornach-Blauen-Burg-Biederthal-area and subdivided the formation in 4 facies types. The sections Burg-Biederthal (47.46463° N / 7.44385° E) and Blauen 3 (47.44968°N / 7.54462° E) represent the lithological diversity of the formation and provide the most extensive outcrops and accordingly have been designated as reference sections (Fig. 16-17). Further outcrops at Kleinblauen, Dornach and Dürrmattgraben lie close to the northernmost anticlines of the folded Jura (Fischer 1965a; Roussé 2006). An overview of (former) outcrops in the Delémont and Ajoie subbasins is given in Liniger (1925) and Schneider (1960).

The section in the abandoned sand pit Eguisheim (Fig. 18) at the base of the Vosges foothills near Colmar (Alsace; 48.03850° N / 7.309656° E) illustrates the interfingering of the coastal Lörrach Fm with the basinal Wallau Fm (see 6.7).

6.5.4 Differentiation from other units

The Lörrach Fm is distinguished from coeval sediments (Wallau, Hochberg, Pulversheim Fms; see 6.7-6.9) by its much coarser grain size, common occurrence of coastal marine macrofossils, sedimentary structures and beige colour. A transitional zone exists between these coeval formations (e.g. Fischer 1965a). A vertical transition is recorded at the locality Eguisheim (Fig. 18), where at the base of the section passes from (microfossil-rich) offshore marls of the Wallau Fm within 4 m to an increasingly sandy lower shoreface environment (Pirkenseer et al. 2010; Pirkenseer & Berger 2011). They are erosively overlain by coarse-grained upper shoreface sands (Roussé 2006). An oscillating short-term trangressive-regressive pattern has been observed in shoreface to beachface sediments of the equivalent Alzey Fm in the Mainz Basin (Roussé et al. 2012), which may hint at similar transitions in a slightly more offshore position at Eguisheim.

From the older Turckheim Fm the Lörrach Fm is separated by the difference in color (ochre vs. red) and sedimentary structures (beach front vs. fan-delta). The Lörrach Fm generally lies erosively on Jurassic carbonates, but in some localities the conglomerates of the Turckheim Fm form the underlying stratigraphic unit (e.g. at Eguisheim, see inset Fig. 18).

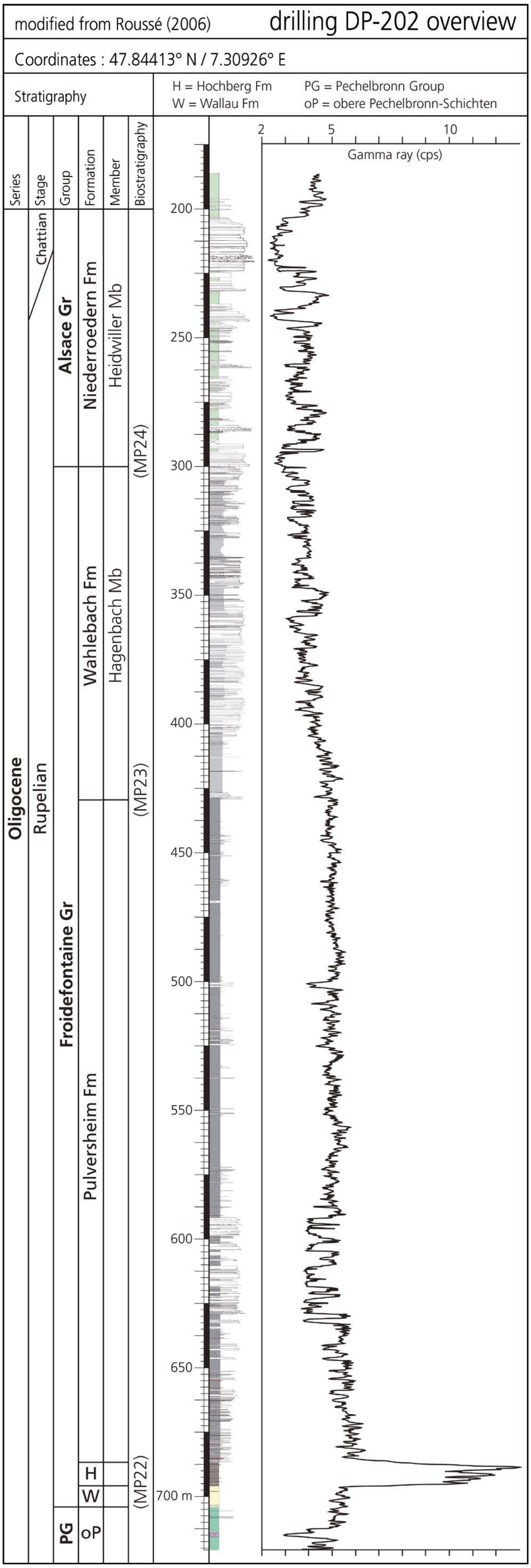
The “Calcaires, grès et marnes jaunes à fossiles marins” sensu Gressly & Mayer (1853) and the equivalent “Gompholithe d’Ajoie” sensu Rollier (1910) belong mostly to the Lörrach Fm, since the Lörrach Fm includes deposits comparable in lithology and fauna. Liniger (1925) adopted the term “Gompholithe d’Ajoie” for conglomeratic deposits in the Delémont subbasin. The latter are deposited on and include reworked marls of the underlying Rossemaison Fm. They are interpreted within a “Meeressand / Cerithienkalk” context (as for the Ajoie), hence being equivalent to the coarse-grained facies of the Lörrach Fm sensu Roussé (2006). A similar coeval stratigraphic position of the “Gompholithe d’Ajoie” has been indicated by GeORG (2013).

6.5.5 Age and fossil content

It is difficult to pinpoint the age of the Lörrach Fm. In older literature the mollusc fauna has been correlated with adjacent areas (e.g. Mainz Basin), which is of little biostratigraphic value in view of modern standards.

For the equivalent Alzey Fm an absolute $^{87}Sr/^{86}Sr$ age of 30.1 (± 0.1) Ma and the attribution to calcareous nannoplankton zones upper NP23-lower NP24 has been cited in Grimm (2006). In the southern URG the coeval Wallau Fm adheres to the interval of planktic foraminifera zones mid O3 and end O4 (sensu Berggren & Pearson 2005) and calcareous nannoplankton zones NP23-24 (Pirkenseer et al. 2010). NP23 has been indicated for the Wallau Fm in the Mainz Basin (Grimm et al. 2011b).

Picot et al. (2008) correlate the initial transgressive sediments of the research area with somewhat older biozones (MP22, NP22-base23). The numerous pitfalls of biostratigraphic dating in the area (abundant reworked nannoplankton) has been outlined in Picot (2002) and is partly



due to the uncertainty of the individual extent of calcareous nannoplankton zones NP22-24 (e.g. Vandenberghe et al. 2012). Since for the underlying Rossemaison Fm in the Delémont subbasin charophyte assemblages correlate with small mammal biozones MP20 and MP21 (Gander 2013), a transgression of the marine sequence in biozone MP22 is however not entirely implausible. In conclusion the initial late Rupelian flooding of the URG coincides roughly with the upper part of the transgressive system tract of the global Ru2 sequence.

Similar to the Alzey Fm of the Mainz Basin abundant and diverse shallow marine macrofauna may be present. Faunal lists of molluscs have been provided in older literature (e.g. Gressly & Mayer 1853; Sandberger 1863; Delbos & Köchlin-Schlumberger 1867; Greppin 1870; Kissling 1896; Kessler 1909; Wurz 1912; Liniger 1925; Wittmann 1952), since most historical outcrops are no longer accessible. Mammals (6 taxa), sharks (6), rays (1), bivalves (44) and gastropods (36) for the Kleinblauen reference area are listed in Bitterli (1945). Foraminifera have been analysed in thin sections therein. Foraminifer and ostracod taxa from the transitional facies between Lörrach and Wallau Fm at Eguisheim are listed in Pirkenseer et al. (2010) and Pirkenseer & Berger (2011).

6.6 Près Roses Mb (partim ex-cyathula-Bank/Mergel)

6.6.1 Synonomy

- banc à *Ostrea cyathula* (Greppin 1870)
- non Schicht mit *Ostrea cyathula* (Gutzwiller 1893)
- ?marne grise à dents de *Lamna*, ossement de *Halitherium*, *Ostrea cyathula* (Rollier 1910)
- *Ostrea cyathula*-Bank, Austernbank, partim Cyathulamergel (Liniger 1925)
- non *Ostrea cyathula*-Bank (Koch 1923)
- non Cyathulabank (Baumberger 1927, Fischer 1965a)
- Austernlumachelle [at Löwenburg] (Fischer 1965a)
- partim Cyathulamergel (Picot 2002, Becker 2003, Picot et al. 2008)

Fig. 20 - Overview sedimentary and gamma ray log of drilling DP-202 near Pulversheim (France), documenting the entire transgression-regression cycle of the late Rupelian marine ingression into the URG. Note the distinct peak designating the Hochberg Fm, the increase of the sand fraction in the lower Pulversheim Fm denoting a first deltaic progradation event and the final regression during the increasingly coarser clastic Wahlebach Fm.

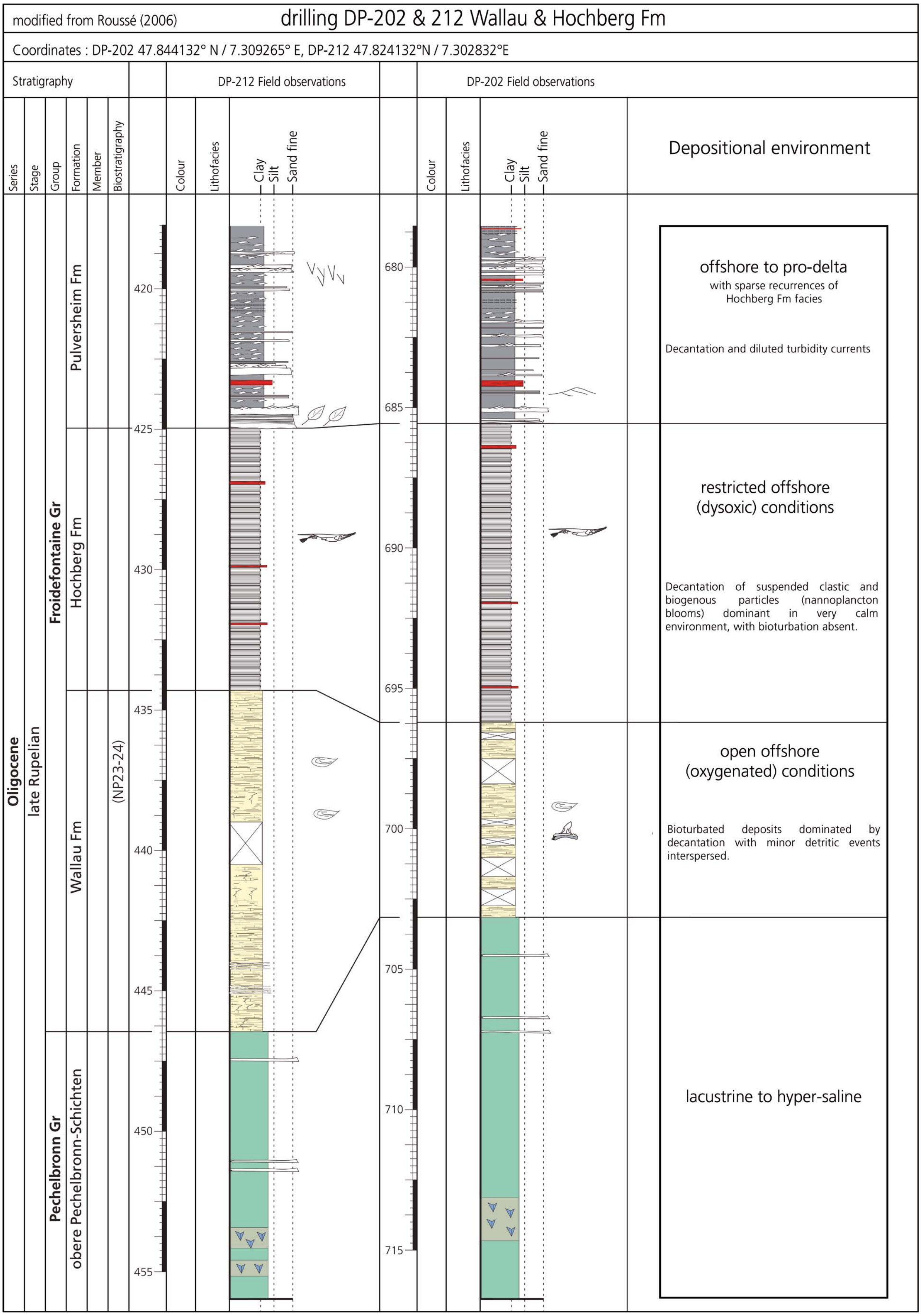


Fig. 21 - Reference sections of the emended Wallau and Hochberg Fms in the neighbouring drillings DP-202 and DP-212 north of Mulhouse (France). Note the distinct changes in sediment colour, granulometry and stratification.

6.6.2 Definition, distribution and thickness

A bed of densely packed complete or fragmented oyster shells within a sandy to marly matrix, ranging in thickness from 0.1 to 2 m (Sorne section, Liniger 1925; Weidmann 1990). It is interpreted as a lateral lagoonal member of the Lörrach Fm restricted to the Delémont subbasin. Thickness varies considerably in the area of deposition. The member transgresses bioerosively either directly on the underlying Rossemaison Fm (HRT-F8/9, 19.22 to 19.14 m / 22.85 to 22.25 m; COM-F5, 65.0 to 61.4 m), or is intercalated in the proximal extension of the Pulversheim (Près Roses, Sorne river) or Lörrach Fm (ridge near Develier; Liniger 1925).

6.6.3 Type, reference and classic localities

The log of the former mine shaft of Près Roses has been described in Liniger (1925) and is accordingly designated as type locality (Fig. 19). Only two surface outcrops were accessible in the past (Sorne river, Develier). The oyster-bearing, fossil-rich marls in levels 1800-2100 in outcrop Beuchille-Est section 19 (Picot et al. 2008) may be attributed to this member, but the entire succession at Beuchille is tectonically disturbed. As reference profiles we define the relevant parts of the COM-F5 and HRT-F8/F9 drill cores (Fig. 10-12).

6.6.4 Differentiation from other units

The Près Roses Mb is distinguished from other lithostratigraphic units as densely packed oyster coquina. It represents a distinct facies within the shallow marine context of the Lörrach Fm.

For some time the supraregional oyster-bearing sediments were considered as coeval (e.g. Greppin 1870). This erroneous interpretation was however rectified by Gutzwiller (1893), who separated the bed-like occurrences of oysters in the Delémont area from the so-called "Cyathulabank" s.s.. While the former are positioned at the base of the marine series of the Froidefontaine Group, the latter occur in the area south and west of Basel as a member of the younger Wahlebach Fm (Therwil Mb; see 6.12). Interpreting oysters as marker for a "shallow marine, partly brackish palaeoenvironment", non-coeval oyster beds certainly represented a recurring theme in the continuous context of the coastal marine depositional system of the marginal Froidefontaine Group.

Liniger (1925) grouped the oyster bed(s) of the Delémont subbasin with the subsequent fossil-rich marls (only about 0.2 m thick) and termed the ensemble "Cyathulamergel". Based on the abundant macrofauna (but absence of oysters) and the occurrence of quartz and glauconite grains these marls seem to represent a pinching out, shallower outlier of the Wallau Fm (see 6.7.2). More recently the stratigraphic range of the "Cyathulamergel" has erroneously been extended and interpreted as an equivalent to the Hagenbach Mb (see 6.11; e.g. Picot et al. 2008).

Since only a very cursorily account of a *cyathula*-bearing marl exists for a former outcrop near Bonfol (Rollier 1910), its status as equivalent stratum in the Ajoie subbasin cannot be verified.

6.6.5 Age and fossil content

The Près Roses Mb has not been dated, but its age should be similar to its host formation.

Macrofossils are dominated by the oyster taxa *Crassostrea cyathula* and *C. callifera*. Further marine molluscs are listed in Liniger (1925). A preliminary analysis confirmed the occurrence of shallow marine Ostracoda (e.g. *Cytheridea sandbergeri*) in drilling HRT-F8. The thin marls deposited directly on the oyster bed (see above) bear abundant marine micro- and macrofauna (molluscs, shark teeth, Foraminifera, Ostracoda, crab claws; Liniger 1925; Picot et al. 2008).

6.7 Wallau Fm emended (ex-Foraminiferenmergel) (Fig. 13b)

6.7.1 Synonomy and generalities

- partim terrain tertiaire marin (tongrien), marnes bleues (Delbos & Köchlin-Schlumberger 1867)
- partim Tongrien: facies vaseux (Greppin 1870)
- Mergel mit *Ostrea callifera*, *Ostrea callifera*-Mergel, ?Meeressandmergel (Andreae 1884, 1890)
- Mergelfacies des Meeressandes (Andreae 1888)
- Marnes (molassiques) de Dannemarie, partim marnes bleues (Rollier 1893a, 1910)
- partim Septarienthon (Gutzwiller 1893, Rollier 1893a, 1910)
- partim Meeressand (Gutzwiller 1914)
- ?partim Cyathulamergel, ?partim Septarienton (Liniger 1925)
- Marnes à foraminifères (Meyer 1928, Barbier 1938, Schnaebele 1948, Lagneau-Herenger 1965, Sittler 1965, 1992, Ménillet et al. 1970, Doebl et al. 1976, Duringer 1988, Roussé 2006, Pirkenseer et al. 2010, Pirkenseer & Berger 2011)
- Couches à foraminifères (Maïkovsky 1941)
- Foraminiferenmergel / Foraminiferen-Mergel (Förster 1909a, Vonderschmitt 1941, 1942, Bitterli 1945,

Wagner 1950, 1955, Hess & Weiler 1955, Schneider 1960, Fischer 1965a, 1969, Doebl 1970, Fischer et al. 1971, Brianza et al. 1983, Wittmann 1983, Bitterli-Brunner & Fischer 1988, Grimm 1994, 1998, Ohmert 1993, Huber 1994, Schwarz 1997, Hinsken 2003, Berger et al. 2005a, Picot et al. 2008, Pirkenseer et al. 2013, GeORG 2013, Schäfer 2013, SKS 2014)

- Foraminifera Marls (Sissingh 1998, 2006)
- partim Bodenheim-Formation, therein Wallau-Subformation, ?partim Hochberg-Subformation [rather applicable to the Mainz Basin] (Grimm 2005, Grimm et al. 2011b, DSK 2016)
- partim Froidefontaine Fm (LGRB 2011, DSK 2016)

Historically the Wallau Fm has been either regarded as separate lithostratigraphic unit or as a part of the extensive marine "blue marls" or "Septarienton" (before the widespread use of micropaleontology). The most commonly used term is "Foraminiferenmergel" (or its French counterpart), which alludes to its micropalaeontological content, a distinction that is not applicable in the field and thus should be avoided.

The Bodenheim-Formation that includes the former "Foraminiferenmergel" was defined by Grimm et al. (2000) in the Mainz Basin, with a formal designation of the Wallau-Subformation by Grimm & Radtke (2002). The concept of the Bodenheim Fm and its subformations has been applied to the entire URG in Grimm (2005) and Grimm et al. (2011a,b). The exact boundaries of these subformations however remain somewhat unclear due to a merging of not universally applicable micropalaeontological and lithological aspects (see discussion below and Fig. 22) and thus required an emendation.

In LGRB (2011) and GeORG (2013) the "Foraminiferenmergel" was included in the Froidefontaine Fm as subformation. The lithologic definition of the Froidefontaine Fm therein however deviates in its upper part strongly from the "classic" sedimentary succession of the basin centre. Relationships are outlined below.

The ex-"Marnes à foraminifères" of the URG should not be confused with non-coeval sediments from the lowermost Oligocene in eastern France similarly called "Marnes à foraminifères" (e.g. Charollais et al. 1980).

6.7.2 Definition, distribution and thickness

The Wallau Fm consists of bioturbated, generally massive or indistinctly stratified brown, green and grey marls with occasional silt/sand layers and rare macrofossils (Grimm & Radtke 2002; Roussé 2006). Closer to the basin margin the silt/sand content may be higher. The Wallau Fm is recorded from the entire URG and represents the basinal analogue of the coeval coastal Lörrach Fm. It is however absent in the Laufen, the Delémont and probably the Ajoie subbasins, which has already been illustrated schematically by Schneider (1960) and Fischer (1965a).

The thickness of the Wallau Fm in the Mainz Basin amounts to 7.7 m at the type locality and to 16.8 m in the reference profile BK I/2 (Grimm & Radtke 2002). In the middle URG the approximate thickness reaches about 15 m in drilling 3879 near Hochstett (Barbier 1938).

The thickness in the different subbasins of the southern URG ranges from 6-7 m (drilling DP202, Roussé 2006; drilling Hirtzbach, Vonderschmitt 1942, drillings in Wittmann 1983) and 29 m (drilling Allschwil-1; Fischer et al. 1971). In the destructive drilling Otterbach (DHM1) Foraminifera taxa typical for the Wallau Fm have been recorded in the interval 520-290 m (Picot 2002, without details about drilling angle or quantitative analysis). This would compute an exceptional thickness of 330 m, which appears unlikely and is certainly due to downhole contamination. The technical log positions the Wallau Fm between 290.5 and 281 m (Häring 2002), which coincides with the maximal richness in Foraminifera species (Picot 2002) characteristic for the formation.

6.7.3 Type, reference and classic localities

The Wallau Fm is based on the log of drilling IN311 (23.80 to 20.40 m) in Grimm & Radtke (2002). In the research area detailed log descriptions are available for the drilling DP212 and DP202 (dossier 04132X0067/DP212 and 04132X0064/DP202 on http://infoterre.brgm.fr., as well as Roussé 2006) (Fig. 21). Drilling DP212 (near Wittenheim, Alsace; 47.82413069° N / 7.30283448° E) and DP202 (near Pulversheim Alsace; 47.8441323° N / 7.30926536° E) are located in the central Potash Basin north of Mulhouse.

Surface outcrops are rare and allow only a fragmentary documentation of the Wallau Fm. The interfingering of the Wallau Fm and the coastal Lörrach Fm can be observed at the locality Eguisheim (48.03850° N / 7.309656° E; Fig. 18), Blauen-5 (approx. 47.45710° N / 7.544796° E) and

Burg-Biederthal (approx. 47.46462° N / 7.443650° E; Fig. 17) as well as Oltingue (Fischer 1965a). Due to an intercalation of the Lörrach Fm in the latter outcrop and a change in the microfossil assemblage (small vs. large Foraminifera; see below) Förster (1909a) and Fischer (1965a) subdivide the Wallau Fm in a "lower" and "upper Foraminiferenmergel" (similar to the initial subdivision in the Mainz Basin, e.g. Grimm 2002).

In the Delémont, Laufen and Ajoie subbasins the Wallau Fm is generally missing or not recognisable due to the condensed sedimentary succession. The thin marls just above the Près Roses Mb (see 6.6) in the Delémont subbasin possibly represent a not fully developed equivalent with an incomplete microfossil assemblage (Liniger 1925).

6.7.4 Differentiation from other units

At the type locality in the Mainz Basin the Wallau Fm overlies variegated marls silts and occasional thin-bedded conglomerates of the Obere Pechelbronn-Schichten (Grimm & Radtke 2002).

In the Potash Basin centre (drilling DP202 & 212) the Wallau Fm overlies dark grey to green marls and dolomites of the "Obere Pechelbronn -Schichten" (sensu Grimm et al. 2011b) that are partly rich in gypsum and anhydrite (e.g. Maïkovsky 1941). The sediments immediately below the Wallau Fm consist of very dark massive marls exclusively containing reworked Cretaceous nannoplankton (Pirkenseer & Berger 2011). The situation is comparable in the Sierentz-Wolschwiller subbasin (drilling Alschwil-1-& 2; ibid., Christ 1924; Fischer et al. 1971), though evaporites are much less common in the underlying marly sediments and contain intercalated conglomeratic levels. A more gradual transition has been observed in the middle URG in the drilling 3879 Hochstett near Haguenau (Barbier 1938), were finely laminated grey, brown to green mica bearing marls of the "Obere Pechelbronn -Schichten" transition via marls with a high sand content to the classic Wallau Fm lithology. In the outcrops Eguisheim and Burg-Biederthal coastal outliers of the formation lie discordantly on the conglomeratic reddish Turckheim Fm or the Jurassic limestone substratum (Roussé 2006).

The definition of the upper boundary of the Wallau Fm (subformation sensu Grimm & Radtke 2002) in the Mainz Basin (and correspondingly in the URG) was based on inconsistent micropalaeontological and lithological criteria (see below). Using the presence or absence of (micro)fossil content as marker for formation boundaries bears the danger of misinterpretations. This has been illustrated (Pirkenseer & Berger 2011) for the former "Cyrenenmergel" (now Wahlebach Fm) in drilling DP202, where its lower boundary is positioned more than 50 m downhole when applying the determining sedimentary instead of micropalaeontological criteria (Fig. 22a). The present definition of the Wallau-Hochberg Fm boundary therefore remains uncertain and requires an emendation.

6.7.5 The Wallau-Hochberg Fm boundary

The differentiation of the Wallau, Hochberg and Rosenberg Subformations (subsequently treated as formations) sensu Grimm et al. (2000) and Grimm & Radtke (2002) in the Mainz Basin (and the URG) based on benthic foraminifera assemblages (in addition to lithological criteria) was specified in Grimm (1994, 1998). Therein the former "Foraminiferenmergel" (now Wallau Fm), the "Fischschiefer" (now Hochberg Fm) and the "Obere Rupelton" (Rosenberg Subfm, now lower part of the Pulversheim Fm) were respectively subdivided in the benthic foraminifera assemblage zones FM1-3, FS1-6 and ORT1-3 (for details see cited literature).

We deem the application of this concept sensu Grimm et al. (2000) and Grimm (2002) as regional biostratigraphical subdivision based on long-ranging, ecologically-constrained benthic foraminifera taxa as unsuitable for over-regional (non-palaeoecological) correlations. Potential issues arise from the general uncommon development of FM3 in the Mainz Basin in Grimm (1994, 1998), as well as the absence of FM1 at the type locality of the Wallau Fm (Grimm & Radkte 2002). Different occurrences (or absences) of particular comparable benthic foraminifera assemblage zones (e.g. Barbier 1938; Pirkenseer et al. 2010) in the middle and southern URG, to which this concept has then been applied (e.g. Grimm et al. 2011b), is illustrated in Fig. 22b. These micropalaeontological subdivisions thus cannot collectively be extended to the entire URG and they should not be used in a biostratigraphical sense.

Further discrepancies arise from inconsistencies in the changes of sediment colour and type and their correlation to respective benthic foraminifera assemblage zones in the Mainz Basin and the URG. Grimm (1998) does not indicate lithological dif-

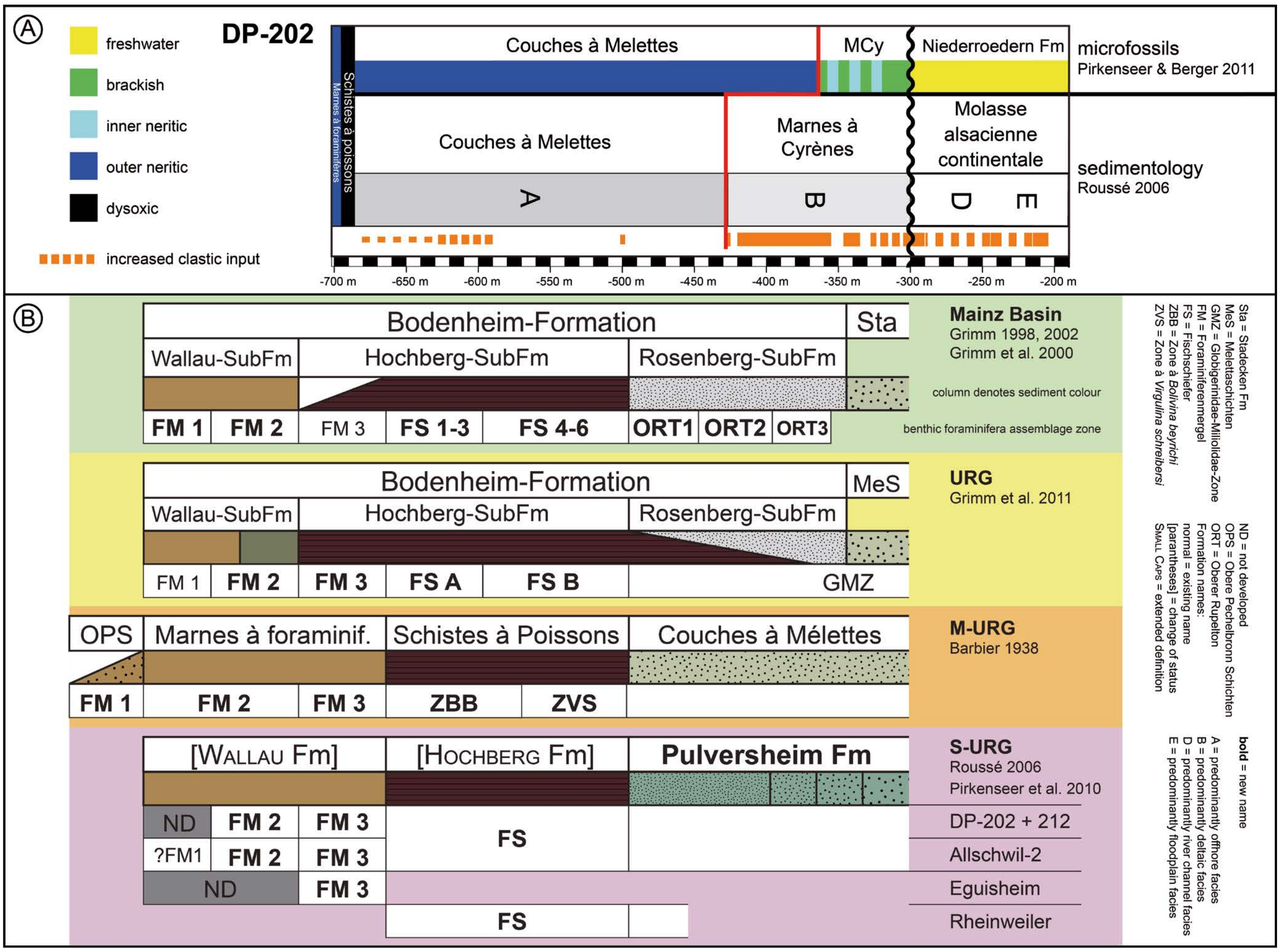


Fig. 22 - Inconsistency of lithostratigraphical versus micropalaeontological criteria when applied to formation definition.
22A) An offset of about 70 m of the Pulversheim-Wahlebach Fm boundary is implied (see Pirkenseer & Berger 2011 for details).
22B) Varying development of benthic foraminifera assemblage zones (sensu e.g. Grimm 1998) in relation to sediment colour and lithology and their attribution to formations in respective parts of the URG and the Mainz Basin. Note the different association of particularly FM3 with varying lithologies and sediment colours. As a consequence formation definition should not be based on assemblage zones, since this leads to non-correlative boundaries. (Solid colour = marls, striated dark brown = dysoxic laminated marls, dotted colours = (marly) silts or sands)

ferences between benthic foraminifera assemblage zones FM2 and FM3 when separating the Wallau and Hochberg Fms in the Mainz Basin, while basically focusing on the colour shift (brown-beige to gray, "darker"). However, since FM3 is only scarcely developed in the Mainz Basin (and is thus per se not suitable as distinctive criterion), the most pronounced changes in lithology, colour and fauna coincide largely with the emended Wallau-Hochberg Fm boundary.

Despite these uncertainties FM3 was later integrated as lowermost assemblage zone of the Hochberg Fm, preceding the distinct sedimentological change (Grimm et al. 2000). Confusingly this ambiguity of the boundary definition has been stressed in Grimm & Radtke (2002) when defining the Wallau Fm. According to the authors the boundary coincides exactly with the change in lithology from lighter grey to greenish or brown massive clays of the Wallau Fm to the dark bituminous, finely laminated clays and marls of the Hochberg Fm, whereas the (here more distinct than described in Grimm 1998) initial colour shift is still attributed to the change from FM2 to FM3 (thus additionally negating their validity as separating criterion).

Despite emphasising a similarly distinct lithological change between both formations in the northern and the southern URG, Grimm et al. (2011b) also globally assign the assemblage zone FM3 to the lowermost Hochberg Subfm. In the middle and southern URG a benthic foraminifera assemblage comparable to FM3 occurs unequivocally in the higher part of the Wallau Fm (e.g. Barbier 1938; Pirkenseer et al. 2010), whereas a strongly impoverished assemblage replaces the FM3 in the lowermost Hochberg Fm (Fig. 22b). In the URG the most distinct change in colour, fauna and lithology thus exactly coincides with the Wallau-Hochberg Fm boundary.

To simplify the definition of the latter we consequently exclude the microfossil content as correlative tool, since it rather represents the expression of quickly shifting palaeoenvironmental conditions (e.g. increasing water depth in the transgressive system tract) in a palaeogeographically complex area. The transition to the overlying Hochberg Fm therefore sees an abrupt change to dark brown to black, finely laminated marls bearing abundant marine macrofossils and intercalations of calcareous nannoplankton mass occurrences (white laminae). Near the basin margins (e.g. southern Sundgau and Laufen subbasin; Förster 1909a; Koch 1923) this lithological change can be somewhat less distinct, but remains recognisable.

6.7.6 Age and fossil content

The age conforms largely to the coeval Lörrach Fm (see 6.5), and the slightly younger overlying Hochberg Fm (see 6.8).

The Wallau Fm is renowned for its highly diverse and abundant microfauna (e.g. Andreae 1884; Förster 1909a; Schnaebele 1948; Fischer 1965a; Huber 1994). Pirkenseer et al. (2010) and Pirkenseer & Berger (2011) list 67 benthic and 5 planktic Foraminifera as well as 9 marine Ostracoda species, indicating outer shelf environments.

The tripartite microfaunal subdivision of the Wallau Fm in the northern URG and the Mainz Basin has also been observed in the middle URG (Fig. 22b), with an increasingly diverse and abundant fauna at the base (Barbier 1938). This more gradual (microfaunal) transition in the middle URG has already been hinted at in Andreae (1898). The impoverished fauna at the base of the "Foraminiferenmergel" (FM1) sensu Grimm (1994, 1998) is generally not developed in the southern URG (Pirkenseer et al. 2010), whereas the somewhat less diverse benthic Foraminifera assemblage FM3 is present (e.g. drilling DP-202, Allschwil-2, Eguisheim).

Macrofauna however is scarce (e.g. fish remains; Bitterli-Brunner & Fischer 1988), but becomes more abundant where the formation interfingers with the Lörrach Fm (e.g. oyster fragments; Förster 1909a).

6.8 Hochberg Fm emended (ex-Fischschiefer) (Fig. 23a)

6.8.1 Synonomy and generalities

- Amphisyle-Schichten / Schistes à *Amphysile* or Amphisiles (Andreae 1884, Meyer 1920, 1928, Sittler 1965)
- Fischschiefer / Fisch-Schiefer (Andreae 1884, 1887, 1888, Förster 1888, Gutzwiller 1893, 1914, Rollier 1893a, 1910, partim Kissling 1896, Förster 1909a, b, van Werveke 1918, Meyer 1920, 1928, Koch 1923, Christ 1924, Buxtorf & Christ 1936, Vonderschmitt 1941, 1942, Bitterli 1945, Wagner 1950, 1955, Wittmann 1950, 1952, Diebold 1960, Schneider 1960, Fischer 1965a, Doebl 1970, Brianza et al. 1983, Wittmann 1983, Ohmert 1993, Grimm 1994, 1998, Schwarz 1997, Pharisat & Micklich 1998, Trunkó & Munk 1998, Picot 2002, Becker 2003, Berger et al. 2005a, b, Le Metayer 2007, Picot et al. 2008, de Pietri et al. 2010, Pirkenseer et al. 2013, Schäfer 2013, SKS 2014)
- Schiste(s) à poisson(s) (Delbos & Köchlin-Schlumberger 1867, Kilian 1884, Rollier 1910, Barbier 1938, Schnaebele 1948, Lagneau-Herenger 1965, Ménillet et al. 1970, Doebl et al. 1976, Duringer 1988, Sittler 1992, Scherler 2005, Roussé 2006, Pirkenseer et al. 2010, Pirkenseer & Berger 2011)
- Couches à Meletta et à Amphisile: niveau à Amphisile et à Meletta avec foraminifères (Maïkovsky 1941)
- Fish Shale (Sissingh 1998, 2006)
- partim Hochberg-Subformation [Mainz Basin] (Grimm et al. 2000, Grimm et al. 2011b)
- Frauenweiler-Fischschiefer [subformation] (LGRB 2011, GeORG 2013)
- partim Froidefontaine Fm (LGRB 2011, DSK 2016)

The Hochberg Subfm (part of the Bodenheim Fm sensu Grimm et al. 2000) shows a uniform lithology throughout the URG. Accordingly the subformation represent a discrete lithological unit of considerable thickness and extent that merits a formation status (in agreement with Wittmann 1952).

The ex-"Fischschiefer" of the URG should not be confused with numerous homonymous but not coeval sediments from the Lutetian, lowermost Oligocene and Aquitanian of Bavaria and western Austria similarly called "Fischschiefer", "Latdorf-Fischschiefer", "Aquitan-Fischschiefer" or "Schöneck-Fischschiefer" (now Schöneck Fm) (e.g. Hagn 1960, 1981; Freudenberger & Schwerd 1996; Steininger & Wessely 2000; Rupp 2008).

6.8.2 Definition, distribution and thickness

The Hochberg Fm consists of finely laminated bituminous dark brown to black, clayey marls

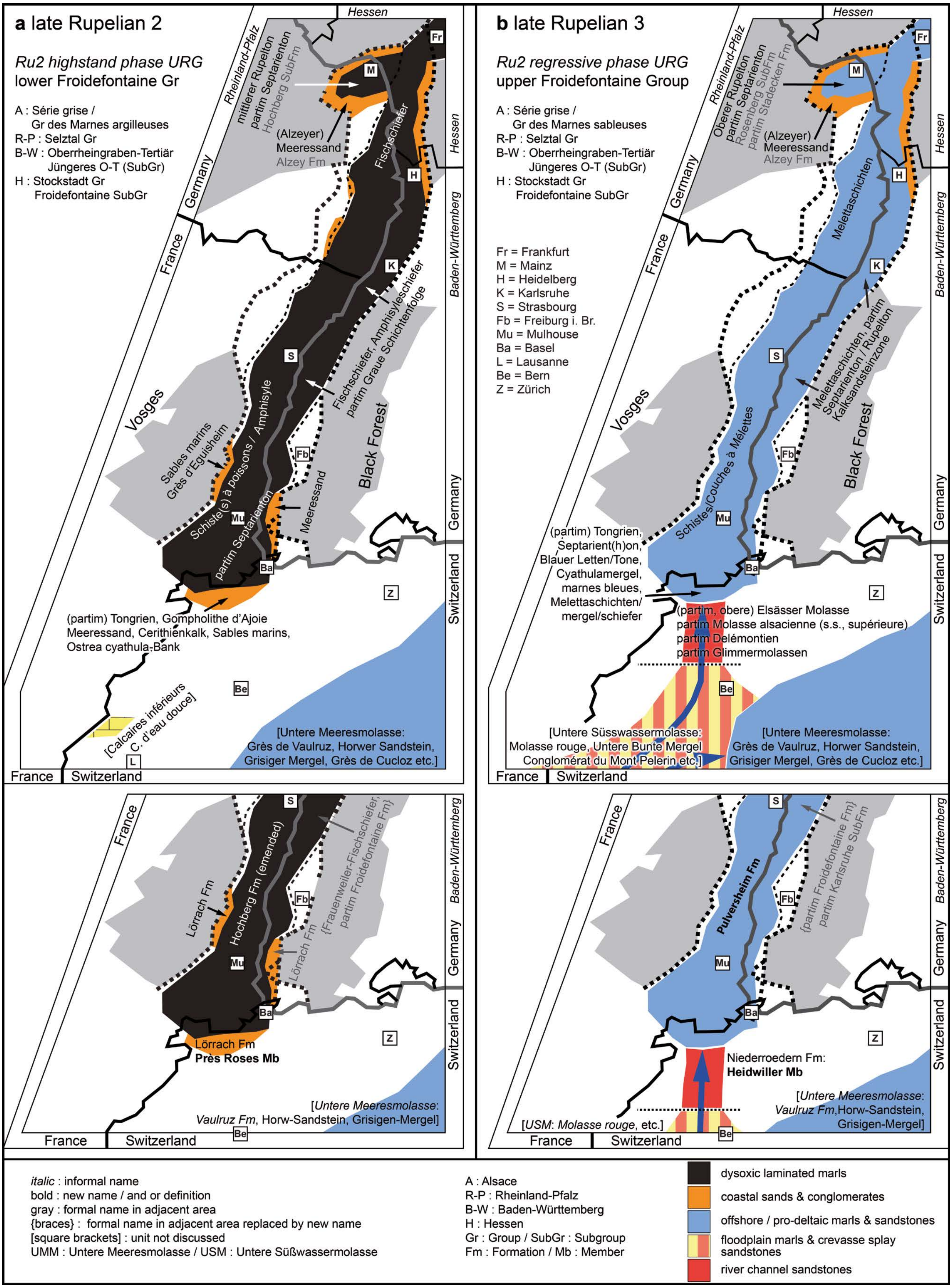


Fig. 23 - Palaeogeographic representation of major facies and regional lithostratigraphic terms (updated from and based on maps in Berger et al. 2005b). Top of the figure represents the formerly used most common terms, lower part the status after revision and simplification. 23a Map for the late Rupelian (part 2), 23b Map for the late Rupelian (part 3).

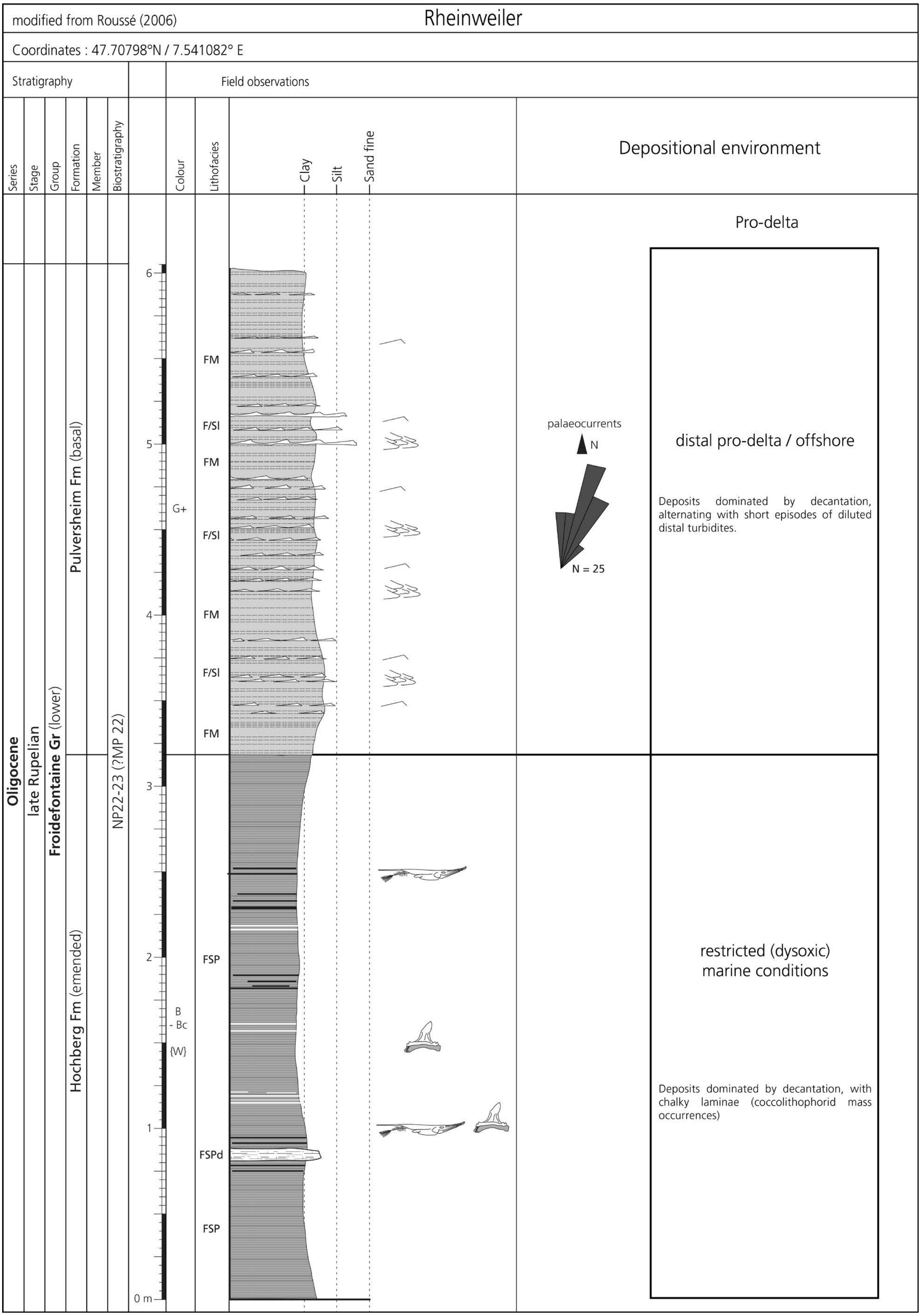


Fig. 24 - Reference section of the Hochberg-Pulversheim Fm transition near Rheinweiler (Germany).

with intercalated chalky laminae (coccolithophore mass occurrences), occasional silt layers and abundant vertebrate macrofossils. Towards the basin margin the sand content increases.

The Hochberg Fm occurs in the entire URG, except in the Delémont subbasin. The southernmost deposits in the research area are found in the Laufen (Brislach; e.g. Koch 1923) and Ajoie (Bonfol, probably Bressaucourt; Rollier 1910; Schneider 1960) subbasins.

Thickness in the southern upper URG varies between 4-5 m (drillings Hirtzbach, Vonderschmitt 1942, drillings in Wittmann 1983), 10 m (drilling Allschwil-2; Fischer et al. 1971; Pirkenseer et al. 2010), 22 m (drilling Leymen; Brianza et al. 1983) and 54 m (drilling DP6, Staffelfelden; Maïkovsky 1941). At the locality Froidefontaine its thickness reaches 2.6 m (Pharisat 1991a, b), whereas near Rheinweiler about 3.5 m crop out (upper part of an incomplete section; Scherler 2005; Roussé 2006; Fig. 24). In the abandoned mine "Alex" near Feldkirch (Alsace; 47.85466° N / 7.278260° E) the Hochberg Fm attained a thickness of 8.5 m (Maïkovsky 1941).

In the middle URG the thickness in drilling 3879 Hochstett amounts to 12 m (Barbier 1938), about 17 m in drilling Schwabwiller (van Werveke 1918) and ranges between 5-35 m according to Schnaebele (1948) in the Pechelbronn subbasin.

6.8.3 Type, reference and classic localities

Drill core Bodenheim 28 (120.0 to 52.0 m; 49.908251° N / 8.303704° E) was designated as type section by Grimm et al. (2000) and named after the local subdistrict Hochberg (south of Bodenheim) in the Mainz Basin. The thickness of the Hochberg Fm at the type locality amounts to approximately 50 m.

Surface outcrops in the entire URG are rare. The most continuously and extensively exposed area is situated near the town Wiesloch (Baden-Württemberg). Several detailed sections were logged in 1992 in the clay pit of the former brickyard Bott-Eder near Frauenweiler and summarized in Trunkó & Munk (1998). An elaborate section of the former locality with a detailed sedimentological and micropalaeontological analysis is available in Grimm et al. (2002). Both sections do not cover the entire stratigraphical extent of the Hochberg Fm.

The remaining accessible outcrop in the southern URG (though in poor condition) at the border of the village Rheinweiler (Baden-Württemberg; 47.70798°N / 7.541082° E; Scherler 2005; Roussé 2006; Pirkenseer et al. 2010; Fig. 24). The most well-known locality is a now flooded quarry situated near the village Froidefontaine (e.g. Meyer 1928; 47.56430° N / 6.954539° E), being accessible until the 1990ies (palaeontological study of Pharisat 1991a, b). Further historical outcrops in the research area include Bonfol, Brislach and Bouxwiller-Oltingue (see below).

The Hochberg Fm is recorded in most drillings of the southern URG (e.g., Allschwil-1/2, Leymen). The logs of the drillings DP202/212 (696.25 to 685.50 m / 434.25 to 425.00 m) and the outcrop Rheinweiler have been designated as reference profiles (Fig. 21, 24).

6.8.4 Differentiation from other units

The Hochberg Fm is easily distinguished from neighbouring formations due to its unique sedimentology and a strong peak in gamma ray logs (Roussé 2006; Fig. 20). The onset of the Hochberg Fm coincides with an abrupt change from the lighter coloured massive marls of the underlying Wallau Fm to finely laminated dark brown argillaceous marls (Fig. 21). The upper boundary is defined by an instantaneous shift to the bluish grey, silty, less densely layered marls of the overlying Pulversheim Fm (see 6.9; also for the discussion of the Rosenberg Subfm). Both the underlying Wallau Fm and the Hochberg Fm represent distinct reflectors in seismic profiles (GeORG 2013). Close to the southern border of the URG (but north of the Ajoie, Delémont and Laufen subbasins) the Hochberg Fm may directly be overlain by the distal delta-front sands of the diachronous Hagenbach Mb of the Wahlebach Fm (see 6.11; Roussé 2006).

Towards the basin margins the Hochberg Fm intercalates with the coeval yellowish sand-dominated Lörrach Fm. Proximal occurrences of the Hochberg Fm indeed contain increased sand content, e.g. in outcrops near Brislach (Koch 1923), Bouxwiller and Oltingue (Förster 1909a), but still remain easily distinguished due to prevailing lamination and dark sediment colour. Only the southwesternmost occurrences near Bressaucourt (Diebold 1960; Schneider 1960) and Courgenay

(Tschopp 1960) (Ajoie) attributed to the Hochberg Fm remain difficult to interpret lithologically due to lack of information. They are described as brown sandy marls in context with the underlying Lörrach Fm, and thus may represent an extremely marginal equivalent of the Hochberg Fm.

6.8.5 Age an fossil content

The nannoplankton and dinoflagellate zones recorded in the Bott-Eder clay pit correlate to NP23 and D14a respectively (Grimm et al. 2002). The Hochberg Fm conforms to the maximum flooding of the global Ru2 sequence (Roussé 2006). Vandenberghe et al. (2012) correlate this event with an absolute age of about 30.5 Ma, small mammal zone MP23 and calcareous nannoplankton zone NP23.

Abundant and diverse macrofossils are known from the type region, the Froidefontaine and Rheinweiler outcrops (as well as from other localities in the URG). These include seabirds (e.g. Cheneval 1995; Mayr 2004; de Pietri et al. 2010) and mesopelagic to littoral subtropical to tropical ray finned fish and shark assemblages (e.g. Pharisat 1991a, b; Pharisat & Micklich 1998; Hovestadt et al. 2010). The centriscid fish *Aeoliscus* and gill rakers of the basking shark *Cetorhinus* have also been recorded in drillings of the Potash Basin (Maïkovsky 1941; Pirkenseer 2007).

Analyses of the (compared to the Wallau Fm) impoverished foraminiferal assemblages are available for the southern URG (Huber 1994; Rheinweiler; Scherler 2005; DP202 and Allschwil-2, Pirkenseer et al. 2010) and the middle URG (Barbier 1938; Schnaebele 1948; Grimm et al. 2002). These assemblages are characterized by an impoverished benthos of low-oxygen tolerant species, whereas planktic Foraminifera generally are abundant. The highly detailed subdivision of the coeval Hochberg Subformation of the Mainz Basin in six assemblage zones (e.g. Grimm 1998, 2002) cannot be observed in the southern URG (Fig. 22). In the middle URG the Hochberg Fm has been split in a lower and upper part based on the foraminiferal assemblages (Grimm et al. 2002). Detailed records of calcareous nannoplankton and dinoflagellate cysts are available in Grimm et al. (2002). Ostracoda are absent (Pirkenseer & Berger 2011), since only very few taxa tolerate dysoxic conditions.

6.9 Pulversheim Fm (ex-Melettasschichten) (Fig. 23b)

6.9.1 Synonomy and generalities

- ? Marnes bleues et jaunes, micacées, avec écailles de poisson (Gressly & Mayer 1853)
- (partim) Septarient(h)on (Sandberger 1863, Förster 1888, Andreae 1888, 1890, 1898, Gutzwiller 1893, Rollier 1893a, 1910, Hagmann 1897, Gutzwiller 1914, van Werveke 1918, Meyer 1920, Koch 1923, Christ 1924, Liniger 1925, Baumberger 1927, Buxtorf & Christ 1936, Bitterli 1945, Wittmann 1950, Hess & Weiler 1955, Diebold 1960, Schneider 1960, Fischer 1965a, b, Fischer et al. 1971, Brianza et al. 1983, Naef et al. 1985, Bitterli-Brunner & Fischer 1988, Schwarz 1997, Picot 2002, Becker 2003, Berger et al. 2005b, Picot et al. 2008, SKS 2014)
- partim Tongrien: facies vaseux (Greppin 1870)
- (partim) Melettaschichten / *Meletta*-Schichten / Melettazone / Melettamergel / Melettaschiefer (Andreae 1883, Förster 1888, Rollier 1904, Gutzwiller 1914, van Werveke 1918, Meyer 1920, Vonderschmitt 1942, Bitterli 1945, Wagner 1950, 1955, ?Hasemann & Heinemann 1956, 1957, Fischer 1965a, b, Doebl 1970, Fischer et al. 1971, Wittmann 1983, Bitterli-Brunner & Fischer 1988, Sonne 1988, Schwarz 1997, Picot 2002, Hinsken 2003, Grimm 2005, Picot et al. 2008, Grimm et al. 2011b, GeORG 2013, Schäfer 2013, DSK 2016)
- partim Système de Bourogne (Kilian 1884)
- (partim) Blaue(r) Letten (Gutzwiller 1893, Fischer 1965a, b, Fischer et al. 1971, Brianza et al. 1983, Bitterli-Brunner & Fischer 1988)
- partim Marnes à *Ostrea cyathula* et à *Meletta* (Rollier 1898)
- partim Molasse et marnes bleues (Rollier 1910)
- partim Blaue Tone (Liniger 1925, Oertli 1956)
- Schistes / Couches à Mélettes / melettes / Meletta (Meyer 1928, Barbier 1938, Schnaebele 1948, Lagneau-Herenger 1965, Sittler 1965, Ménillet et al. 1970, Pharisat 1991a, b, Sittler 1992, Roussé 2006, Pirkenseer et al. 2010, Pirkenseer & Berger 2011)
- Couches à Meletta et à Amphisile: niveau à Meletta et à Amphisile sans foraminifères (Maïkovsky 1941)
- Meletta Marls / Meletta Beds (Sissingh 1998, 2006, Spiegel et al. 2007, Pirkenseer et al. 2011)
- Meletta Marl or Bed Formation / Marnes à Mélettes (Le Metayer 2007)
- Meletta Shale Member (Hinsken et al. 2007)
- partim UMM (Clément & Berger 1999), UMM III (Berger 2011)
- partim Bodenheim Fm: Rosenberg Subfm [applies to the Mainz Basin] (Grimm et al. 2011b)
- partim Froidefontaine Formation and/or partim Karlsruhe-(Sub)formation (LGRB 2011, GeORG 2013, Schäfer 2013, DSK 2016)

The term "Septarien-Thon" sensu Beyrich (1848) comprises early Oligocene grey blue clays and marls in northeastern Germany (Hermsdorf near Berlin). The name has since been widely applied to similar sediments in northern Germany and the URG. It gained its name due to the abundant occurrence of so-called "septarias", large sized concretions of clayey or marly matrix with an internal precipitation of a network of calcite crystals. These

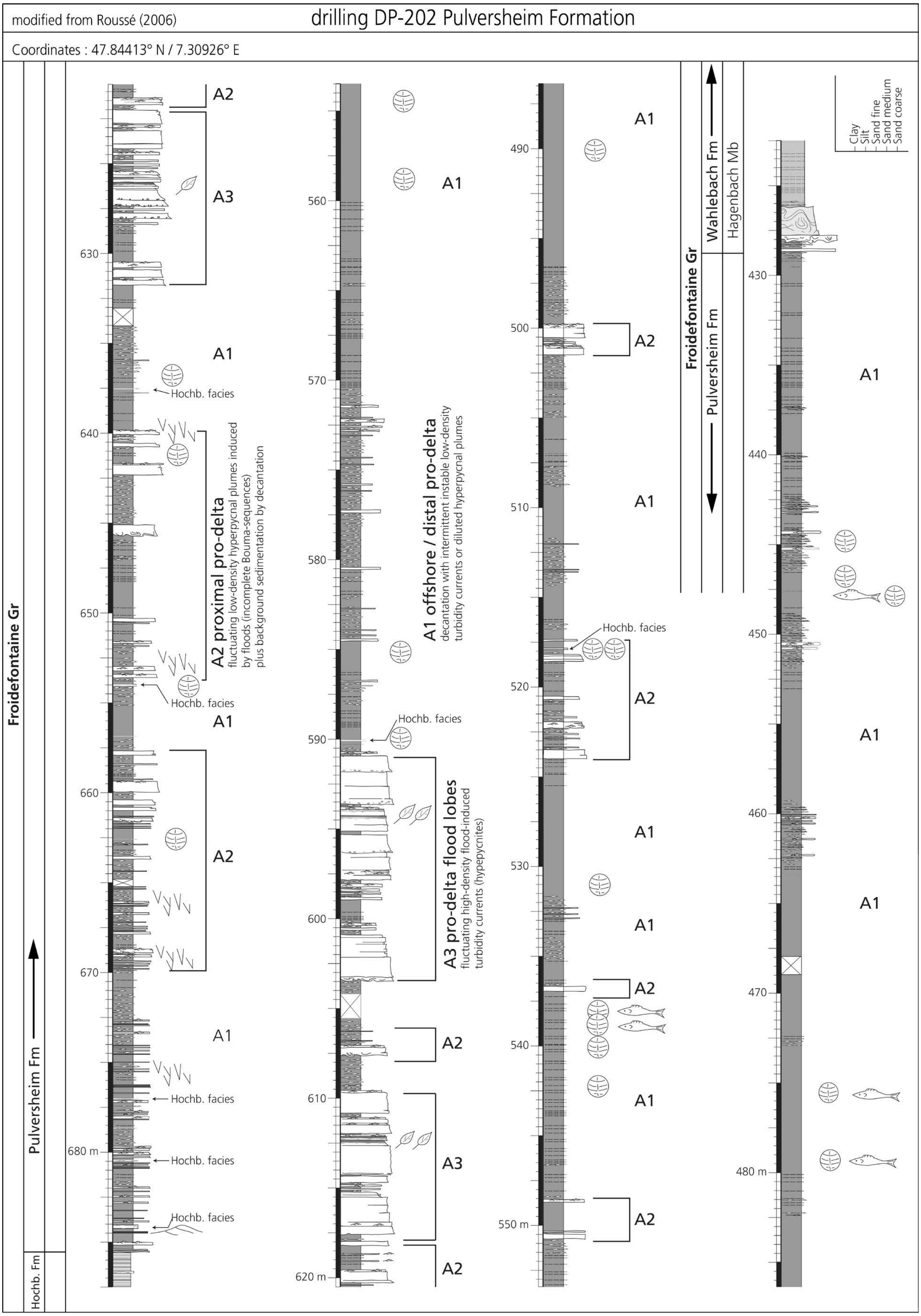


Fig. 25 - Type section of the Pulversheim Fm in drilling DP-202. Note the sedimentary impact of turbiditic pro-delta lobes in a basinal offshore setting. Abbreviations A1-3 explained on figure.

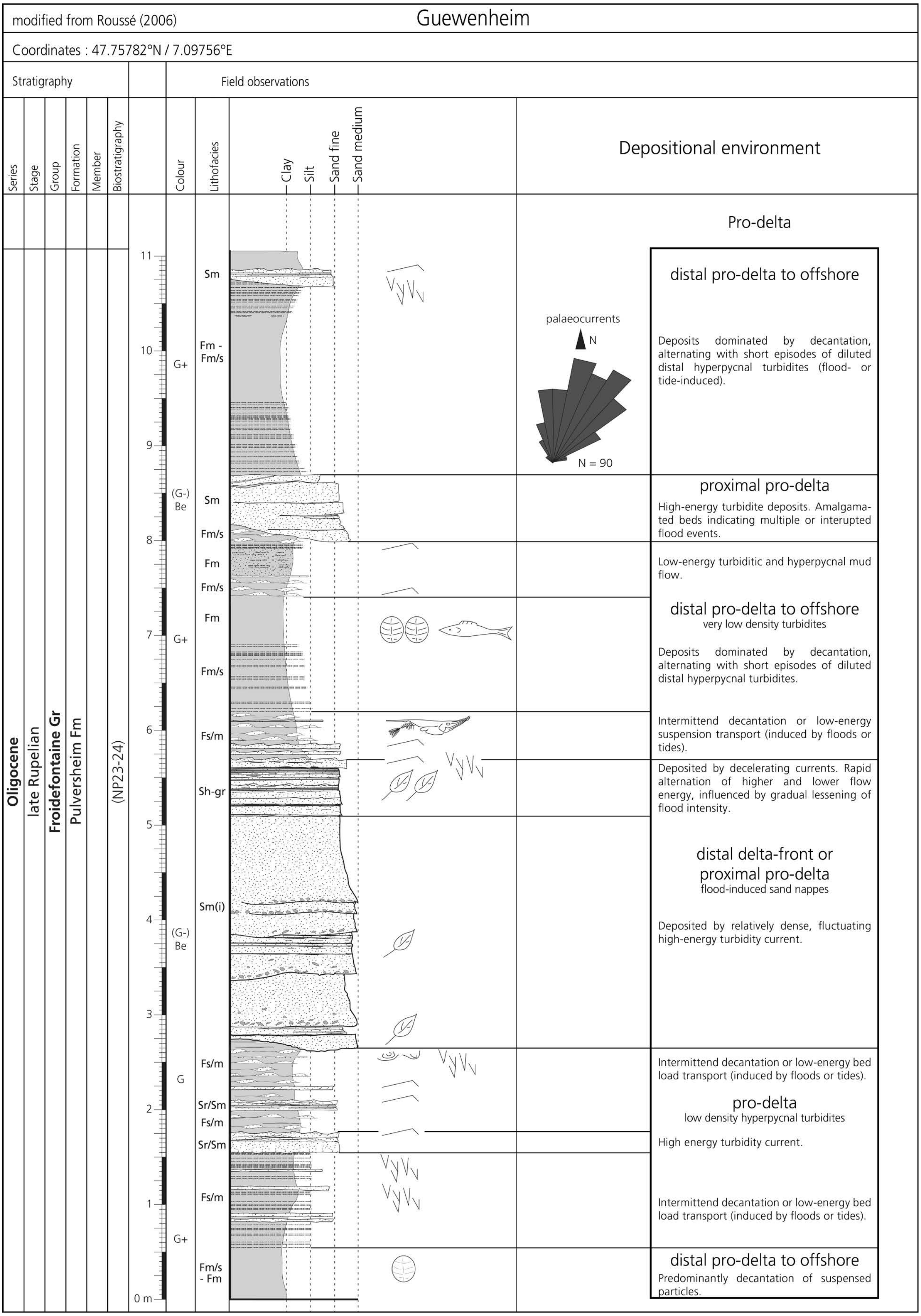


Fig. 26 - Reference section of the Pulversheim Fm in an outcrop near Güwenheim (France). Documentation of a flood induced distal deltaic turbidite event.

septarias however are generally not developed in the southern URG (for superficially resembling sandstone nodules in the Wahlebach Fm see 6.11).

The ex-"Couches à Mélettes" of the URG should not be confused with not-coeval sediments from the lowermost Oligocene in eastern France called "Schistes à *Meletta*" (e.g. Charollais et al. 1980; Gaudant et al. 1994). Similarly the term "Melettaschichten" was used in Bavaria for Oligocene sediments resembling the Hochberg Fm (e.g. Hagn 1960; see 6.8). Consequently the formation has been renamed.

6.9.2 Definition, distribution and thickness

The Pulversheim Fm consists mainly of grey to blue massive marls, marls laminated with thin layers of silt or fine sand and marls with intercalated centimetric micaceous fine sand layers and lentils. Fine sands and silts feature planar or rippled bedding (Fig. 25). Massive or rippled fine to medium sand bancs containing plant debris or basal mud intraclasts are occasionally intercalated (Fig. 26). At the base of the Pulversheim Fm millimetric layers of the underlying Hochberg Fm facies may be present. Macrofossils are rare.

Roussé (2006) distinguishes seven facies types and three facies associations (for a detailed analysis see ibid.). They are interpreted as distal delta-front to proximal pro-delta fan lobes (hyperpycnal turbidites triggered by flood events; silt-sand facies) and offshore marls (mud facies). Palaeocurrent directions in the southern URG are oriented north- to northeastward. Marl-sand doublets and mud drapes on cross-stratified sand lentils represent indirect downslope tidal influence in a pro-delta setting. According to Roussé (2006) two large-scale and several small-scale coarsening-up cycles were recorded during the deposition of the Pulversheim Fm and the subsequent diachronous Hagenbach Mb of the deltaic Wahlebach Fm (see 6.11, Fig. 28a). Closer to the southern basin margin the Pulversheim Fm is subdivided by the Hagenbach Mb in relation to the pro- and retrograding stages of the Wahlebach Fm (ibid., Pirkenseer et al. 2011).

The thickness increases from a few meters at the southern Delémont subbasin margin (drillings HRT015-F8/9), around 100 m in front of the first Jura anticline to about 400 m in drilling DP207 towards the north, corresponding to a simultaneous decrease in thickness of the subsequent Hagenbach Mb (see 6.11 and log correlations in Roussé 2006). Outcrops do not reach a thickness of more than a couple of decametres. The entire condensed succession is possibly exposed in the Laufen clay pit (Fig. 27a).

6.9.3 Type, reference and classic localities

The Pulversheim Fm is based on the log description of drilling DP202 (685.5 to 428.75 m) in Roussé (2006) and dossier 04132X0064/DP202 (http://infoterre.brgm.fr). Drilling DP202 is located in the central Potash Basin north of the village Pulversheim (Alsace; 47.8441323° N / 7.30926536° E). At the type locality the thickness of the Pulversheim Fm reaches 257 m. Reference localities in the southern URG include the outcrops Güwenheim (11 m including a distal delta front lobe, Fig. 26), Burnhaupt-Le-Haut (11 m of pro-delta turbidites) and the Laufen clay pit (13 m of offshore to distal pro-delta sediments, Fig. 27a), with detailed descriptions available in Picot (2002), Scherler (2005), Roussé (2006) and Picot et al. (2008). The Pulversheim Fm reaches around 370 m in drilling Allschwil-2 (47.54304° N / 7.51790° S) located in the Sierentz-Wolschwiller halfgraben (Pirkenseer & Berger 2011). The abrupt transition from the underlying Hochberg to the Pulverheim Fm has been observed in the outcrop Rheinweiler (Roussé 2006, Fig. 24).

In the Delémont subbasin localities comprise the drillings C1-6 / COM-1 (47.35608° N / 7.32880° E; Clément & Berger 1999), Delémont-Beuchille (Est) (47.35224° N, 7.352428° E; Picot et al. 2008), drillings COM990-F5 (Fig. 10) and HRT015-F8/9 (Figs 11-12). All localities represent proximal / marginal palaeogeographical settings and consequently show strongly reduced thicknesses (2.40 m at HRT-F8, 3.75 m at HRT-F9) or an amalgamation of Pulversheim Fm and Wahlebach Fm facies (19 m at COM-F5).

In the Ajoie subbasin similar conditions were documented near Bonfol and Bressaucourt (Schneider 1960), however without detailed information. More recently several drillings indicate an amalgamated thickness of Pulversheim and Wahlebach Fm facies ranging from 5 to 20 m (drillings CLJ-F1, RNA-F1 & 2, ETA-F2, CHM-F4).

6.9.4 Differentiation from other units

The lithological change from the underly-

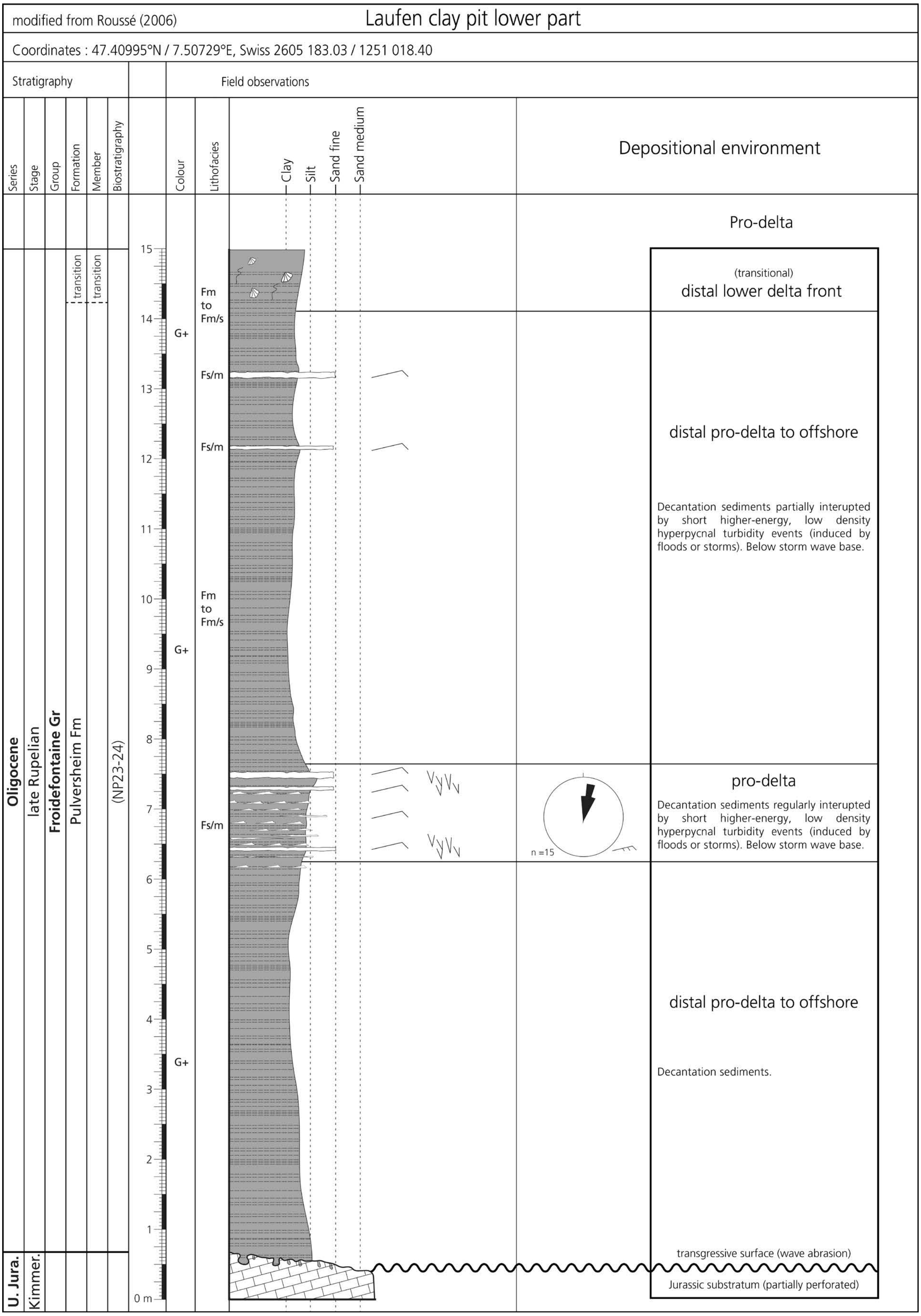


Fig. 27a - Reference section of the Pulversheim Fm in the lower part of the Laufen clay pit (ZZ Wancor AG, Switzerland). Note the absence of the Wallau and Hochberg Fms.

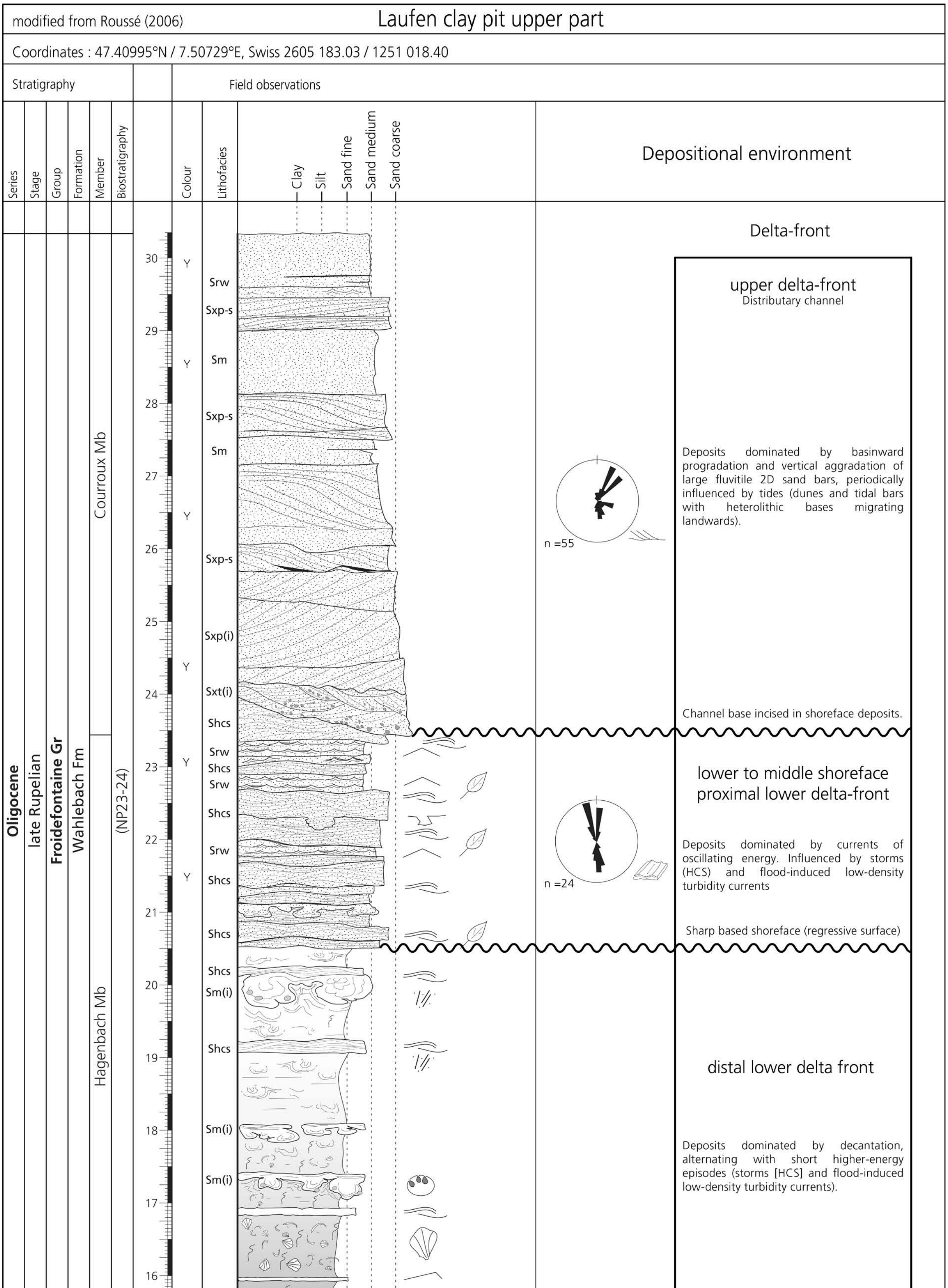


Fig. 27b - Type section of the Wahlebach Fm in the upper part of the Laufen clay pit (ZZ Wancor AG, Switzerland).

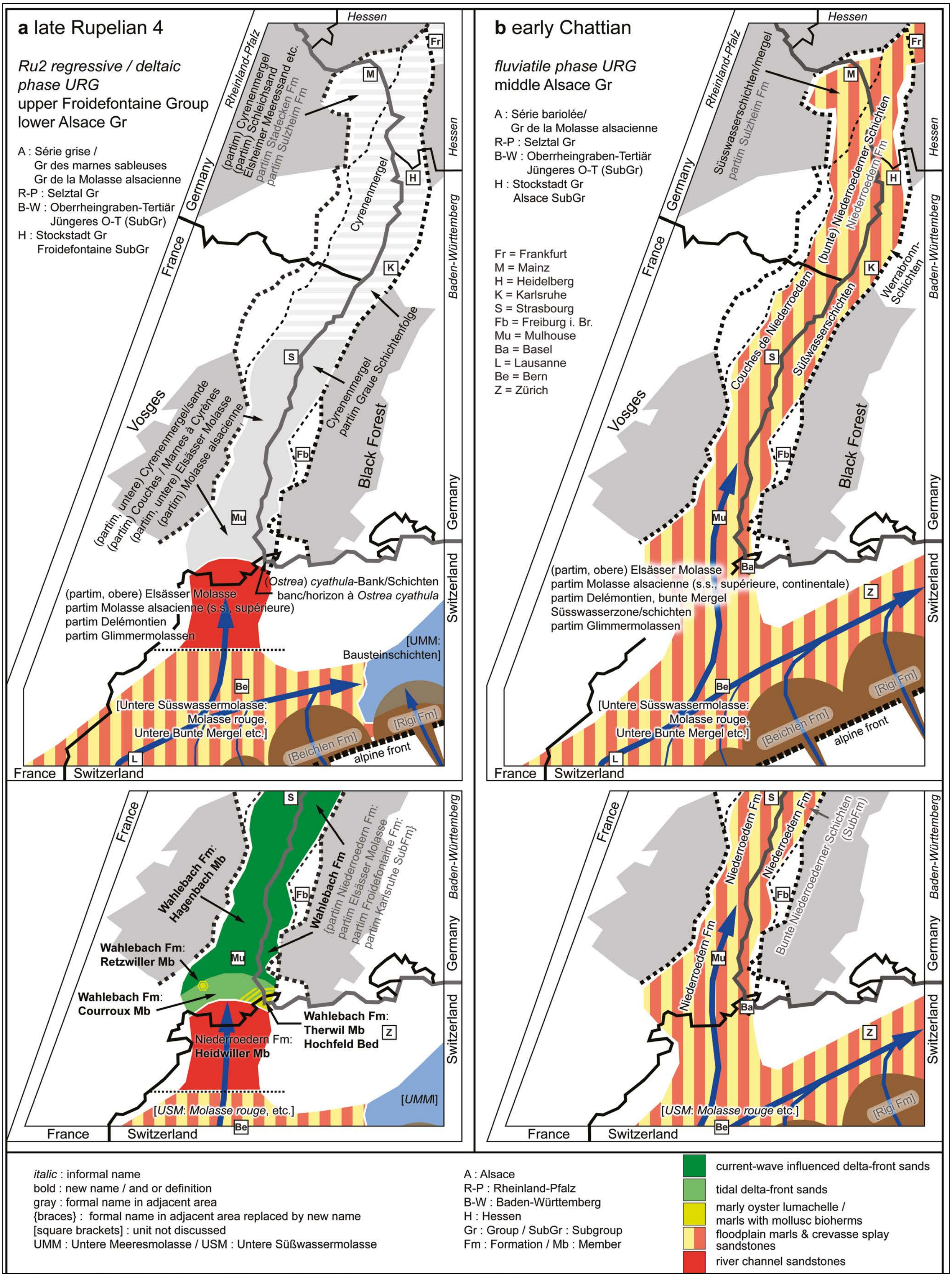


Fig. 28 - Palaeogeographic representation of major facies and regional lithostratigraphic terms (updated from and based on maps in Berger et al. 2005b). Top of the figure represents the formerly used most common terms, lower part the status after revision and simplification. 28a Map for the late Rupelian (part 4), 28b Map for the early Chattian.

ing dark, finely laminated bituminous marls of Hochberg Fm is distinct in the entire southern URG.

Near the southern URG margin, but north of the southernmost subbasins the Pulversheim Fm intercalates with the diachronous Hagenbach Mb of the Wahlebach Fm (see 6.11; Fig. 40-41), due to oscillating progradation/retrogradation stages of the deltaic system at the southern end of the URG (Roussé 2006). In this area the upper part of the Pulversheim Fm consequently overlays a stratigraphic unit, which it in turn underlies further to the north. The Hagenbach Mb in drilling DP202 starts at 428.8 m depth after a transitional zone of about 24 m (Fig. 29) and is characterised by coarser clastic, mica and plant debris-rich light-coloured delta front sands. With the onset of the Pulversheim Fm the heavy mineral suites change rather abruptly from a prevalence of zircon, tourmaline and rutile to suites dominated by garnet and epidote (see 8.2).

The underlying Hochberg and Wallau Fms are not developed in the Delémont and parts of the Laufen as well as the Ajoie subbasin. In this area the Pulversheim Fm lies either directly on the Lörrach Fm (e.g. Liniger 1925) or discordantly on bioeroded Jurassic limestones (e.g. Picot et al. 2008; Fig. 27a). As stated above the sediment thickness is greatly reduced in the southernmost subbasins, leading to a very dense amalgamated succession of several facies. In the Delémont subbasin the Pulversheim Fm consists of one to few metres of bedded marls, which pass gradually into the increasingly sandy Hagenbach Mb (e.g. drillings COM990-F5, HRT015-F8/9, Fig. 10-12). A repeated diachronous intercalation of these two units was demonstrated in Clément & Berger (1999) and can be interpreted as shorelines of rapidly shifting delta lobes.

In Baden-Württemberg the ex-"Melettaschichten" constitute part of the Karlsruhe Subfm (LGRB 2011, GeORG 2013, raised to formation status in Schäfer 2013). The latter was defined in the eastern middle URG based on a highly variable assemblage of lithologies and fossil contents (grey to coloured marls and sands, brackish to freshwater biota). In our opinion this represents partly a separate, apparently coeval basin-marginal unit ("Karlsruhe Kalksandstein") that was influenced by freshwater influx and partly an amalgamation of (parts of) the former "Melettaschichten" and "Cyrenenmergel" (now Hagenbach Mb, see 6.11) as well as the fluviatile Niederroedern Fm (see 6.16 and Fig. 40).

The more finely layered marly to silty upper part of the classic "Septarienton" or "Rupelton" in the Mainz Basin has been included as transgressive Rosenberg Subfm (Grimm et al. 2000) in the underlying Bodenheim Fm (Fig. 22b; Grimm et al. 2000, Grimm & Radtke 2002), a concept that has been applied to the URG in general in Grimm (2005) and Grimm et al. (2011b). We however consider this concept to be invalid, since the discriminative lithological change between the Rosenberg Subfm and the subsequent "Melettaschichten" ("clayey-silty" to "marly-sandy") is much less pronounced than between the Hochberg and Rosenberg Subfms ("bituminous laminated dark clayey marls" to "bedded greyish silty marls"). Grimm (2011a) also confusingly state that during the transgression of the Rosenberg Subfm on the basin margins the deposition of the dysoxic Hochberg Fm in the graben centre continued due to an even greater water depth, effectively negating a development of Rosenberg Subfm in most parts of the URG.

The generalised definition of the "Meletta-Schichten s.s." in the URG according to Grimm et al. (2011b) comprises a sandy and micaceous lithology with intercalated marls, displaying a general coarsening upward trend. In the southern URG a distinct global increase of clastic sediments and colour change however does not set in until the development of the subsequent Hagenbach Mb (see 6.11). Localized increase of silt and sand content within the Pulversheim Fm is related to the deposition of pro-delta lobe turbidites (see above).

The late Rupelian stratigraphic subdivision of the Mainz Basin should accordingly not be comprehensively and indiscriminately applied to the entire URG.

6.9.5 Age and fossil content

The age of the Pulversheim Fm is constrained between the data of the underlying Lörrach, Wallau and Hochberg Fms (see 6.5, 6.7-8) and the overlying Heidwiller Mb (see 6.17), without concise autochthonous dating.

Fossils in the basin centre are generally not common, whereas their abundance increases towards the margin. The most common macrofossils include the centriscid fish *Aeoliscus*, the herring *Clupea* and other fish remains (e.g Hess & Weiler 1955; Pharisat 1991a,b; Pharisat & Micklich 1998)

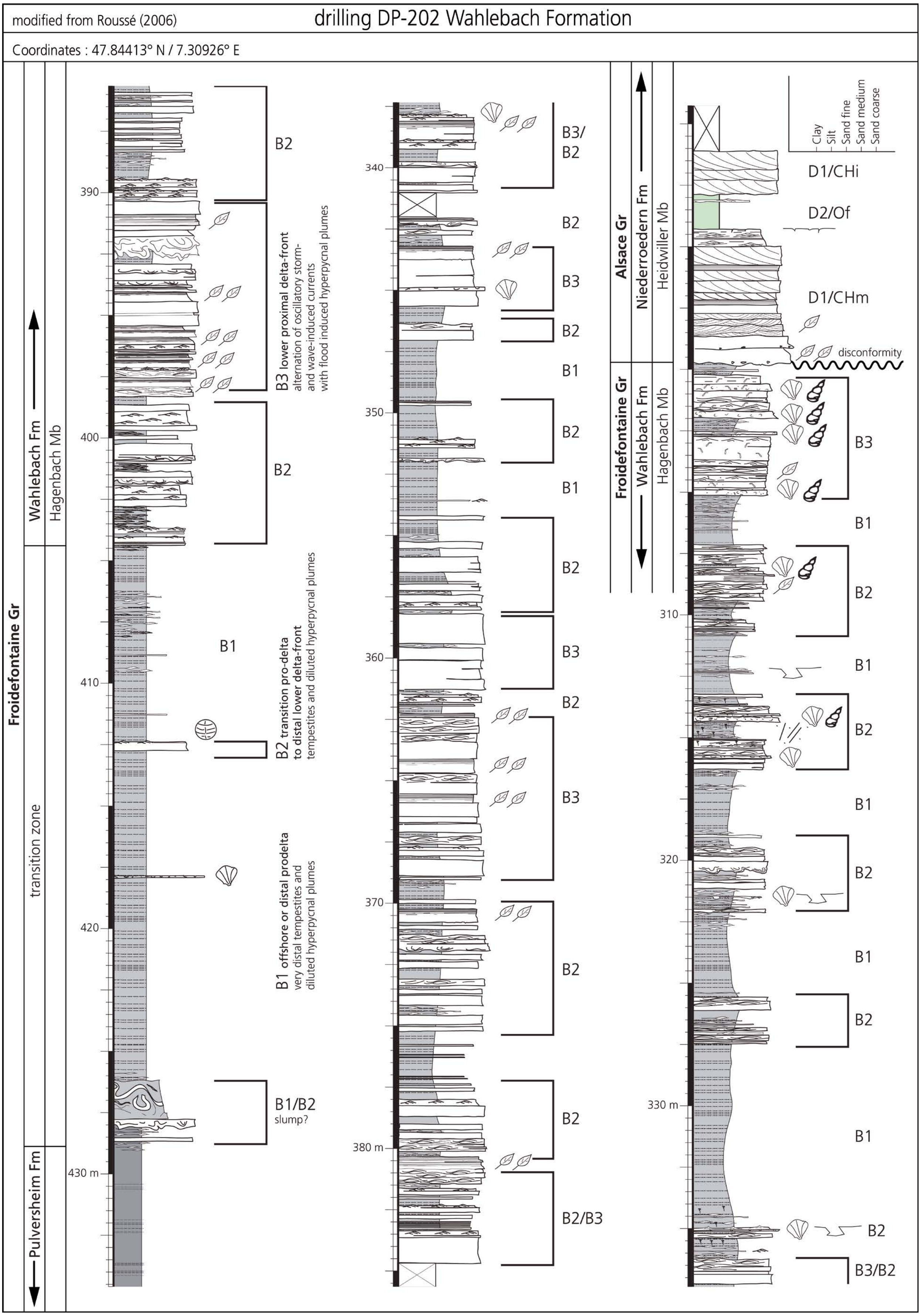


Fig. 29 - Reference section of the Wahlebach Fm in drilling DP-202. Abbreviations B1-3 explained on figure, for D1-D2 see Fig. 35. The green colour in the uppermost part of the section indicates the shift to floodplain marl deposition.

as well as plant debris in the turbiditic facies (Roussé 2006). Echinoderms are rare (e.g. Hagmann 1897; Pirkenseer et al. 2013). Molluscs were often recorded in the historical context of the "Septarienton", which should rather be attributed to the subsequent shallow marine and brackish Hagenbach Mb, though some molluscs and shark teeth do occur in the Pulversheim Fm (e.g. Koch 1923). Hess & Weiler (1955) also mention a relatively rich and diverse assemblage of insects from a thin marlstone level of the Allschwil clay pits.

Microfossils are found throughout the formation, though they are generally not abundant (especially in the basin centres). They show a much lower diversity than in the Wallau and even the Hochberg Fm (Pirkenseer et al. 2010), with a prevalence of planktic taxa. Ostracoda are not recorded (Pirkenseer & Berger 2011). A peculiar aspect is the occurrence of reworked late Cretaceous and Eocene planktic Foraminifera in the coarser clastic parts of the formation (pro-delta turbidites) (Pirkenseer et al. 2010, 2011), which was already recognized by Hasemann & Heinemann (1956, 1957) and Fischer (1965a, b) (see 8). Schwarz (1997) indicates a slow increase of charophyte diversity throughout the Pulversheim formation (or its northern equivalents).

A subdivision of the Pulversheim Fm and the subsequent Hagenbach Mb based on microfossils has been discussed in Pirkenseer & Berger (2011) and compared to the lithological results of Roussé (2006). Based on reappearance of abundant and diverse shallow marine to brackish microfossils (Foraminifera and Ostracoda) the ecostratigraphical limit between both units is positioned about 65 m higher than based on sedimentological criteria (Fig. 22a). This indicates a delayed response of crucial palaeoenvironmental proxies (e.g. water depth) relative to the change of sedimentary processes, rendering microfauna ambigous as tools for lithostratigraphic analysis (see discussion 6.7.5-6).

6.10 Wahlebach Fm (partim ex Cyrenenmergel, Molasse alsacienne) (Fig. 28a)

6.10.1 Synonomy and generalities

- ?partim Système de Bourogne (Kilian 1884)
- (partim) Cyrenenmergel / Cyrenen-Mergel (Gutzwiller 1914, van Werveke 1918, Koch 1923, Bitterli 1945, Wagner 1950, 1955, ?non Schnaebele 1948, Naef et al. 1985, Schwarz 1997, Roussé 2006, Picot et al. 2008, Grimm et al. 2011b, Schäfer 2013, DSK 2016)
- partim *Meletta*-Schichten (van Werveke 1918)
- partim Système de Froidefontaine (Meyer 1928)
- partim graue sandige Mergel (Schneider 1960)
- (partim) Elsässer Molasse / Elsässermolasse (Liniger 1925, Wittmann 1950, 1983, Fischer et al. 1971, Brianza et al. 1983, Bitterli-Brunner & Fischer 1988, Grimm et al. 2011b, LGRB 2011, SKS 2014)
- (partim) Molasse alsacienne (s.l.) (?Rollier 1893a,b, Rollier 1898, non Rollier 1910, Baumberger 1927, Sittler 1965, Bitterli-Brunner & Fischer 1988, Clément & Berger 1999, Picot 2002, Becker 2003, Berger et al. 2005a, b, Picot et al. 2008)
- (partim) Groupe de la Molasse Alsacienne (Roussé 2006)
- partim Froidefontaine Fm (LGRB 2011, DSK 2016)

The definition and exact attributions of (parts of) this formation has historically been ambigous. The revision characterizes four new members: the Hagenbach, Courroux, Therwil and the Retzwiller Mbs. The depositional context of the prograding delta system and the associated depositional environments lead to a complex interlock of and heterochronies between members of the Wahlebach Fm. Accordingly the attribution of synonymies is confusing, especially for the Courroux Mb (see 6.14). The "Elsässer Molasse" has formerly either been assigned as a "subformation" to the "Cyrenenemergel", or vice versa, or both have been treated as discrete formations. The term "Molasse" in any case should be avoided since the sediments of the area do not represent a molassic deposit sensu stricto (see 8.5). Historically both the "Elsässer Molasse" and the "Cyrenenemergel" have been split into (partly analogue) lower and upper parts, adding to the uncertainty.

The differentiation from the underlying Pulversheim Fm is sometimes difficult (e.g. Vonderschmitt 1942), since a transition over several tens of meters may be observed. The complex interlock between both formations has been demonstrated for the Delémont subbasin (Clément & Berger 1999), and on a larger scale for the southern URG (Roussé 2006).

Small-scale exposures may be difficult to assign to either formation in this transitional zone (e.g. Hasemann & Heinemann 1956, 1957), which may possibly be solved by analysing their microfossil content (keeping in mind the caveats, see 6.7.5, Fig. 22a). Ostracoda, abundant benthic Foraminifera and Charophyta are absent in the Pulversheim Fm, whereas autochthonous planktic Foraminifera (mainly *Globigerina praebulloides*) are comparatively abundant (Pirkenseer et al. 2010; Pirkenseer & Berger 2011).

6.10.2 Definition, distribution and thickness

The Wahlebach Fm is characterised by a fine to coarse-grained sandy facies, a change to lighter colours from the dark marls of the underlying Pulversheim Fm and a strong increase in muscovite and plant debris. The successive sedimentary environments include the delta-front, tidal bay and tidal river channel settings (Roussé 2006). For more details consult the individual member descriptions.

Due to the complexity and lateral variability of the formation no type locality featuring all members exists. The most common unit is the Hagenbach Mb. Important sections are recorded in drilling DP202 (Hagenbach Mb, Fig. 29) and the Laufen clay pit (condensed succession, Fig. 27b).

An approximate thickness of the formation cannot be given due to the large lateral variations and the uncertainties of former descriptions. In drilling DP202 the formation reaches a thickness of about 105 m (404.25 m to 299.75 m; Roussé 2006) in the Potash Basin centre and at least 15 m in the Laufen clay pit near the basin margin. In the Delémont subbasin the Wahlebach Fm is reduced to few meters on its southern margin (drillings HRT015-F8/9, Fig. 11-12).

The formation is named after the Wahlebach Brook near the town of Laufen. The adjacent clay pit displays the most important lithological features of the formation in a condensed succession (Fig. 27).

The facies variation and their lateral interlock, change in fossil assemblages and the apparent pinchout towards the basin margins of all members illustrate exemplarily the infilling of a marine basin by a large fluviatile system with external sediment source (see 8).

6.10.3 Age

Based on the analysis of sedimentary sequences Roussé (2006) correlated the erosional unconformity between the Wahlebach and the Niederroedern Fm with the Rupelian – Chattian boundary. Biostratigraphic evidence from the Mainz Basin and the southern URG (Mödden et al. 2000; Pirkenseer et al. 2013) however indicates a slightly older position in the European small mammal biozone MP24 and accordingly the Late Rupelian.

Further to the southeast in the area of Basel and the Laufen Basin the Wahlebach Fm seems to set in much earlier, as a locality near Dornachbrugg was correlated to small mammal biozone MP22 (e.g. Engesser & Mödden 1997) and calcareous nannoplankton zone NP22.

6.11 Hagenbach Mb (partim ex-Cyrenenmergel)

6.11.1 Synonomy and generalities

- (partim) Couches/Marnes à Cyrènes (?Delbos & Köchlin-Schlumberger 1867, Kilian 1884, non Rollier 1893a, Meyer 1928, Maïkovsky 1941, Lagneau-Herenger 1965, Sittler 1965, Ménillet et al. 1970, Naef et al. 1985, Sittler 1992, Roussé 2006, Pirkenseer et al. 2010, Pirkenseer & Berger 2011)
- partim ?Marnes de Méroux (Kilian 1884)
- Glimmersande (Wurz 1912)
- Brackwasserbildung (Gutzwiller 1914)
- ?Grès à feuillles (Meyer 1928)
- Molasse alsacienne (Meyer 1928)
- ?oberer Septarienton (Fischer 1965b)
- (partim) (untere) Elsässer Molasse / Elsässermolasse (Liniger 1925, Fischer 1965a, Doebl 1970)
- (partim) (untere) Cyrenenmergel / Cyrenen-Mergel / Cyrenensande (?Andreae 1884, 1887, Gutzwiller 1893, Meyer 1928, Buxtorf & Christ 1936, Vonderschmitt 1942, Bitterli 1945, Wagner 1950, 1955, Hess & Weiler 1955, Fischer 1965a, Doebl 1970, Fischer et al. 1971, Brianza et al. 1983, Bitterli-Brunner & Fischer 1988, Schwarz 1997, Picot 2002, Becker 2003, Berger et al. 2005 a, b, Picot et al. 2008, Grimm et al. 2011b, Pirkenseer et al. 2013)
- partim graue sandige Mergel (Schneider 1960)
- Cyathulamergel (Picot 2002, Picot et al. 2008)
- partim ?Karlsruhe-Subformation (LGRB 2011)
- Cyrena Marls (Pirkenseer et al. 2011)

The historical term “Cyrenenmergel” should be avoided since the Chattian to Aquitanian “Cyrenenschichten” of the Bavarian Molasse represent a homonymous term (e.g. Freudenberger & Schwerd 1996; Reichenbacher & Schwarz 1997).

6.11.2 Definition, distribution and thickness

The Hagenbach Mb consists mainly of light grey, muscovite-rich fine to coarse grained sandstones to sands and subordinately of grey silty marls, with more frequent intercalations of marls at the base of the member. Abundance and size of plant debris generally increases towards the top of the member. Sandstones show a variety of wave and current induced sedimentary structures of different water energy regimes, linked to a general shallowing-up in a delta-front / shoreface setting. In drilling DP202 the onset of a transitional zone between the Pulversheim Fm and the Hagenbach Member is marked by slumped sediment, probably due to the higher gradient of the approaching delta-front. For

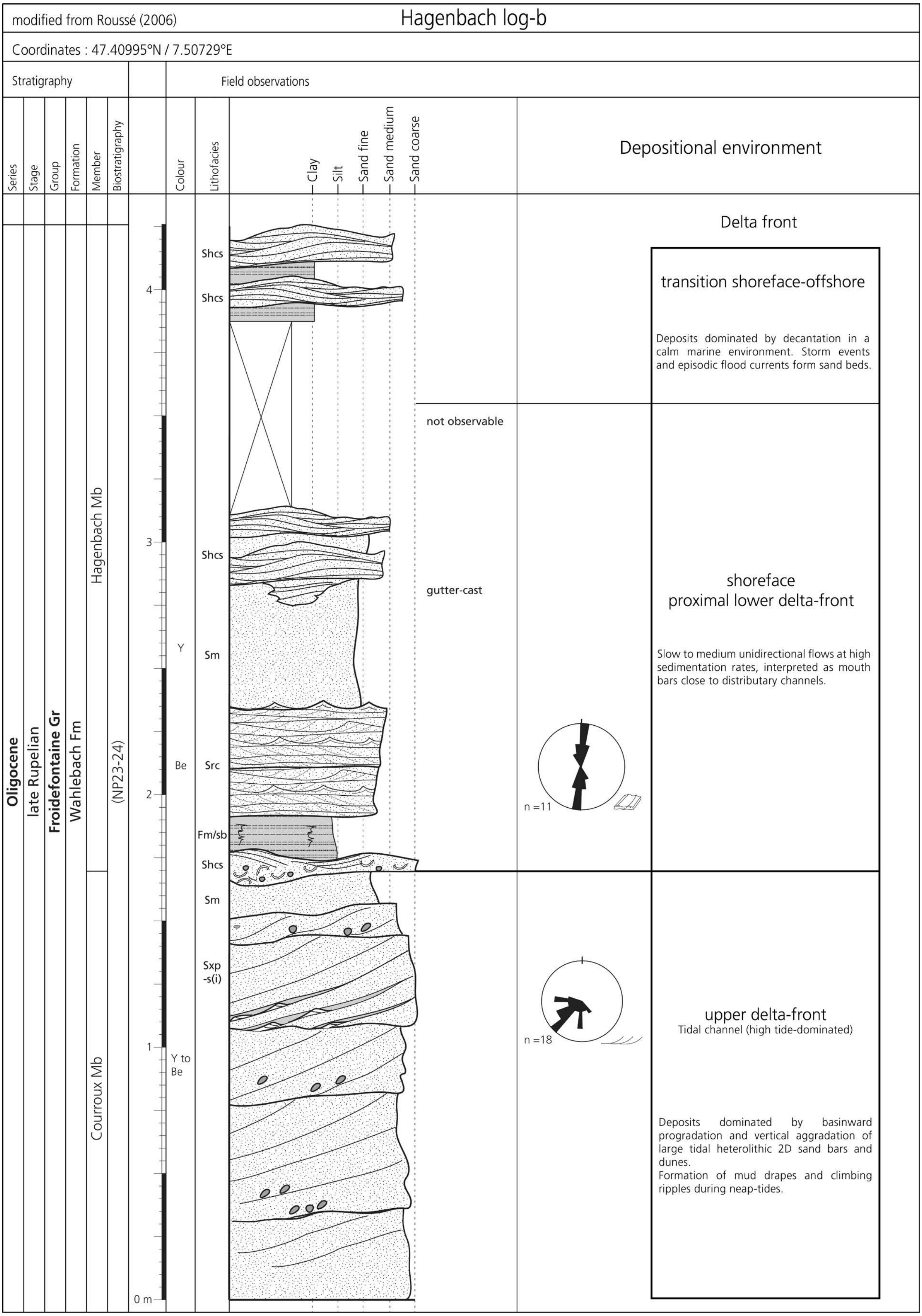


Fig. 30 - Type section of the Hagenbach Mb in the upper part of the Hagenbach outcrop (France). Note the superposition of the Hagenbach Member on the Courroux Member, illustrating the heterochrony and intercalation of both members indicating shifting delta lobes.

more details on sedimentary facies and structures consult Roussé (2006).

Near the margins of the Ajoie and Laufen subbasins local occurrences of either conglomerates (e.g. Courgenay; Tschopp 1960) or limestones (e.g. Therwil; Koch 1923) may be intercalated as lenses or thin beds.

6.11.3 Type, reference and classic localities

The name of the member is derived from the type outcrop near the village Hagenbach (47.65199° N / 7.161482° E), which illustrates its main facies types (Fig. 30; Roussé 2006). The localities Biel-Benken, Leymen 1-3 as well as Laufen represent reference sections. A more complete overview of the Hagenbach Mb is based on the log description of the drilling DP202 (428.75 to 299.75 m; Fig. 29) in Roussé (2006) and dossier 04132X0064/DP202 (http://infoterre.brgm.fr). Drilling DP202 is located in the central Potash Basin north of the village Pulversheim (Alsace; 47.8441323° N / 7.30926536° E). Formerly described outcrops in the area of Basel and further to the north (e.g. Wurz 1912) and west need to be reanalysed, as far as they are still accessible.

6.11.4 Differentiation from other units

The change from the underlying Pulversheim Fm occurs in a transitional zone, shifting from offshore and pro-delta to delta-front settings. The main distinguishing feature is the dominance of sandstones and the increased fine sand content of the marls, the strong increase in size and abundance of muscovite and plant fragments as well as wave-generated sedimentary structures. Difficulties separating both units have been mentioned in Doebl (1970) and Grimm et al. (2011b), which was mainly due to the lack of a precise lithological analysis of the respective sand dominated beds (pro-delta turbidites vs. delta-front sands). The statement in Grimm et al. (2011b) that the "Cyrenenmergel" carry much less sand and mica than the underlying "Meletta-Schichten" is not applicable to the stratigraphic context of the southern URG.

The overlying and interfingering Courroux Mb (see 6.14) features even coarser-grained sands, less marls and tidally influenced sedimentary structures. The likewise overlying or interfingering Retzwiller Mb contrasts strongly in combining a dominance of massive lagoonal marls and molluscs in life position. In the area south and west of Basel the regional Therwil Mb (oyster coquina) and the lacustrine to brackish limestone bed immediately below the Therwil Mb (Hochfeld Bed) are intercalated in the Hagenbach Mb.

The grey to coloured marls and sandstones of the very inhomogeneous freshwater influenced Karlsruhe-Subformation from the middle URG sensu LGRB (2011) represent a stratigraphic equivalent to the Hagenbach Mb in this area.

6.11.5 Fossil content

Macrofossils mainly include marine to brackish molluscs and plant fragments (e.g. Gutzwiller 1893; Wurz 1912; Maïkovsky 1941). The upper part of the increasingly sandy section described in Hess & Weiler (1955) that may belong to the Hagenbach Mb yielded marine fishes. The locally intercalated, thin limestone bed (Hochfeld Bed) below the Therwil Mb carries limnic to brackish gastropods (Gutzwiller 1893; Gutzwiller 1914; Koch 1923; Baumberger 1927).

Microfossils are dominated by Ostracoda and benthic Foraminifera (Picot 2002; Pirkenseer et al. 2010; Pirkenseer & Berger 2011), with intermittent occurrences of charophyte oogonia, fish otoliths and echinoderm fragments (Schwarz 1997 Pirkenseer et al. 2013). They indicate by and large a progressive shallowing-up and a final desalination of the basin. Due to the shifting lobes of the prograding delta this was not a gradual process, as has been evidenced by a short recurrence of somewhat more marine conditions (*Bolboforma* / marine ostracod events) in the upper part of the member (Pirkenseer et al. 2013). The microfauna clearly differs from the preceding Pulversheim formation (see 6.9). Charophyte diversity increases even further, especially of the "halophobe" association, indicating gradually decreasing marine conditions (Schwarz 1997).

Planktonic Foraminifera are not uncommon, but a high ratio consists of reworked late Cretaceous and Eocene taxa (Fischer 1965a; Pirkenseer et al. 2010, 2011) (see 8).

6.12 Therwil Member (ex Cyathulabank s.s.) (Fig. 28a)

6.12.1 Synonomy

- Banc / horizon à *Ostrea cyathula* (non Greppin 1870, Meyer 1928, Roussé 2006)

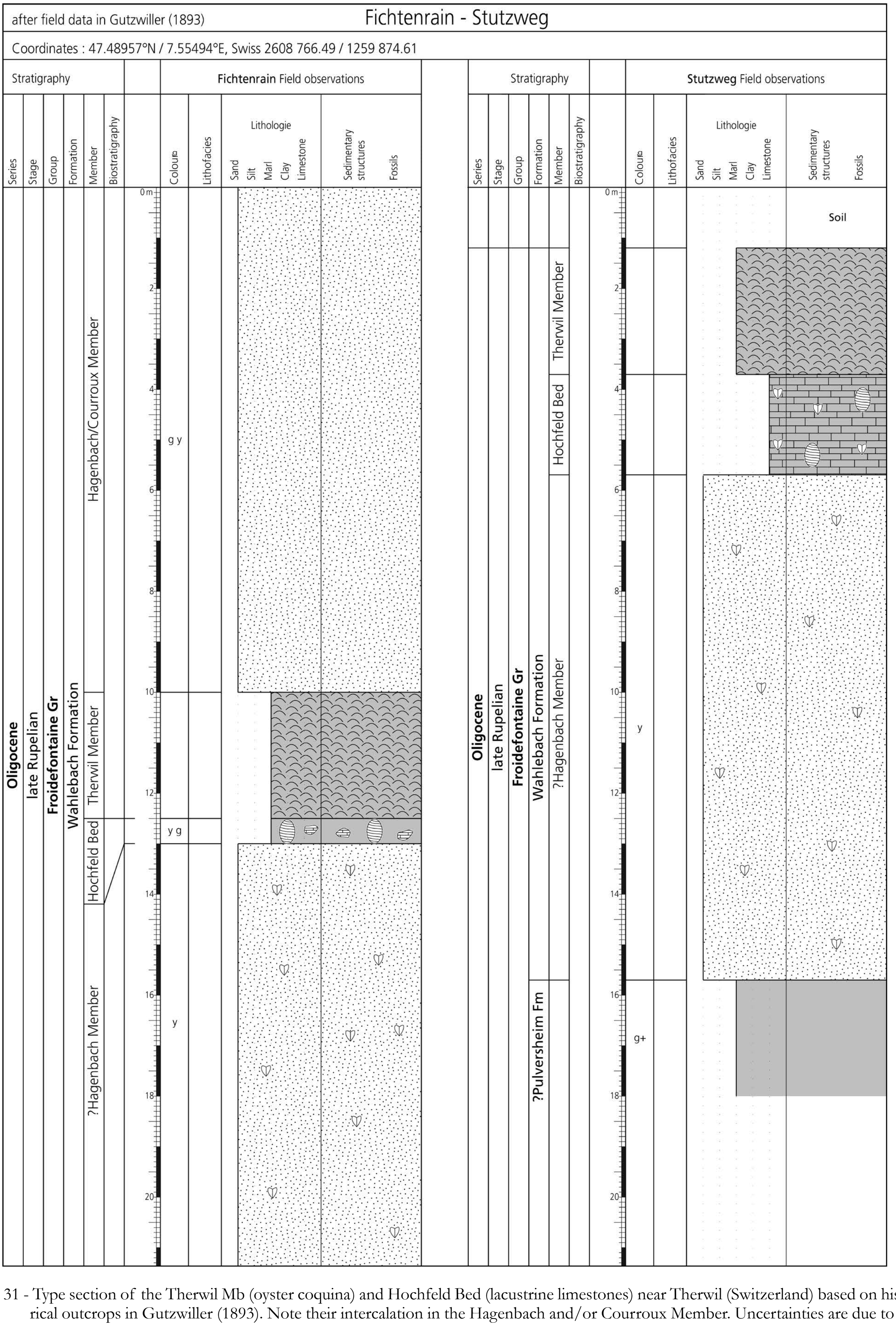


Fig. 31 - Type section of the Therwil Mb (oyster coquina) and Hochfeld Bed (lacustrine limestones) near Therwil (Switzerland) based on historical outcrops in Gutzwiller (1893). Note their intercalation in the Hagenbach and/or Courroux Member. Uncertainties are due to the insufficient data in the historical account. Formerly synonymised with the Près Roses Mb (see Fig. 19) by some authors.

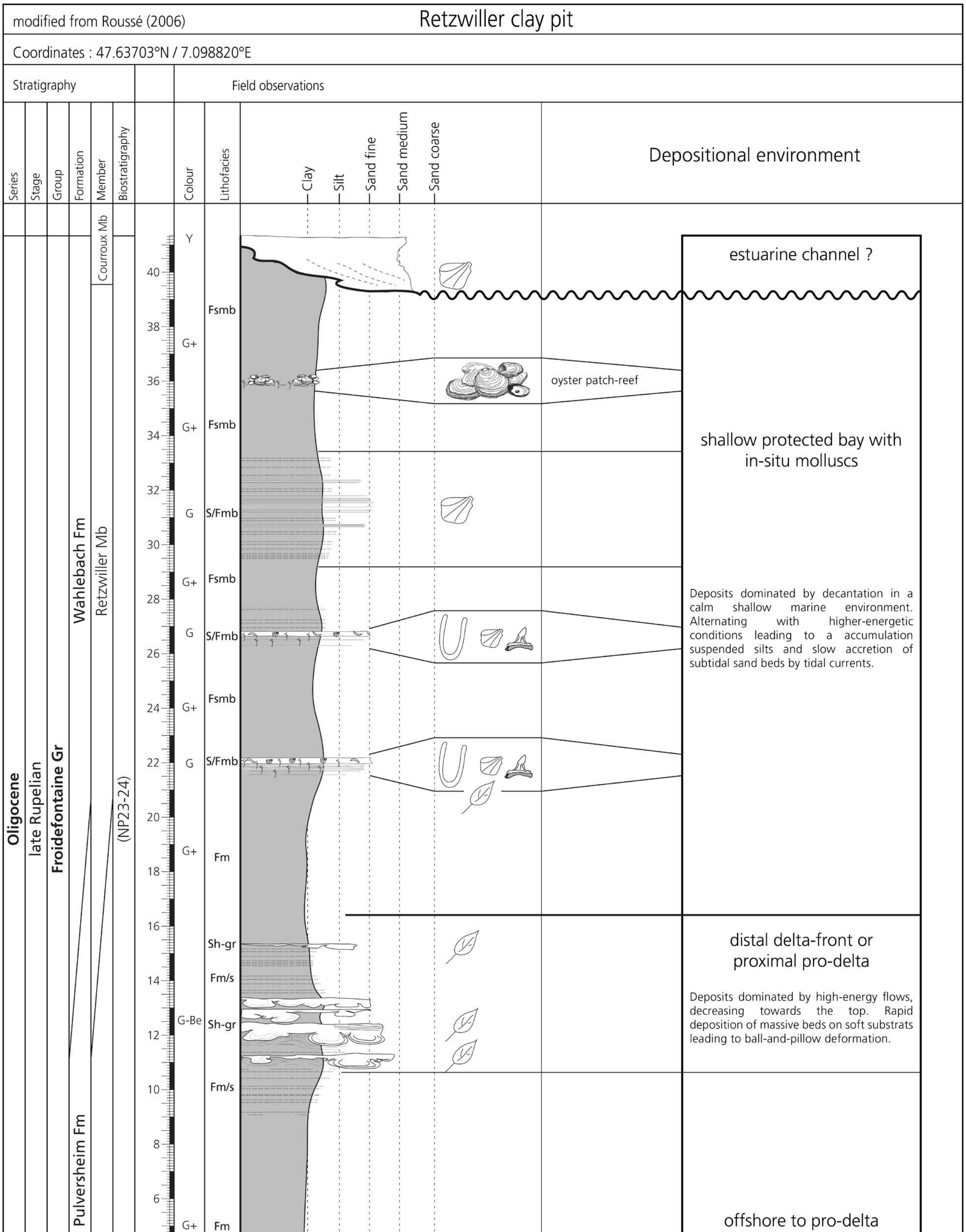


Fig. 32 - Type section of the Retzwiller Mb. Note the in-situ position of bivalves versus the allochthonous accumulation of oysters in the Therwil Mb (Fig. 31) and the erosive incision of the Courroux Mb at the top of the section.

- partim Cyrenenmergel (Gutzwiller 1893, Rollier 1893a)
- Banc de molasse à *Ostrea cyathula*, partim Marnes à Cyrènes etc. à *Ostrea cyathula* (Rollier 1910)
- Horizont / Bank mit *Ostrea cyathula* (Gutzwiller 1914, Herzog 1956, ?Tschopp 1960, Bitterli-Brunner & Fischer 1988)
- (partim) Cyathula-Schicht(en) (Buxtorf & Christ 1936, Fischer et al. 1971)
- (Crassostrea/Ostrea)-cyathula-Bank/Cyathulabank (Koch 1923, non Liniger 1925, Bitterli 1945, non Oertli 1956, ?Tschopp 1960, Fischer 1965a, Naef et al. 1985, Picot 2002, Becker 2003, Grimm 2005, Picot et al. 2008)

6.12.2 Definition, distribution and thickness

The Therwil Mb is dominated by disarticulated valves of *Crassostrea cyathula*, which either form a densely packed, sometimes sandy coquina or are distributed in a matrix of mainly bluish grey, massive marls. In the area of Basel the member seems to be developed as a relatively continuous bed of maximal 2 (possibly to 5) m thickness that pinches out near Brislach (30 cm; Koch 1923) in the Laufen subbasin. Gutzwiller (1893) indicates a continuous occurrence of the coquina bed between the villages Therwil and Ettingen (at least 4 km). Towards the north and the west the bed dissolves into oyster patch "reefs", isolated valves in massive marls or is entirely absent (e.g. drilling Hirtzbach; Vonderschmitt 1942).

In the area of Therwil a 2 m thick limestone bed (Hochfeld Bed) underlies the Therwil Mb that contains freshwater and brackish molluscs (Gutzwiller 1893; Baumberger 1927). The Hochfeld Bed was erroneously correlated by Baumberger (1927) with the much younger "Matzendörferkalke" (see 6.16.4).

6.12.3 Type, reference and classic localities

The designation of the type locality of the Therwil Mb is based on descriptions of temporary outcrops near the village Therwil in Gutzwiller (1893), Baumberger (1927) and Bitterli (1945). Further (historical) outcrops in the Laufen subbasin are recorded in Koch (1923) and Buxtorf & Christ (1936). Since no outcrops are accessible at the moment, only an provisional section based on historical accounts is provided (Fig. 31).

The only drilling (Allschwil-1; 47.55654° N / 7.54435° E) that probably recorded the Therwil Mb has been included by Koch (1923) in an idealised composite stratigraphy of the Basel area. Unfortunately the upper 200 m of well Allschwil-1 were destructively drilled without detailed logging (Christ 1924). In the nearby drilling Allschwil-2 (47.54308° N 7.51787° E) the Therwil Mb is not developed (e.g. Pirkenseer & Berger 2011).

6.12.4 Differentiation from other units

In the past the Therwil Mb has been used as a regional marker bed for the area south of Basel separating the so-called "untere / obere Cyrenenmergel / Elsässer Molasse" (depending on author). Together with the just underlying and even more locally restricted Hochfeld Bed (see 6.12.2) the Therwil Mb represents a regional marginal facies aberration of the Wahlebach Fm. It is easily distinguished by the mass occurrence of oyster shells. Towards the northwest in direction of the main basin centre occurrences of oysters decrease. The Therwil Mb should not be confused with the similar oyster-bearing Près Roses Mb (see 6.6), which was deposited in the context of the older Lörrach Fm. Tschopp (1960) cites a *C. cyathula*-bearing "horizon" near the village Courgenay that may represent an equivalent to the occurrences near Basel, but is located much further to the west. It lies above sediments of the Lörrach Fm within marginal equivalents of the Hagenbach Mb.

The Therwil Mb may either be interpreted as a marginal equivalent to the more basinal Retzwiller Mb (see 6.13, shallow bay with oyster patch "reefs") or as independent lithological unit, which in the past has been linked to a (short-term) transgressive event (e.g. Koch 1923, Baumberger 1927). It remains uncertain if the latter can be correlated with the short-term recurrence of marine conditions in the upper part of the Hagenbach Mb (see 6.11). The rapidly changing palaeoenvironmental conditions in the context of the prograding delta system certainly drove a heterochronic distribution of oyster occurrences (as well as other deltaic members) in the entire southern URG (e.g. Retzwiller Mb).

6.13 Retzwiller Member (Fig. 28a)

6.13.1 Synonomy

- "Mergel / Fauna" von Dammerkirch", partim Meeressand (Andreae 1884)
- partim Meeressand (Förster 1892)
- Faune marine de Wolfersdorf (Rollier 1910)
- Sables et marnes de Dannemarie et Wolfersdorf (Meyer 1928)
- Sables marins de Wolfersdorf (Gillet & Theobald 1936, Duringer 1988, Sittler 1992)
- ? Marnes à Cyrènes (Schnaebele 1948)
- Molasse alsacienne marine: faciès C2b (baie peu profonde abritée à récifs d'huitres) (Roussé 2006)

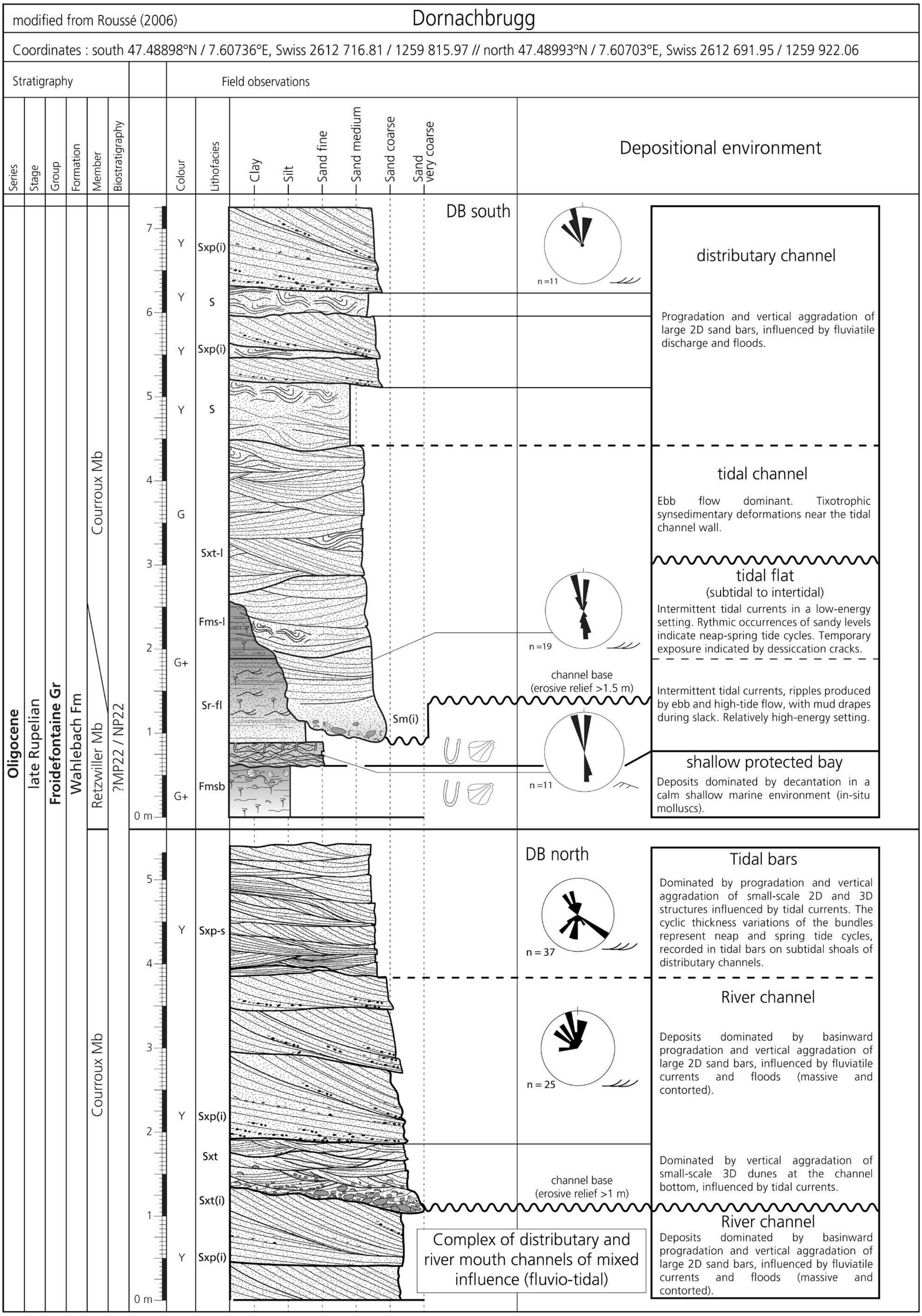


Fig. 33 - Type sections of the Courroux Mb on the River Birs bancs south of Delémont (Switzerland).

6.13.2 Definition, distribution and thickness

Dominated by massive grey marls to silty marls, with occasionally intercalated thin, strongly bioturbated bioclast or mollusc-bearing micaceous fine sand beds and small in-situ oyster bioherms (sensu Roussé 2006). In the Retzwiller section the thickness reaches about 25 m.

A historically well-known part is the thin fossil-rich sandstone (formerly called "Sables marins de Wolfersdorf") in the lower part of the member. The absence of this fossiliferous sandstone in the drilling Hirtzbach (10 km distant) has been mentioned in Vonderschmitt (1942), further highlighting the regional restriction of the members of the Wahlebach Fm.

6.13.3 Type, reference and classic localities

The type section (Fig. 32) is located in the Retzwiller clay pit (approx, 47.63523° N / 7.098560° E). For a detailed description of the outcrop and the related facies type consult Roussé (2006). The only other occurrence attributed to the Retzwiller Mb is recorded in the lowermost part of the outcrop Dornachbrugg-1 (ibid.). Possibly related localities in the southern URG have been proposed based on the presence of similar macrofossils (Meyer 1928).

6.13.4 Differentiation from other units

The Retzwiller Mb constitutes of a calm-water facies coeval to the high(er) energy Courroux and Hagenbach (see 6.14, 6.11) Mbs, which are dominated by coarser sands and sandstones. The Retzwiller Mb possibly represents a heterochronous facies variation of the Therwil Mb (see 6.12).

The Retzwiller Mb approaches the definition of the "Cyrenenmergel" sensu Doebl (1970) and Grimm et al. (2011b) bearing less sand than (parts of) the Pulversheim Fm. This concept has been erroneously applied to the entire Wahlebach Fm (ibid.).

6.13.5 Fossil content

Shallow marine in-situ molluscs are highly abundant in the small oyster bioherms (Roussé 2006) and the fossiliferous sandstone bed (Andreae 1884; Meyer 1928; Gillet & Theobald 1936). Benthic Foraminifera (Andreae 1884; Förster 1892; Pirkenseer et al. 2010) and Ostracoda (Pirkenseer & Berger 2011) support the interpretation as a shallow marine palaeoenvironment. Occurrences of reworked Late Cretaceous and Eocene planktic Foraminifera (Pirkenseer et al. 2010) illustrate the sedimentological context to the other members of the formation.

6.14 Courroux Mb (ex-Molasse alsacienne marine) (Fig. 28a)

6.14.1 Synonomy

- ? partim Grès à feuilles (Delbos & Köchlin-Schlumberger 1867)
- ? Blättersandsteine von Dornach, Sandsteine über der Schicht mit Ostrea cyathula (Gutzwiller 1893)
- partim (unterer) Cyrenenmergel (Koch 1923, Fischer 1965)
- Molasse alsacienne marine: faciès C1 (complexe de chenaux distributeurs fluvio-tideaux et barres tidales) and C2a (replat de marée argilo-sableux) (Roussé 2006)

For further synonymies see parent formation, since the Courroux Mb represents part of the "Cyrenenmergel" s.l. Its lithological properties have only been recently recognised by Roussé (2006).

6.14.2 Definition, distribution and thickness

Dominated by yellowish medium- to coarse-grained sands and sandstones exhibiting planar cross bedding, trough cross-bedding, tangential cross-bedding and partly exhibiting climbing ripples. Bases of individual beds are often enriched in wood fragments and leaves. Current indicators are either unidirectional in larger migrating sandbars (fluviatile dominance), or bidirectional (tidal dominance). Depositional environments range from distributary channels rarely influenced by tidal currents, over incised tidal channels to tidal bars (see facies C1 in Roussé 2006 for more details).

The subordinate facies C2a sensu Roussé (2006) consists of dark silty marls rhythmically intercalated by centimetric fine sandstones and clayey fine sands showing bidirectionally oriented current ripples and mudrapes between beds and on ripple foresets, indicating a sub- to intertidal mud flat setting.

6.14.3 Type, reference and classic localities

The type locality is situated on a cut bank (47.35295° N / 7.370549° E) of the River Birse north of the village Courrendlin in the Delémont subbasin (Fig. 33). Further sections exhibiting similar facies types have been recognised on the banks of the River Birse near the town Dornachbrugg

(47.48917° N / 7.60733° E, Fig. 34), south of the villlage Folgensbourg (47.53691°N / 7.45365° E), and the uppermost part of the Laufen (47.40737° N / 7.50699° E, Fig. 27b) and Retzwiller (47.63523° N / 7.098560° E, Fig. 32) quarries (Roussé 2006).

6.14.4 Differentiation from other units

The Courroux Mb main separating characteristics are the dominance of sands and sandstones, the tidal signature of the sediments, the subordinately intercalated gray sandy marls and the general absence of macrofossils. The overlying Heidwiller Mb of the Niederroedern Fm (5.2.1) consists mainly of migrating fluviatile sandbars and to lesser extent of green, red or black floodplain marls. The contact between both lithostratigraphic units is marked by an erosional unconformity.

6.14.5 Fossil content

The sandstones are generally devoid of macrofossils, except for wood fragments and leaves. The tidal flat marls have not yet been analysed for microfossils.

6.15 Alsace Group (Fig. 28, 39)

6.15.1 Synonomy and generalities

- Molasse micacée à feuilles (Gressly & Mayer 1853)
- (partim) Elsässermolasse (Liniger 1925, SKS 2014)
- Série bariolée (Sittler 1965)
- Untere Süsswassermolasse (Fischer 1969)
- Groupe de la Molasse alsacienne (Becker 2003)
- Niederroedern-Formation (LGRB 2011)
- Elsass-Subgruppe (Grimm et al. 2011b)
- partim Froidefontaine-Subgruppe (Grimm et al. 2011b)
- USM I (Berger 2011), partim USM J (SKS 2014)

The Alsace Group comprises two successive formations that show the development from a fluviatile to a lacustrine setting, which is initially characterised by a prevalence of migrating river channel sandbars of the Heidwiller Mb, a shift to a predominant sedimentation of floodplain marls in the upper Niederroedern Fm and a final deposition of the lacustrine limestones of the Tüllingen Fm. The revised Alsace Group is based on the Elsass Subgroup sensu Grimm et al. (2011b) and invalidates the former not well-defined "Elsässer Molasse". Its relationship with the underlying former Cyrenenmergel (now Wahlebach Fm) is discussed in 6.10-11 and 6.14. The full development of the group is restricted to the southern URG (see also Grimm et al. 2011b).

6.15.2 Differentiation from other groups

The lower boundary of the Alsace Group is characterized by an unconformity and shift from tidal to fluviatile sedimentary structures.

Towards the NAFB the upper part of the Alsace group correlates to the USM (Berger et al. 2005a, b; Berger 2011). In the intermediate Jura area the Alsace Group was deposited directly on the Mesozoic subsurface, the Sidérolithique or on older lacustrine limestones.

In the Delémont subbasin the Alsace Group is discordantly overlain by either Miocene conglomerates and coarse sandstones of the OMM (Liniger 1925; LLS 2014) or the fluviatile red marls, sands and conglomerates of the Bois de Raube Fm (Kälin 1997). Further to the north overlying sediments are represented by the Pliocene "Sundgau-Schotter" (gravels; Grimm et al. 2011b) and the ongoing deposition of the Rhine River system.

6.16 Niederroedern Fm (ex Molasse alsacienne, Süsswasserschichten) (Fig. 28)

6.16.1 Synonomy and generalities

- partim Delémontien: assise inférieure and a. moyenne (Greppin 1870)
- Delémontienmergel (Koch 1923)
- Delémontien: bunte Mergel and pisolithische Mergel (Liniger 1925)
- partim Glimmermolassen, bunte Mergel unter den Delsberger und Tüllinger Süsswasserkalken (Baumberger 1927)
- (Bunte) Niederröderner / Niederroedern Schichten (van Werveke 1918, Fischer 1965a, Doebl 1970, Grimm 1994, Schwarz 1997, Trunkó & Munk 1998)
- Couches à / de Niederroedern (Schnaebele 1948, Sittler 1965, 1992, Ménillet et al. 1970, Roussé 2006)
- Süßwasserzone (Wagner 1950, 1955)
- Tüllinger Süsswasserschichten: Mergelfazies (Wittmann 1950, Fischer et al. 1971)
- Freshwater Beds (Sissingh 1998)
- Molasse alsacienne supérieur / s.s. (Picot 2002, Becker 2003)
- Niederroedern Beds (Berger et al. 2005a, b)
- Molasse alsacienne continentale (Roussé 2006)
- Couches d'eau douce détritique (Sittler 1992, Roussé 2006)
- Niederrödern-Formation (Grimm 2005, Pirkenseer et al. 2010, 2011, Grimm et al. 2011b, LGRB 2011, Pirkenseer & Berger 2011, GeORG 2013, Pirkenseer et al. 2013, DSK 2016)

The definition of this formation has been outlined in detail in Grimm (2005) and Grimm et al. (2011b). For complementary discussion see there, below only relevant information for the discussion in the research area will be outlined. In LGRB (2011) several subformations and beds have been attribut-

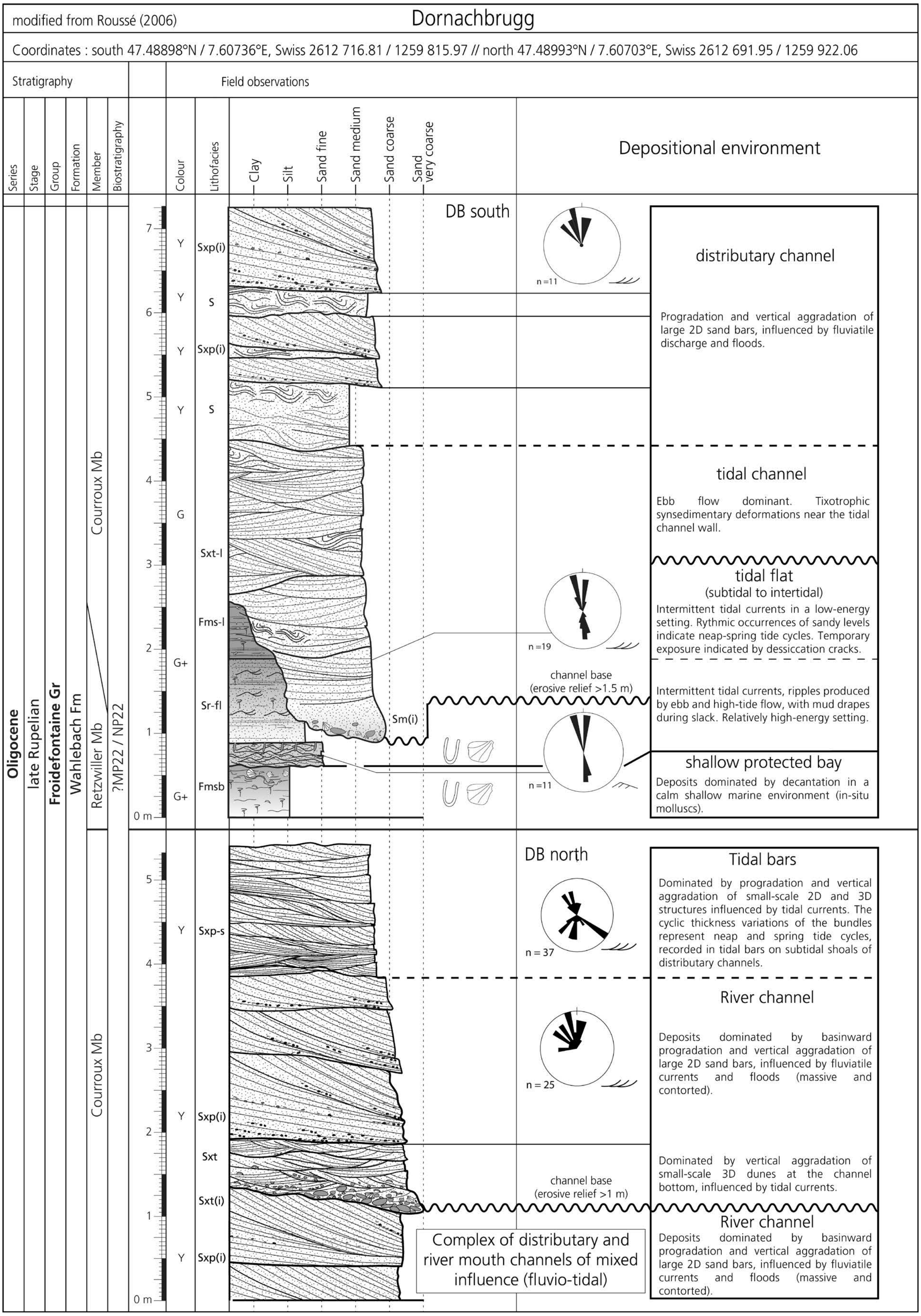


Fig. 34 - Reference sections of the Courroux Mb on the River Birs bancs in Dornachbrugg (Switzerland). Note the erosive incision of the Courroux Mb in the Retzwiller Mb at the base of the Dornachbrugg south section. According to Gutzwiller 1893 the Therwil Mb was exposed below this section.

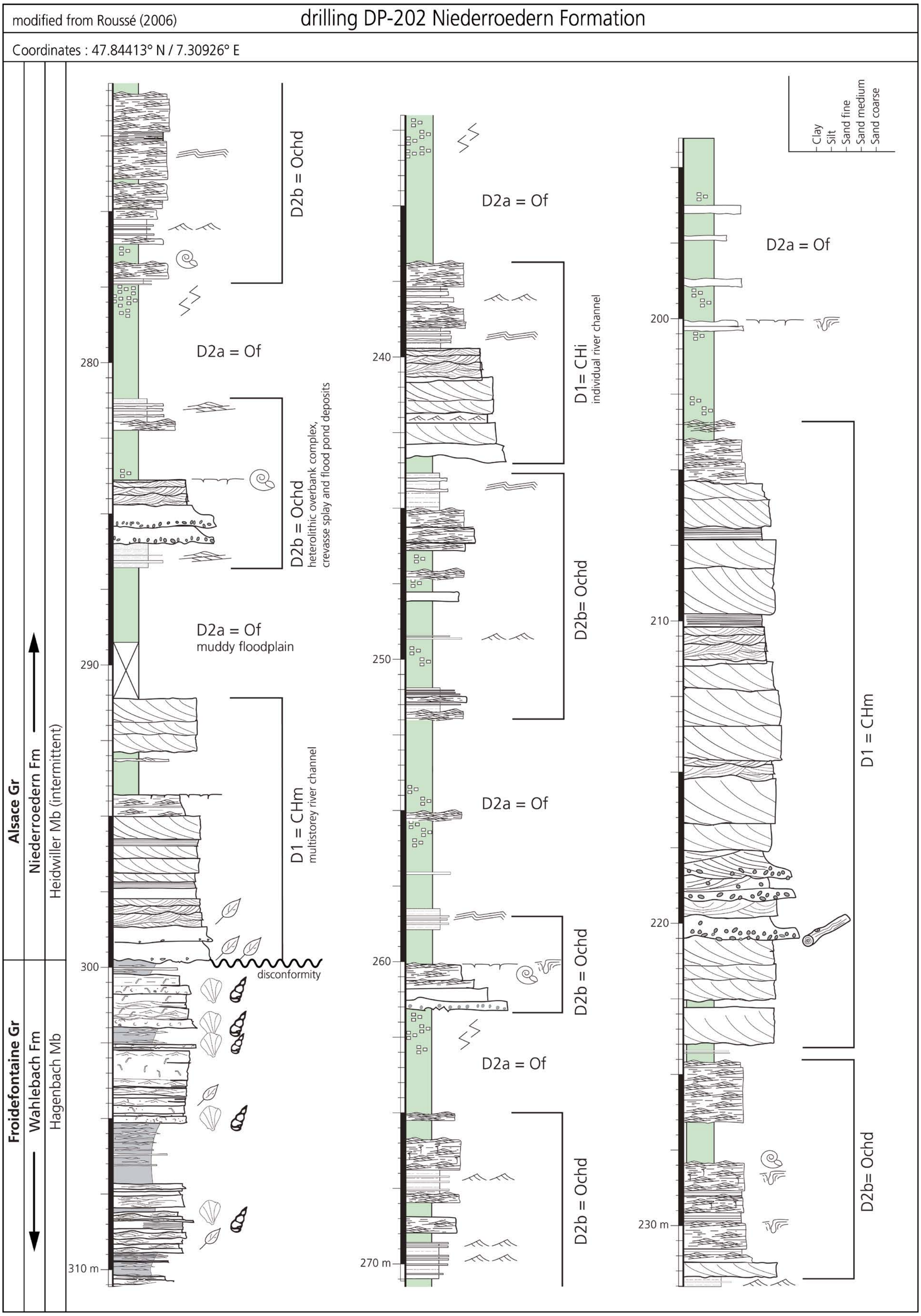


Fig. 35 - Reference section of the lower part of the Niederroedern Fm in drilling DP-202. Note the intermittent nature of the Heidwiller Mb (migrating single- and multistorey river channel facies). Abbreviations D1-2 explained on figure. The green colour represents a shift to floodplain marl deposition.

ed to the Niederroedern Fm (including "Elsässer Molasse", "Tüllingen-Schichten").

6.16.2 Definition, distribution and thickness

In the southern URG a succession of alternating beige coarse cross-bedded river channel sandstones and finer crevasse splay sands as well as green, red and black floodplain marls. While the former deposits are predominant in the lower part of the formation in the southern and middle URG (Heidwiller Mb, see below), the latter sediments seem to prevail in the upper part of the formation and further north in the URG (Berger et al. 2005a b). According to van Werveke (1918) the sandstones are absent in drilling Niederrödern, but dominant in the lower part of drilling Bienwald 9. Locally lacustrine limestones and lignites may be intercalated (e.g. Bernolsheim, middle URG; Schnaebele 1948). Southeast of the Delémont and Laufen subbasins a lacustrine limestone intercalates in the middle part of the formation (Baumberger 1927; see discussion below).

According to Doebl (1970) and Grimm et al. (2011b) the Niederroedern Fm is of highly variable thickness of up to 600 m. Van Werveke (1918) cites a thickness of 330 m for drilling Bienwald 9.

6.16.3 Type, reference and classic localities

Grimm et al. (2011b) indicate that the original type localities (two drill cores) were never described in detail. A log description is indeed missing in van Werveke (1918), where the name "Niederrödener Schichten" gets established. Since no extensive surface outcrops of the Niederroedern Fm exist, Grimm et al. (2011b) assign ad interim the log of the drilling Rheinzabern 3 as type section.

The river channel dominated facies of the lower part of the formation is illustrated under Heidwiller Mb below (Fig. 36-38). Part of the facies dominated by floodplain marls has been documented in drilling DP202 (Fig. 35).

6.16.4 Differentiation from other units

The massive river channel sandstones and intercalated coloured floodplain marls at the base of the Niederroedern Fm lie unconformably (Fig. 35, 38) on the deltaic, tidally influenced sandstones of the Courroux Mb (see 6.14) or the grey marls and sandstones influenced by wave action and unidirectional currents of the Hagenbach Mb (see 6.11). The unconformity and change in marl colour is observable in several cored drillings and always concides with a negative amplitude in gamma-ray logs (Roussé 2006).

The upper limit of the Niederroedern Fm in most parts of the southern URG is characterised by a widespread post-Chattian erosion and/or non-deposition (except for the Rhine river system). Only in the southernmost and southeasternmost parts of the URG the Late Chattian to Aquitanian lacustrine limestones and marls of the Tüllingen Fm (5.3) either conformably overlie the Niederroedern Fm (Koch 1923; Liniger 1925; Baumberger 1927; Schneider 1960; Picot 2002; Becker 2003; Berger et al. 2005a, b; Roussé 2006), or are partly coeval to the latter (Wittmann 1950).

In the Delémont subbasin the Niederroedern Fm is discordantly overlain by either Miocene conglomerates and coarse sandstones of the OMM (Liniger 1925; LLS 2014) and the fluviatile red marls and conglomerates of the Bois de Raube Fm (Kälin 1997). Further to the north the much younger Pliocene "Sundgau-Schotter" (gravels; Grimm et al. 2011b) of Alpine provenance were deposited on the Niederroedern Fm.

Grimm (2005) and Grimm et al. (2011b) define a calcareous sandstone bed bearing marine fossils as lower boundary of the Niederroedern Fm (in the area between Karlsruhe and Strasbourg). This bed however is not present in the northern (ibid.) and southern URG, and hence may be separated as regional member in its type area.

Coeval sediments (e.g. "untere bunte Mergel") of the distal USM in the NAFB are generally quite similar in lithology, since they were deposited by the main branch of the same palaeo-drainage system (Berger et al. 2005a, b; Berger 2011).

In terms of correlative issues the so-called "Matzendörferkalke" or "Mittlerer Süsswasserkalk" sensu Baumberger (1927) and "Calcaires à *Helix rugulosa*" (sensu Rollier 1898) that are based on occurrences further to the southeast in the Mümmliswil and Welschenrohr-Balsthal syncline need to be discussed. Baumberger (1927) subdivides the "Glimmermolassen" (approximately equivalent to Niederroedern Fm and part of the Wahlebach Fm) in six main units, of which the aforementioned limestone lies in the middle part and ranges from the area around Basel and the Delémont subbasin to the Swiss Molasse Basin. However already Liniger (1925) does not indicate an "intermediate" lime-

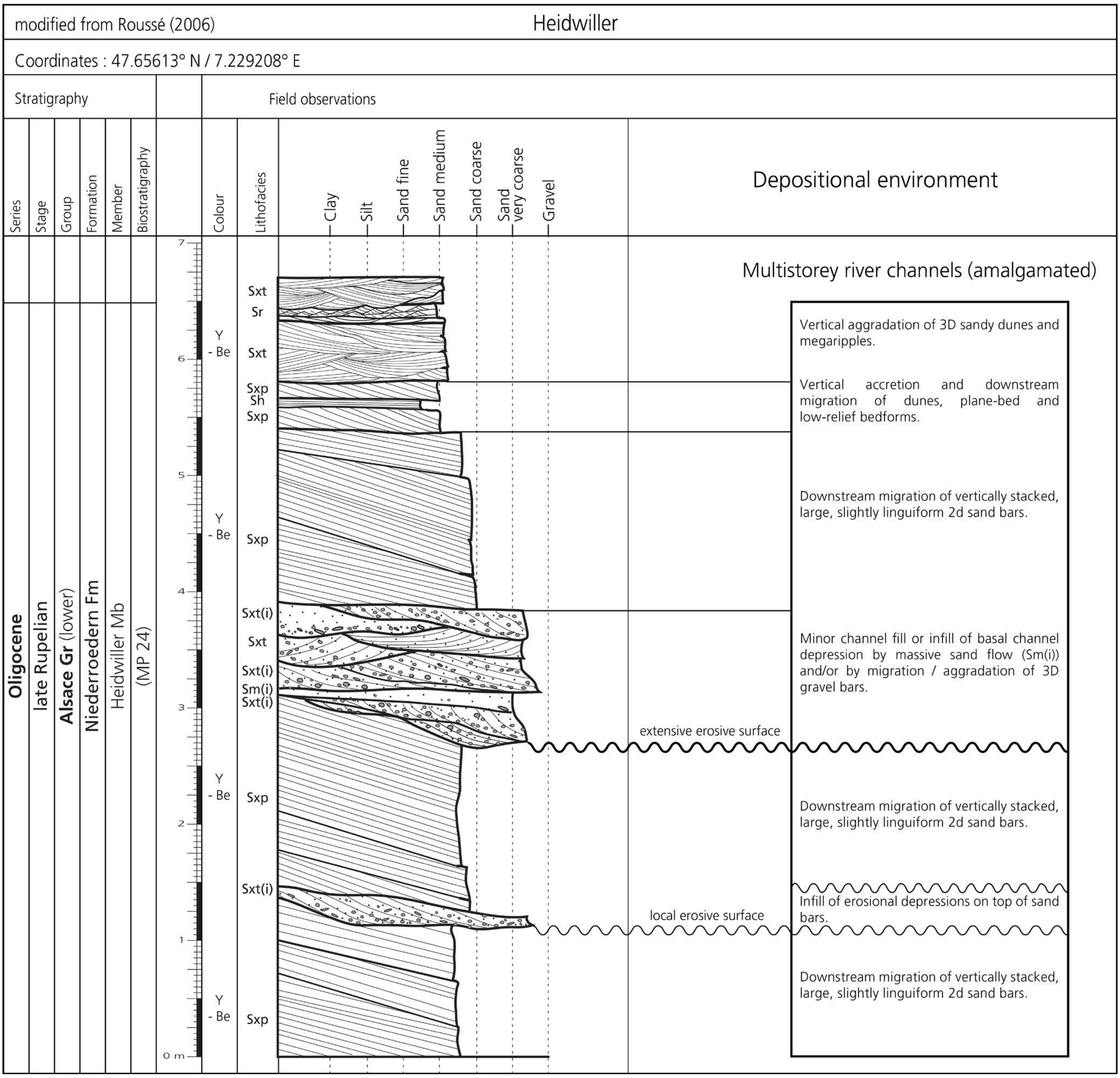


Fig. 36 - Type section of the Heidwiller Mb.

stone bed between the base of the formation and the overlying Tüllingen Fm ("Calcaires delémontiens") for the Delémont subbasin. The correlation of the "Matzendörferkalk" with the local freshwater limestone below the Therwil Mb (ex Cyathulabank s.s.) near Basel is rendered obsolete by newer biostratigraphic data (MP26 vs. MP22 respectively; Engesser & Mödden 1997; Picot 2002; Becker 2003). This confirms however the intermediate position of the "Matzendörferkalke" in its type area (correctly indicated in Becker 2003), since the "Oberer Süsswasserkalk" sensu Baumberger (1927) (now Tüllingen Fm, see 6.18) straddles the Paleogene-Neogene boundary (MP29-MN1; e.g. Picot et al. 1999). On the new geological map sheet "Balsthal" the occurrence of the "Matzendorf-Süsswasserkalk" is now restricted to the Welschenrohr-Balsthal syncline and the use of "untere, mittlere, obere Süsswasserkalke" was rendered obsolete (Bläsi et al. 2015).

The attribution of other scattered local lacustrine limestone beds in the southern URG that have been cited and correlated in older literature (e.g. Kilian 1884) remains dubious due to a lack of biostratigraphic data and newer lithostratigraphic analyses.

6.16.5 Age and fossil content

As has been outlined above the contact of the Wahlebach and Niederroedern Fm in the southern URG and the adjacent subbasins displays a heterochronous development, with an implied, progressively younger age of the boundary towards the north and west. The lowermost part of the formation has been pinpointed by a small mammal assemblage to biozone MP24 (Becker et al. 2013a) in the Delémont subbasin. A small mammal tooth from the middle of the formation in drilling COM990-F5 (Delémont subbasin centre) allows a tentative correlation with small mammal biozone MP27-29 (Weidmann 1990; Becker 2003).

The coeval "Süsswasserschichten" in the Mainz Basin (now part of the Sulzheim Fm, Fig. 40) have also been attributed to biozone MP24 (Mödden et al. 2000; Grimm et al. 2011a).

In the Delémont subbasin near the village Courrendlin remains of larger vertebrates from the Heidwiller Mb have been documented just above the disconformity to the Courroux Mb. These include a skull of the rhinoceros *Molassitherium delemontense* (Becker et al. 2013a) and a not yet described large terrestrial turtle.

Freshwater and terrestrial molluscs are recorded from the marls intercalated in the Heidwilller Mb on the Birs River outcrops (Greppin 1870, Rollier 1910, Baumberger 1927). Microfossils in the southern URG consist of (partly) very abundant charophyte oogonia in marly sediments, few fish otoliths, freshwater ostracods and in the more sandy marls some reworked Late Cretaceous and Eocene planktic Foraminifera (Schwarz 1997; Pirkenseer & Berger 2011; Pirkenseer et al. 2010, 2011, 2013).

6.17 Heidwiller Mb

6.17.1 Synonomy

- partim Grès à feuilles (Delbos & Köchlin-Schlumberger 1867)
- Blättersandsteine von Dornach, Sandsteine über der Schicht mit Ostrea cyathula (Gutzwiller 1893)
- (partim) Elsässer Molasse / Elsässermolasse (Koch 1923, Buxtorf & Christ 1936, Fischer 1965, Grimm et al. 2011b, LGRB 2011)
- partim Glimmermolassen (Baumberger 1927)
- partim Molasse alsacienne (Sittler 1965)
- USM / Molasse alsacienne s.l. (Clément & Berger 1999)
- Molasse alsacienne supérieur / s.s. (Picot 2002, Becker 2003)
- partim Molasse alsacienne (Sittler 1992, Berger et al. 2005a,b)
- Molasse alsacienne continentale (Roussé 2006)

6.17.2 Definition, distribution and thickness

Greenish to yellowish middle to coarse-grained sands of multistorey or single river channel deposited as massive bundles, as vertical aggradation of megaripples or planarly cross-bedded migrating sandbars. At the base of channels and beds commonly accumulations of mud pebbles or fragments of bank collapses (up to 50 cm), wood fragments and caliche nodules. Fine to medium sands deposited either in planar bedding as sheet flows or as asymmetrical ripples in a crevasse splay context. Green, red or black floodplain marls with subordinate marly limestones of shallow or temporary lakes. For more details see Roussé (2006).

The predominantly coarse clastic Heidwiller Mb seems to be restricted to the southern URG (Berger et al. 2005 a, b, Roussé 2006), which is reflected in the geographical restriction of the classic sand-dominated "Elsässer Molasse" in the literature (most recently Grimm et al. 2011b). Due to its depositional environment it represents a highly diachronous and disjunct member distributed throughout the Niederroedern Fm, with decreasing frequency towards the top of the latter.

The Heidwiller Mb in the southern URG in drilling DP202 is intermittently developed and reaches 5-20 m thickness (Fig. 35). In the Delémont subbasin in drilling COM990-F5 more than 35 m (truncated by Quaternary deposits; Weidmann 1990) have been recorded (Fig. 10). The thickness of the "Molasse alsacienne" in the Delémont subbasin reaches a maximum of about 200 m according to Liniger (1925), with a dominance of the sandstones of the Heidwiller Member (150 m sandstones, 50 m floodplain marls).

6.17.3 Type, reference and classic localities

The member is named after a 7 m thick section of migrating river channel sandbars near the village Heidwiller (approx. 47.65613° N / 7.229208° E, Fig. 36). The type section is located in drilling DP202 (204.0 to 299.75 m; 47.8441323° N / 7.30926536° E, Fig. 35). A further outcrop of about 8 m of yellowish sands, silts and discontinuous sandstone beds without obvious sedimentary structures on the north face of the Wessenberg (approx. 47.51106198° N / 7.45602613° E) between the villages Liebenswiller and Hagenthal-le-Haut may tentatively be attributed to the Heidwiller Mb (Pirkenseer et al. 2010).

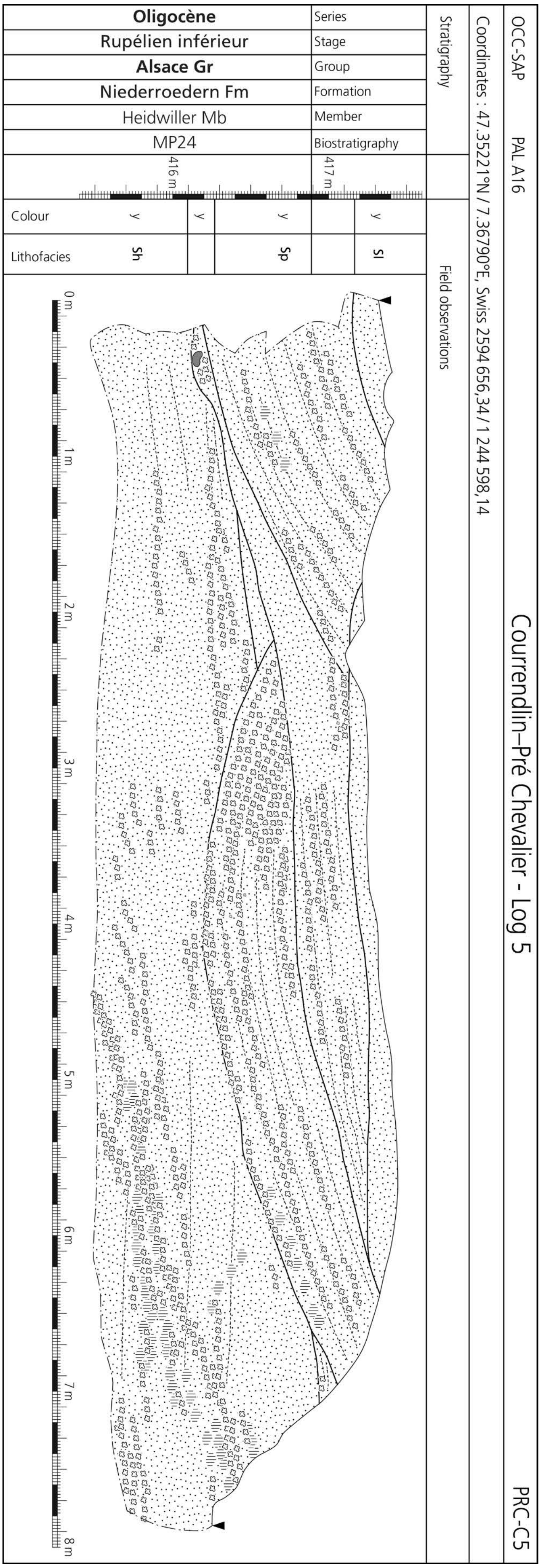


Fig. 37 - Lateral detail section in the Heidwiller Mb at Pré Chevalier south of Delémont (Switzerland). Note the internal bedding of individual, partially eroded channel fills traced by caliche nodule arrangement.

In the Delémont subbasin several lateral detail sections of the lower part of the Heidwiller Mb were elaborated at the site Le Poillat (CRD-POI; 47.35216° N / 7.369895° E, Fig. 37-38), showing cross-bedded river channel sandbars.

6.17.4 Differentiation from other units

The river channel sands discordantly overly the Wahlebach Fm. Roussé (2006) indicates a widespread erosional unconformity at the base of the Heidwiller Mb. This unconformity could be observed at the locality Courrendlin-Poillat, where the palaeoriver cut down more than 1.5 m into the underlying marly sands of the Courroux Mb (Fig. 38). Best indicators for passing from the Courroux Mb into the Heidwiller Mb are the presence of abundant mud pebbles and caliche at the base of individual bedforms and the less common plant fragments.

The Heidwiller Mb represents a discontinuous unit, which may occur repetitively on several levels within the main Niederroedern Fm and intercalates with the dominant coloured floodplain deposits of the latter. The Heidwiller Mb however always constitutes the first deposits overlying the Courroux Mb, with decreasing occurrences northwards (due to reduced gradient when entering the sedimentary basin of the URG). Towards the south in the Delémont subbasin the Heidwiller Mb represents the dominant facies of the Niederroedern Fm (80 m sandstones, 20 m coloured marls; Liniger 1925). In the Ajoie subbasin only part of the Heidwiller Mb seems to be present, with the remainder of the Niederroedern Fm apparently eroded (Schneider 1960).

Historically a lacustrine gastropod bearing marl bed called “Marnes noires” (“black marls”) has been recognised within the Niederroedern Fm of the Delémont subbasin on the River Birs bank near Courrendlin (e.g. Greppin 1870; Liniger 1925; Baumberger 1927; Picot 2002). These marls represent a laterally limited facies variation of the Niederroedern Fm floodplain deposits and may represent the dysoxic sediments of a larger ephemeral pond and lake. According to Liniger (1925) these marls lie between two larger sandstone beds, hence indicating an interfingering of the floodplain deposits within the Heidwiller Mb. Accordingly the lithostratigraphic term "Marnes noires" is rendered invalid.

6.18 Tüllingen Formation (ex Calcaires delémontiens, Tüllinger Kalk) (Fig. 39)

6.18.1 Synonomy and generalities

- Süsswasserformation am Dillinger Berg (Merian 1821)
- partim Delémontien: assise supérieur (Greppin 1870)
- Süsswasserkalk von Tüllingen (Gutzwiller 1893)
- (Groupe des) Calcaire(s) delémontien(s) (Rollier 1893a, b, 1910, Picot et al. 1999, Picot 2002, Becker 2003)
- Delémontienkalk, Süsswasserkalk von Wannematt (Koch 1923)
- Obere Süsswasserkalke (Baumberger 1927)
- Delsbergerkalk(e) (Liniger 1925, Baumberger 1927)
- Süsswasserkalk(e) vom / am / des Tüllinger Berg(s) / Tüllingerberg (Andreae 1884, Wurz 1912, Gutzwiller 1914)
- Tüllinger Kalk(e) / Tüllingerkalk (Andreae 1884, Baumberger 1927, Wittmann 1950, 1965, Doebl 1970)
- Tüllinger Süsswasserschichten: Kalkfazies (Fischer et al. 1971)
- Tüllingen-Formation (Grimm 2005, Grimm et al. 2011b)
- partim (Groupe des) Couches d'eau douce carbonatées (Sittler 1992, Roussé 2006)
- Tüllingen-Schichten [subformation] (LGRB 2011)
- partim Niederroedern Fm (DSK 2016)

The definition of this formation has been outlined in detail in Grimm (2005) and Grimm et al. (2011b). Wittmann (1965) also gives a detailed overview on the stratigraphy and older literature. In the research area the formation has historically been termed as "Calcaire(s) delémontien(s)". The Tüllingen Fm was ranked down to a subformation / member in LGRB (2011) due to interfingering with the Niederroedern Fm.

6.18.2 Definition, distribution and thickness

In its type area the Tüllingen Fm consist of an alternation of white to grey or brown, rarely black (bituminous) massive lacustrine limestones containing macrofossils and intercalated coloured calcareous marls. The so-called basal "Gipsmergel" near Tüllingen represents a facies variation of the Tüllingen Fm (Wurz 1912; Fischer et al. 1971). Wittmann (1950, 1965) detected seven lacustrine transgression-regression cycles. In the upper part of the formation the frequency of beds with high organic matter content increases (ibid.). Baumberger (1927) mentions a pronounced lateral variability in lithology and thickness, but correlates the occurrences near Tüllingen with localities further to the south and southwest ("obere Süsswasserkalke"). North of Mulhouse the formation similarly consists of an alternation of (partially) gypsiferous palustrine / lacustrine marls and limestones (Roussé 2006).

The Formation occurs in most parts of the investigated area south of the line between Tüllingen and Roppentzwiller and is still present in the southernmost synclines of the central Jura (Baumberger 1927, Picot et al. 1999). It is largely absent in the Ajoie, except for a small relict in its southwesternmost part (Schneider 1960). According to core logs the formation reappears north of Mulhouse (Roussé 2006). Its thickness varies from 15 m in the Delémont subbasin (Liniger 1925; Picot et al. 1999) over 50 m in the Brochene Fluh section (Baumberger 1927; Becker et al. 2002; Picot 2002) to more than 150 m at the Tüllingen Hill (Wurz 1912; Wittmann 1950, 1965). Thicknesses of at least 100 m are recorded in core logs north of Mulhouse ("Couches d'eau douce carbonatées"; Roussé 2006).

The analysis of drilling DP207 (at the latitude of Freiburg i.Br.) revealed a superposition of some 280 m of lacustrine marls and limestones on the Niederroedern Fm (Roussé 2006).

6.18.3 Type, reference and classic localities

The most prominent and well-known localities include (historical) outcrops around the Tüllingen Hill (Wurz 1912, Wittmann 1950, 1965; approx. 47.60420° N / 7.639854° E) near Lörrach and the Brochene Fluh section (Baumberger 1927; Schlunegger et al. 1996; Becker et al. 2002; Picot 2002; 47.37852° N / 7.72957° E) near Waldenburg. A type section was designated in Grimm (2005) near the summit of the Tüllingen Hill (47.609885° N / 7.633896° E), whereas the reference section for the base of the formation is located close to the railway tunnel entrance near Lörrach-Stetten (47.597658° N / 7.647977° E). For an overview of drill cores documenting the Tüllingen Fm north of Mulhouse consult Roussé (2006).

Further (historic) outcrops in the Jura area are listed in Rollier (1910), in more detail in Baumberger (1927), and for the Delémont and Laufen subbasins in Liniger (1925) and Koch (1923) respectively.

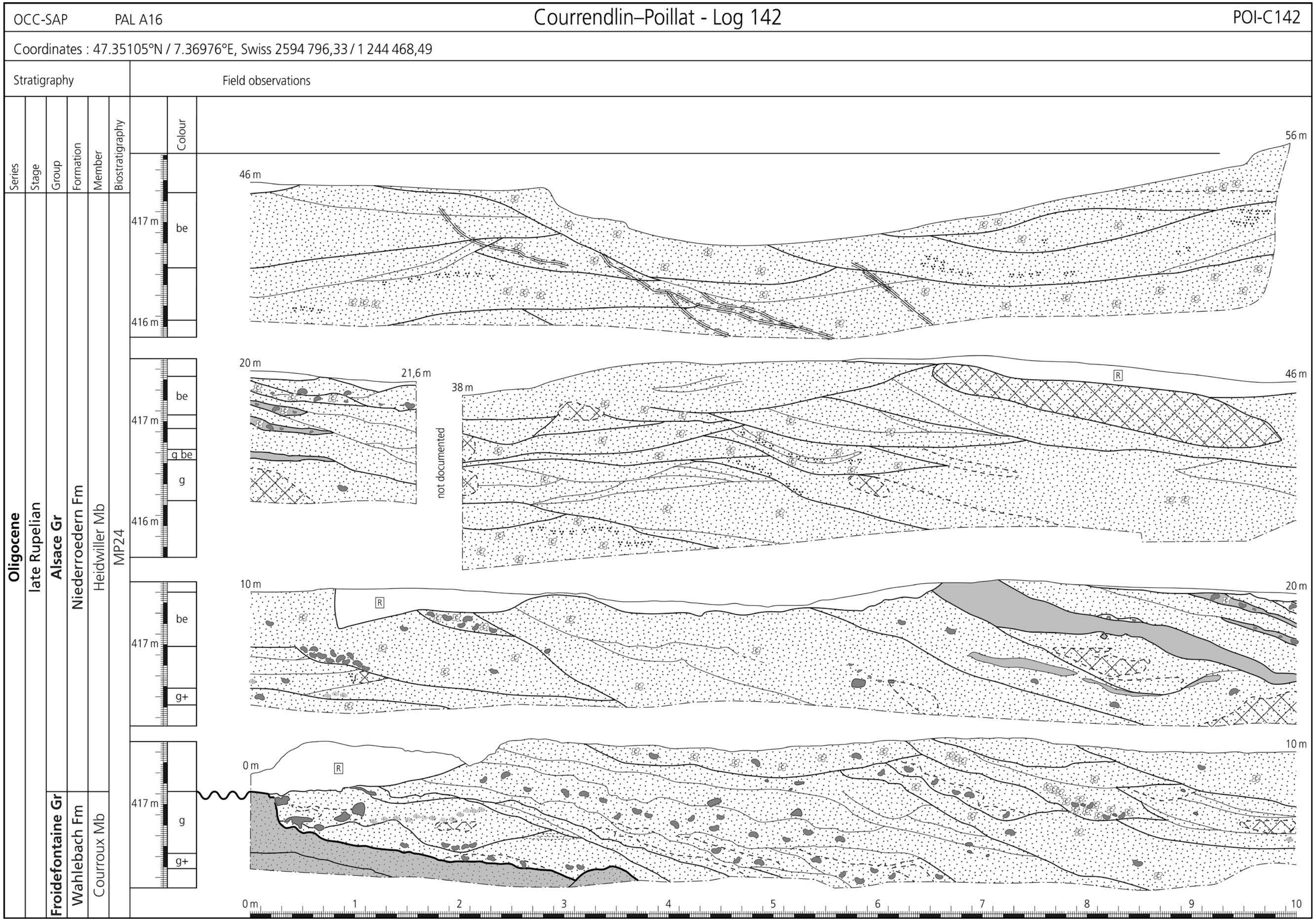


Fig. 38 - Lateral detail section in the Heidwiller Mb at Le Poillat south of Delémont (Switzerland). Note the incised channel in part 0-10 m in the underlying Courroux Mb. Large mud clasts in part 10-20 m possibly indicate nearby banc collapses of flood plain deposits.

6.18.4 Differentiation from other units

The top of the formation remains unknown in most of the investigated area due to the regional post Chattian hiatus. The generally light-coloured limestones of the Tüllingen Fm either were deposited conformably on or partly as coeval sediments of the underlying coloured marls or sandstones of the Niederroedern Fm (e.g Delémont subbasin, Tüllingen Hill) or discordantly on the Jurassic substratum (e.g. Brochene Fluh section). At the Tüllingen Hill the limestone beds seem to pinch out towards the north (Wittmann 1950). North of Mulhouse the bottom of the formation consist of a group of lower limestone beds, a thick interval of gypseous coloured marls and an upper limestone bed followed by some limestone bearing coloured marls (Roussé 2006). A further distinguishing criterion of the Tüllingen Fm is the complete absence of river channel and crevasse splay sandstones characteristic for the underlying Niederroedern Fm. This change represents a shift form a fluviatile to a predominantly lacustrine depositional environment.

Grimm et al. (2011b) regard the occurrences around the Tüllingen Hill as unique, but consider the "Calcaires delémontiens", "Matzendörfer Kalk" etc. as lateral equivalent of the 7 limestone beds of the type locality (see age discussion below). Despite the disjunct actual distribution we consider these occurrence to represent parts of the same formation. Further investigations of drill cores are needed to determine the grade of interfingering with the Niederoedern Fm.

6.18.5 Age and fossil content

Based on the occurrence of charophyte oogonia and the gastropod *Wenzia ramondi* (formerly *Helix ramondi*) Grimm et al. (2011b) attribute the Tüllingen Fm to the lower to middle Chattian. Contrarily the Tüllingen Fm ("Kalkfazies") has been correlated with biozone MP29 (reference level Brochene Fluh 19/20) at Basel St. Jakob (Engesser & Mödden 1997) based on small mammal remains.

This is more in line with the general biostratigraphic correlation (MP29-MN1) of the formation in the Jura assembled in Picot (2002). Based on the record of small mammals adhering to biozones MP29-30 in the aforementioned Brochene Fluh section the interval of normal polarity in the middle part of the section has been correlated with chron 6Cn.3n (Schlunegger et al. 1996). The attribution of the upper part of the Brochene Fluh section to biozone MN1 (lowermost Miocene) based on the occurrence of the charophyte taxon *Lychnothamnus praeberdotensis* has been discussed in Picot et al. (1999) and Picot (2002), since magnetostratigraphy and fish otoliths give opposing results. The forthcoming explanatory note for the map sheet "Hauenstein" (Bläsi et al. 2018; review comm. Daniel Kälin) restricts the entire Brochene Fluh section to the Chattian. The Humbel section east of Waldenburg however yielded a small mammal assemblage correlated to biozone MN1 (Engesser 1990; Engesser & Mödden 1997).

A section near Courfaivre (Delémont subbasin) and a drill core near Reconvilier (Tavannes synclinal) documenting corresponding lacustrine limestones correlate to the *Chara notata* charophyte biozone similar to the Brochene Fluh section (Picot et al. 1999; Picot 2002).

Terrestrial and lacustrine gastropods represent the most common macrofauna. Wurz (1912) indicates a poor preservation and diversity of the latter in the type area. In the Jura the diversity seems to be slightly higher, when consulting the lists of molluscs cited in Greppin (1870) and Rollier (1910). A recent systematic investigation of the macrofauna (and partly the microfauna) is still missing.

The microfauna and –flora has been analysed in detail for the Brochene Fluh section and consists of abundant charophyte oogonia, freshwater Ostracoda and fish otoliths (Picot 2002; Schäfer 2002) as well as small mammal teeth (Engesser 1990; Engesser & Mödden 1997).

7 Overview and status of early groups in the Upper Rhine Graben

A pronounced discrepancy is evident when comparing the status of lithological units in Grimm et al. (2011b) and LGRB (2011) (Fig. 7). The latter treats the entire, lithologically highly variable Cenozoic graben fill as one group ("Oberrheingraben-Tertiär") and demotes all pre-Ru2 transgression sediments (below the Lörrach and Wallau Fms; see 6.6, 6.7) to the "älteres Oberrheingraben-Tertiär" subgroup. These pre-Ru2 formations are in contrast comprised in the Pechelbronn, Haguenau and Oberrhein Groups sensu Grimm (2005) and Grimm et al. (2011b). The

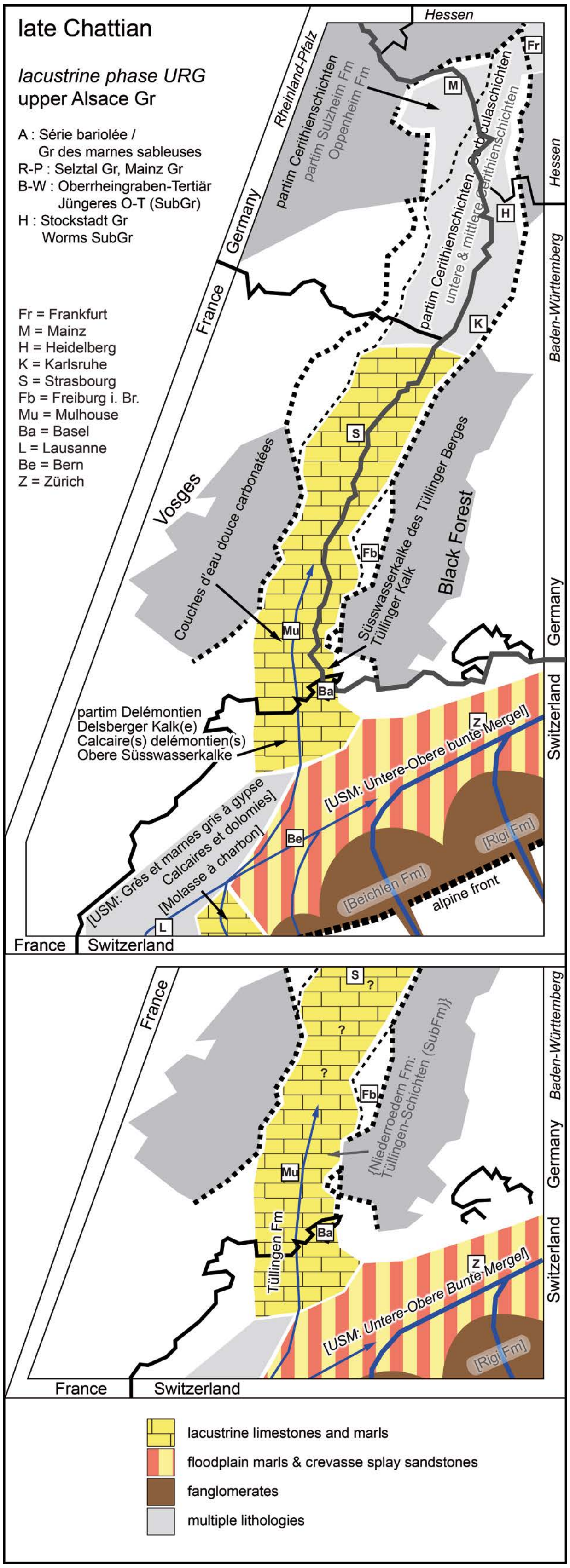


Fig. 39 - Late Chattian palaeogeographic representation of major facies and regional lithostratigraphic terms (updated from and based on maps in Berger et al. 2005b). Top of the figure represents the formerly used most common terms, lower part the status after revision and simplification.

most recent stratigraphic table (DSK 2016) follows the scheme outlined in LGRB (2011), but is not entirely identical.

The Oberrhein Group (Fig. 7) pools the Sidérolithique and the Turckheim Fm (see 6.3), two units of dissimilar tectonosedimentary context. Accordingly we consider this group to be invalid. For the Swiss Helvetic Palaeogene Menkveld-Gfeller et al. (2016) erect a "Siderolithikum-Gruppe" to encompass the formerly informal terms "Bohnerzformation", "siderolithische Brekzien" and others, but without designation of formal members or formations. Further international cooperation is needed to establish a consensus on possible type localities. For the time being the Sidérolithique remains ungrouped in the research area.

The Haguenau Group sensu Grimm et al. (2011b) includes the disjunct Bouxwiller Fm, the "Grüne Mergel" and the "Rote Leitschicht" and is overlain by the tripartite Pechelbronn Group. LGRB (2011) follows a similar arrangement except for a different status of units, but adds the coeval Wittelsheim Fm grouping the sediments dominated by evaporates in the basin centre (Fig. 43). The scheme presented in DSK (2016) extends the Pechelbronn Fm to replace the Haguenau Fm in the southern URG, but sustains the Haguenau Fm in the northern URG and the "Grüne Mergel" in the Mainz Basin (Fig. 40).

In our opinion the status of the formations within Haguenau Group sensu Grimm (2005) and Grimm et al. (2011b) is justified since they are based on discrete lithologies. The subdivision of the Pechelbronn Group is mainly apparent in its palaeontological and palaeoecological context, but less so in a lithological aspect. According to Grimm et al. (2011b) the definition of a limit between these two groups is difficult where the "Rote Leitschicht" is missing. This potentially renders it necessary to either extend the range and definition of the "Grüne Mergel" or the "Untere Pechelbronn-Schichten", and consequently touches the validity and range of the related groups.

With regard of these remaining uncertainties we propose a single provisional group comprising all lower-ranked units of the Haguenau, Pechelbronn and Oberrhein groups sensu Grimm (2005) and Grimm et al. (2011b) except for the Sidérolithique (Fig. 40, 44), since they were depos-

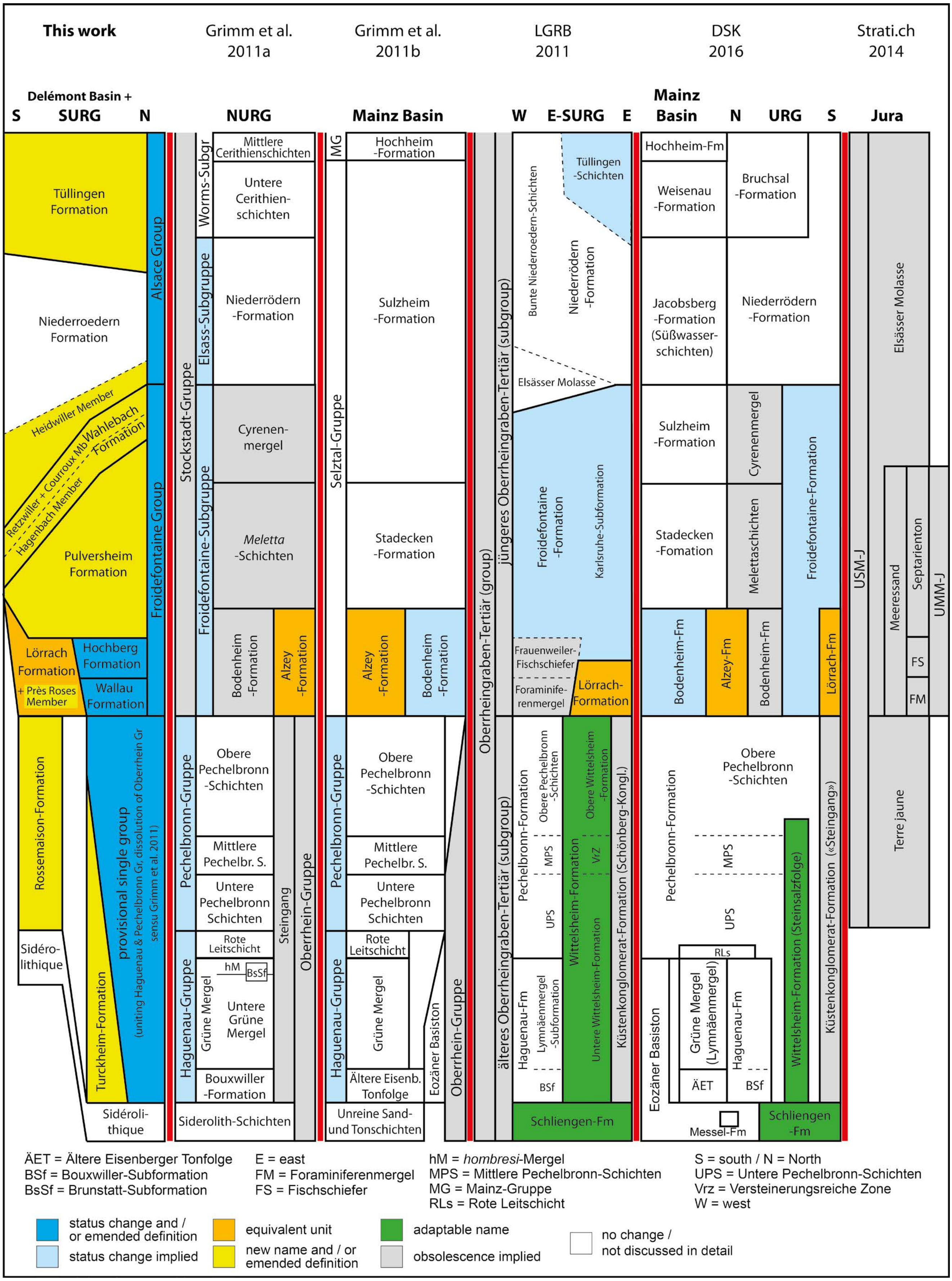


Fig. 40 - Correlation of the most recent lithostratigraphic concepts for the URG-Mainz Basin system. LLS 2014 scheme not displayed due to lack of detail and omission of units.

Fig. 41 - New data on heavy mineral suites in relation to Cainozoic lithostratigraphy in the Delémont Basin based on analysis of drilling HRT-F4 / 8 and localities VRR and POI.

ited in the same tectonosedimentary context. This group includes the isolated Rossemaison Fm (see 6.2) in the Delémont subbasin, since it adheres to similar lithological attributes.

8 Relationships between the North Alpine Foreland Basin and the Upper Rhine Graben

The provenance of the sediments deposited in the Swiss Jura and the (southern) URG was subject to diverse tectonic and sedimentary processes related to the alpine orogeny. Sedimentary evidence stems from pebble analyses, shift of heavy mineral suites through time and the presence of reworked microfossils. Heavy mineral data for the Palaeogene of the URG is scarce (e.g. Grenouillet 1926; von Moos 1935). A first more comprehensive overview in correlation with litho- and/or biostratigraphy is given in Brianza et al. (1983), Becker (2003) and Lavyoer (2013). A detailed description of the occurrence and provenance for reworked microfossils from the southern URG is available in Fischer 1965a; Pirkenseer et al. (2010) and Pirkenseer et al. (2011).

8.1 New (heavy) mineral data from the Delémont subbasin

Heavy mineral suites from the drillings HRT-F4 & 8 as well as the outcrops VRR and POI are summarized in Fig. 41. While the "Huppersand" represents a depositional facies of the highly variable Sidérolithique complex, both their obvious macroscopic sedimentology and their mineral content differ significantly in drilling HRT-F8. The most common minerals of the "Huppersand" consist of garnet (G), apatite (A) and tourmaline (T), with important secondary and accessory minerals topaz, staurolite (S), zircon (Z) and rutile (R). It also contains accessory minerals not present in the subsequent Sidérolithique, Rossemaison Fm and Prè Roses Mb. The Sidérolithique in the

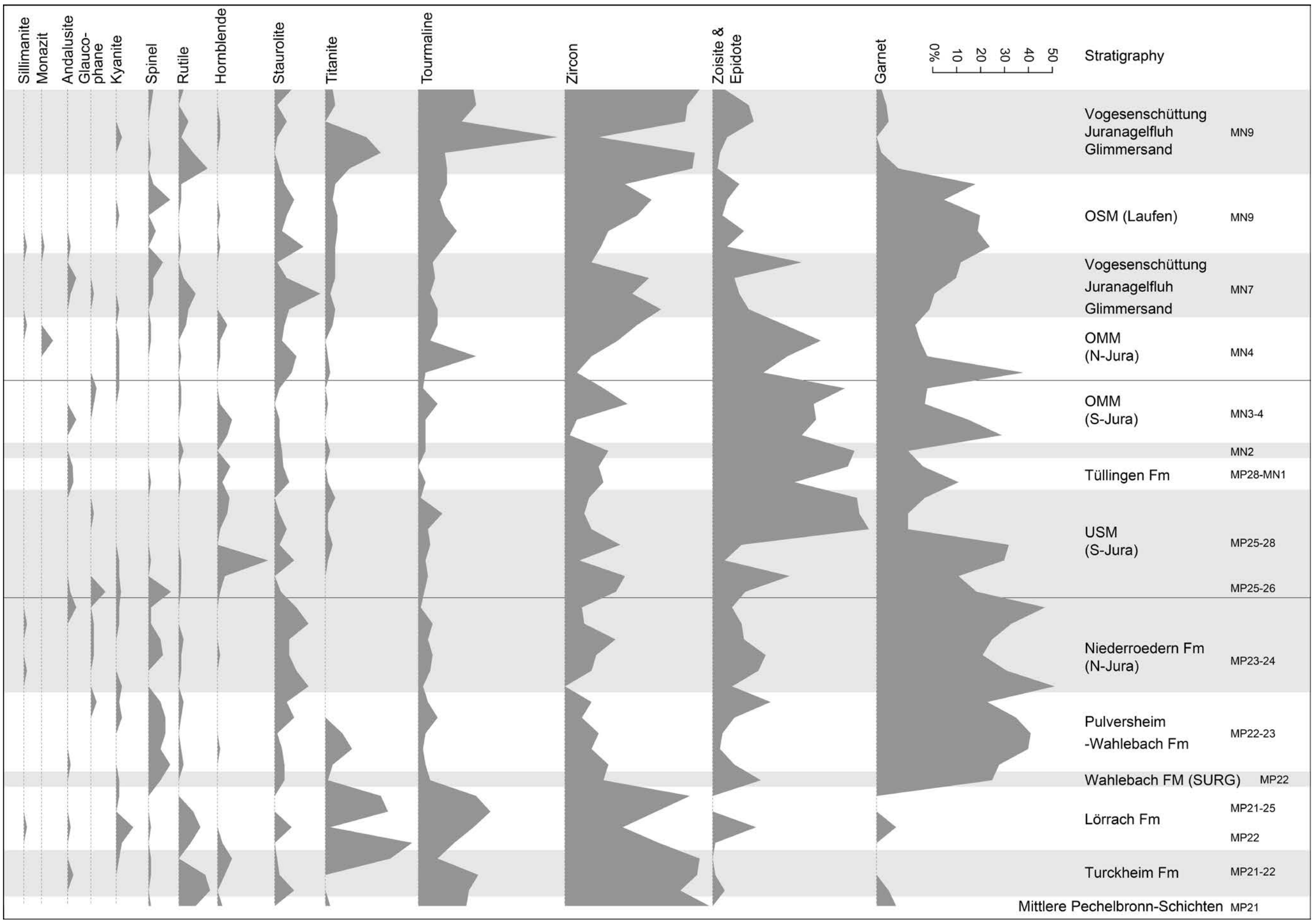


Fig. 42 - Stratigraphical succession of Cainozoic heavy mineral suites in the northern Jura and southern URG (after Becker 2003).

karst pockets of site VRR just a few kilometres to the south of drilling HRT-F8 features a nearly completely different suite, with garnet being dominant in the former and absent in the latter. The Rossemaison Fm in drilling HRT-F8 in its lower part compares roughly with the underlying Sidérolithique, however features the additional minerals apatite, garnet and staurolite. The upper part stands out due to its apatite dominance.

The entirely different depositional environment of the marine Près Roses Mb in drilling HRT-F8 still led to a heavy mineral suite remarkably similar to the Sidérolithique in dominant as well as secondary minerals as the Rossemaison Fm. The accessory minerals spinel and amphibole are absent in the Sidérolithique, Rossemaison Fm and Près Roses Mb of drilling HRT-F8.

Mica are absent or play only a very minor role in lithostratigraphic units underlying the Pulversheim Fm. With the onset of the Pulversheim Fm garnet and mica become nearly continuously dominant, apatite more common, while zircon and rutile decrease strongly. The Niederroedern Fm (including the Heidwiller Mb) continues the general trend of garnet and mica dominance. Sample HRT015-13 however shows an aberrantly high content of baryte, dolomite and mica, whereas sample HRT015-11 is conspicuous due to the absence of mica, hinting at local short-term changes in mineral sources or authigenic mineral formation.

The increase of epidote (E) coincides with the deposition of early Miocene sediments (OMM, OSM).

8.2 Discussion of (heavy) mineral data

Whene comparing our heavy mineral suites to those from the Delémont subbasin and the southern URG compiled in Brianza et al. (1983), Becker (2003) (Fig. 42) and Lavoyer (2013) several consistent trends emerge:

In all lithostratigraphic units below the

Pulversheim Fm abraded ultrastable heavy minerals like zircon, tourmaline, rutile, anatase and titanite are common or dominant (ZTR-suite), moderately stable and stable minerals are much less common. These minerals become again prominent only in the middle Miocene with the deposition of the upper part of the Bois-de-Raube Fm (see also Kälin 1997) and younger sediments.

The Sidérolithique s.l. including the "Huppersand" shows a high variability of suites.

With the onset of the Pulversheim Fm garnet becomes by far the most common heavy mineral, with more moderate increases of epidote, staurolite and spinel. Mica increase drastically.

Glaucophane is absent below the lower part of the Wahlebach Fm and spinel does not occur in the Rossemaison Fm and the Près Roses Mb.

Epidote represents a major component in the upper part of the Niederroedern Fm until the lower part of the Bois-de-Raube Fm (von Moos 1935; Kälin 1997).

Heavy mineral suites from the Sidérolithique range from a ZRT (HRT015-2), SZT (River Talent, Strunck 2001) and ST (Maurer 1983) to a GE-suite with high baryte and dolomite content (VRR005-69). The Huppersand in drilling HRT-F8 shows a puzzling similarity to the GAT-suite (including the accessory amphibole) from the Pulversheim Fm onwards except for the comparatively high content of topaz and the near absence of mica. In contrast a study of "Huppererde" and "Quarzsand" localities ranging from the Alsace to the NAFB shows relatively uniform suites dominated by a ZTR-spectrum (von Moos 1936). Von Moos (1935, 1936) favours a local origin from reworked mid-Cretaceous arenaceous sediments and similar primary deposits, a view that has been already expressed by Rollier (1910). Since topaz has been generally linked to a distant provenance in the Bohemian Massif (e.g. Allen et al. 1985; Görgen 2008), a secondary or tertiary redeposition seems indeed more likely. A secondary Cretaceous provenance of heavy minerals has also been brought forward for the Sidérolithique in Mormont (Switzerland; Maurer 1983) and the French Jura (Latreille 1969), with the latter originating from crystalline rocks of the Massif Central. Further to the north in the southern URG middle to late Triassic clastic sediments represent an important source of secondary ultrastable heavy minerals and apatite but lack any significant ratio of garnet (e.g. Eichler & Hiller 1959; Heling 1963, 1965).

The variability of the mineral suites in the Sidérolithique including the Delémont subbasin probably was induced by a variation of in-situ weathering of variable local source sediments and more far reaching transport from distant sources (garnet in VRR005-69 and HRT015-1). Fluviatile transport for "Huppersand" quartz grains from Cretaceous sources has been proposed by Aubert & Le Ribault (1974).

The continued dominance of the ZTR-suite in the Rossemaison Fm, the Pechelbronn Group and the Lörrach Fm (see also von Moos 1935) can be explained by an initially separate palaeogeographic development of the Delémont subbasin and the southern URG in the Eocene and the early to middle Rupelian, favouring a local or regional provenance of redeposited ultrastable minerals.

The abrupt shift to a GAT-suite with abundant mica takes place simultaneously with the first development of pro-delta sediments in the lower part of the Pulversheim Fm (see 6.9 and Fig. 43; Brianza et al. 1983, Becker 2003) after the transgressive (Wallau and Lörrach Fm) and highstand (Hochberg Fm) phase of the Ru2-sequence. In contrary the entire, partially coeval and older marine Flysch and UMM sediments from the NAFB feature GATZ-suites without significant composition change (von Moos 1935; Füchtbauer 1964; Maurer & Nabholz 1980). The prevalence of a GATZ-suite in the NAFB continues during the deposition of the lower part of the USM. According to Füchtbauer (1964) garnets in Molasse sediments are sourced from central alpine shists.

An alpine source is corroborated by the first record of the accessory glaucophane in the Pulversheim Fm (Grenouillet 1926; von Moos 1935; Brianza et al. 1983; Becker 2003; see Fig. 42). Glaucophane originates exclusively from the Alps south of Lake Geneva area (Füchtbauer 1964; Maurer 1983) and indicates an increasing influence of the NAFB basin-axial "Genferseeschüttung" drainage system. Glaucophane has also been documented from the lowest part of the USM in the interjacent Balsthal area (Bläsi et al. 2015). The increasing ratio of epidote in the late Chattian and the Aquitanian of the research area coincides with the development of suites in the NAFB (e.g. Maurer & Nabholz 1980; Maurer 1983).

8.3 Occurrence and source of reworked microfossils

Reworked planktic foraminifera are reported from the Rupelian and Chattian of the Mainz Basin and the southern URG (Fischer 1965a; Schäfer 2000; Schäfer & Kuhn 2004; Grimm et al. 2005). Reworked planktic foraminifera are also present in the Rupelian, Chattian and Burdigalian of the western Subalpine and Swiss Plateau Molasse (Fischer 1965; Weidmann et al. 1982; Ujetz et al. 1994). The most recent study records 18 Eocene species implying Ypresian, Lutetian and post-Lutetian source sediments and 8 Late Cretaceous taxa indicating Cenomanian, Turonian to Santonian and Campanian to Maastrichtian source rock ages (Pirkenseer et al. 2010, 2011).

Reworked microfossils appear in the URG in the lower part of the Pulversheim Fm after the initial transgressive and highstand units of the Ru2-sequence in several pulses linked to influx of coarser grained clastic sediments. They are more abundant in the Wahlebach Fm, with a gradual decrease in the lower part of the Niederroedern Fm (Pirkenseer et al. 2010, 2011).

The widespread Late Cretaceous sediments on the Helvetic shelf and adjacent areas around the Rhenish Massif (Dercourt et al. 2000) were eroded in the research area and adjacent areas to the south prior to the initial Paleogene sedimentation of the Sidérolithique (large scale buckling; Ziegler & Dézes 2005; Bourgeois et al. 2007). The latter also lies unconformably on late Jurassic to early Cretaceous deposits in the northwestern Helveticum (Herb 1988; Berger et al. 2005b), implying more southern or southeastern source rocks for late Cretaceous foraminifera (e.g. "Couches rouges", see Fischer 1965a; "Niesen-Flysch", see Ackermann 1986).

Since sediments in the URG and the northern Jura older than the Rupelian consist mainly of continental, evaporitic and/or lacustrine sediments (e.g. Berger et al. 2005a,b; Grimm et al. 2011b), an in-situ reworking of Eocene marine microfossils caused by regional synrift uplift can be ruled out. Adjacent sedimentary basins with active Eocene marine sedimentation (France, Belgium, northern Germany, and England) were not exposed to erosion in the late Rupelian (Vinken 1988) or were paleogeographically isolated (Dercourt et al. 2000; Sissingh 2006) and thus can be excluded as source areas. Despite a northwestward migration of the Helvetic shelf and the adjacent foreland bulge in the Palaeocene and Eocene (Herb 1988; Kempf & Pfiffner 2004), marine Eocene sediments were never deposited sufficiently far north as the future Swiss Jura, which accordingly could not have acted as source area for reworked Eocene material.

Marine sediments were however deposited in the future alpine realm during the Palaeocene and Eocene (e.g. Herb 1988; Stampfli et al. 1998; Menkveld-Gfeller 1995). Potential sources of Eocene planktic foraminifera include the "Grès de Samoens" (Wernli et al. 1997), the "Habkern-Mélange" (Bayer 1982) and the Stad Fm (Eckert 1963) in central to southwestern Switzerland and the western Alps (Pairis 1988). In combination with increased uplift rates due to the late mesoalpine orogeny (e.g. Sissingh 2006) in the Rupelian a southwestern alpine provenance of the reworked Eocene planktic foraminifera seems plausible.

8.4 Sediment provenance and pathways

The transport of reworked microfossils (Fischer 1965a, Martini 1990, Sissingh 2006,) and heavy minerals (Kuhlemann et al. 1999; Kuhlemann & Kempf 2002; Spiegel et al. 2007) from the alpine orogen to the URG in the Rupelian by marine currents has been proposed several times, without taking into account the precise timing of these events. The marine transport is based on the idea of a "gulf" (e.g. Rollier 1893a) or depression often dubbed "Raurachische Senke" (e.g. Baumberger 1927) linking both basins. The existence of this depression has been based on the main distribution of Cenozoic sediments in the Jura area, which indeed suggests the presence of a connecting depositional corridor. The southward extension of the URG in the early Rupelian (Delémont, Ajoie subbasins) and the late Rupelian (Laufen subbasin) may have propagated a tectonically weakened zone (but not a true graben structure) further to the south. However, Rupelian marine sediments pinch out at the southern margin of all three subbasins, hence rendering the development of a marine connection unlikely. Roussé (2006) proposed a potential narrow and shallow connection via the eastern Laufen subbasin only during the highstand (Hochberg Fm) of the Ru2 sequence, which then was quickly choked by the rapidly developing deltaic system (Wahlebach Fm) in the area.

Additionally after the initial erosion and re-deposition of source material in the depocentre of the NAFB a subsequent transport perpendicular to a southwest-northeast–directed marine axial paleocurrent system (Diem 1986) would have been mandatory for sand-sized particles to reach the southern URG (see Fig. 43). While suspension transport of reworked calcareous nannoplankton by marine currents is plausible (Martini 1990), bed-load dragging of sand-sized material seems highly unlikely between two deep, tectonically not linked basins via a narrow shallow strait over the gradient of an intermediate forebulge.

In contrast Brianza et al. (1983), Schäfer & Kuhn (2004), Roussé (2006) and Pirkenseer et al. (2011) favour a direct fluviatile transport from northwest alpine origins. The development of a vast deltaic system (see Fig. 23b, 28a) at the southern end of the URG (Roussé 2006) is the result of the overfill of the western NAFB (see also timeline of regression of the Rupelian alpine sea in Berger et al. 2005b). The retreat of the "Molasse Sea" was induced by the progressive development of vast alluvial fans on the alpine thrust front in the Swiss NAFB and a WSW–ENE directed axial drainage system ("Genferseeschüttung") already before the onset of the regressive phase of the Ru2 sequence. While the rapidly retreating alpine sea continued to be fed by axial tributaries towards the northeast, the increasing accumulation of fluviatile sediments in the southwestern part of the Swiss NAFB likely overtopped the palaeorelief of the forebulge and deviated part of the drainage system towards the southern URG following the highstand of the Ru2 sequence (Figs. 43C–2F). The striking simultaneous shift of heavy mineral suites from a ZTR to a GAT dominated suite, the first occurrence of the alpine marker mineral glaucophane and the initial record of reworked planktic Foraminifera in the lower part of the Pulversheim Fm provide a strong signal for a provenance shift from local/regional to alpine sediment sources in the URG in the late Rupelian.

8.5 The Molasse conundrum (Fig. 43)

The term "Molasse" was officially introduced in scientific literature by De Saussure (1779), and applied to USM sediments ("molasse grise", "molasses bigarrée") in the area of Geneva. An unambiguous definition however was never established. When revising literature, the general consensus seems to describe predominantly clastic sediments (marls to conglomerates) of orogenic provenance deposited in an active foreland basin. Further discussion involves the general separation of the NAFB in an older Flysch and younger Molasse Basin with the transition from marine deep-water to shallow (brackish) water deposits (e.g. Füchtbauer 1964). The introduction of the term "Molasse alsacienne" by Rollier (1893a,b, 1898) extended the definition of "Molasse" to sediments of the southern URG, an adjacent but separate tectonic basin.

This raises two questions:

Does the definition of the term "Molasse" need to be extended in the special case of the interaction of the NAFB with the URG?

Where should the nomenclature of cross-basin formations change?

The separation the NAFB in a "Flysch" and "Molasse Basin" is based on the larger tectono-sedimentary context. "Flysch Basin" describes an underfilled sedimentary basin, with the alpine wedge still advancing on the passive margin, while a "Molasse Basin" experiences accelerated widening of the foreland due to collision of the passive margin with the orogenic front and increased sedimentation rates due to the latter's faster uplift (e.g. Sinclair 1997a,b, Ziegler & Dèzes 2005), leading to a filled and/or overfilled basin.

In the past the term "Molasse" has been applied to deposits of "molassic character", but (partially) outside the foreland basin proper ("Molasse du Jura", "Molasse alsacienne"). The Rossemaison Fm for instance has been labelled as USM I / J (e.g. Berger 2011; SKS 2014), but represents a discrete local sediment in the tectonic context of the southern URG (Delémont subbasin). Similarly the subsequent Froidefontaine Group is denominated as UMM III / J (ibid.).

The special case of the proximity of the NAFB to the URG (which tectonically is not part of the NAFB) merits an extended definition of the term "Molasse". All sediments of alpine provenance outside the tectonic context of a foreland basin should not be called "Molasse" to avoid confusion. With the northwards migration of the forebulge / antikline in the early Miocene due to large-scale intraplate crustal folding (Bourgeois et al. 2007) the Jura area however gets integrated into the NAFB (e.g. Bois de Raube-Fm as part of the OSM).

Formations and groups do not stop physically at country borders and may cross tectonic bound-

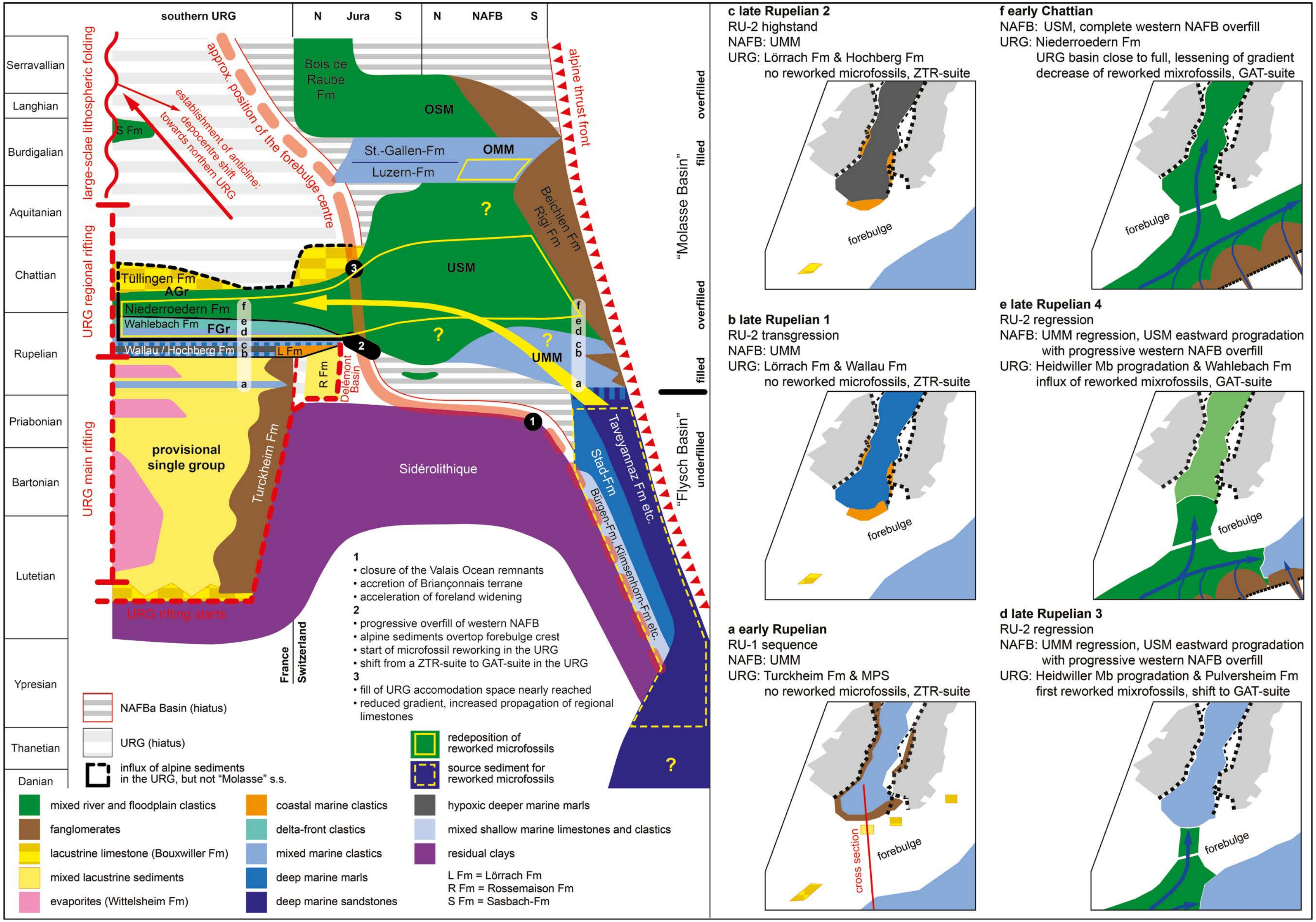


Fig. 43 - Cenozoic tectonosedimentary relationships between the southern Upper Rhine Graben and the North Alpine Foreland Basin (based on Fischer 1965a; Herb 1988; Sinclair 1997a,b; Stampfli et al. 1998; Kempf & Pfiffner 2004; Berger et al. 2005a,b; Ziegler & Dèzes 2005; Sissingh 2006; Bourgeois et al. 2007; Berger 2011; Grimm et al. 2011b; LGRB 2011; Pirkenseer et al. 2011; Strati.ch and new data).

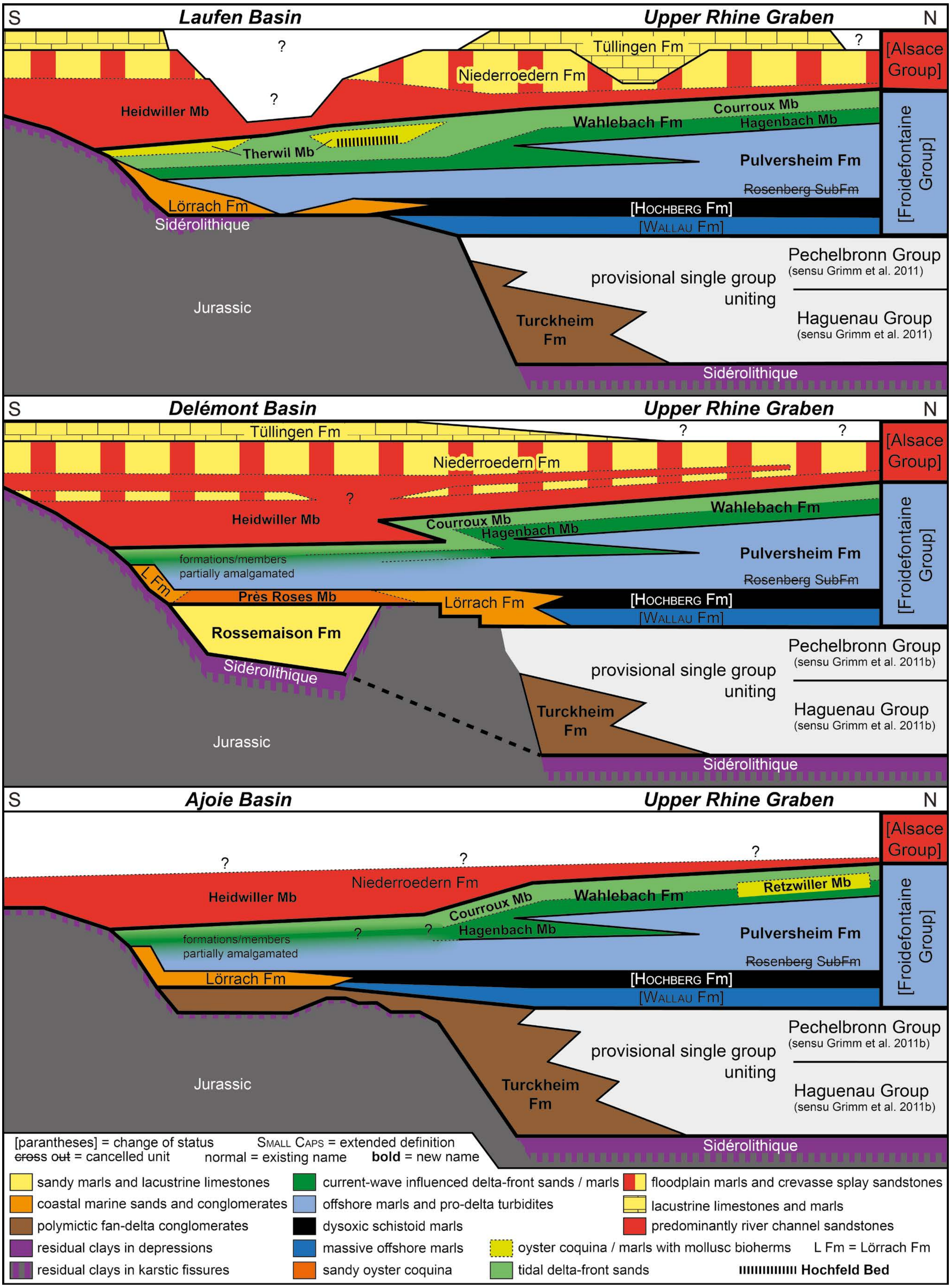


Fig. 44 - Revised schematic lithostratigraphy of the southernmost URG and the adjacent Laufen, Delémont and Ajoie subbasins (Neogene deposits of the subbasins omitted; thicknesses of individual units are not to scale, thicknesses in subbasins are strongly exaggerated).

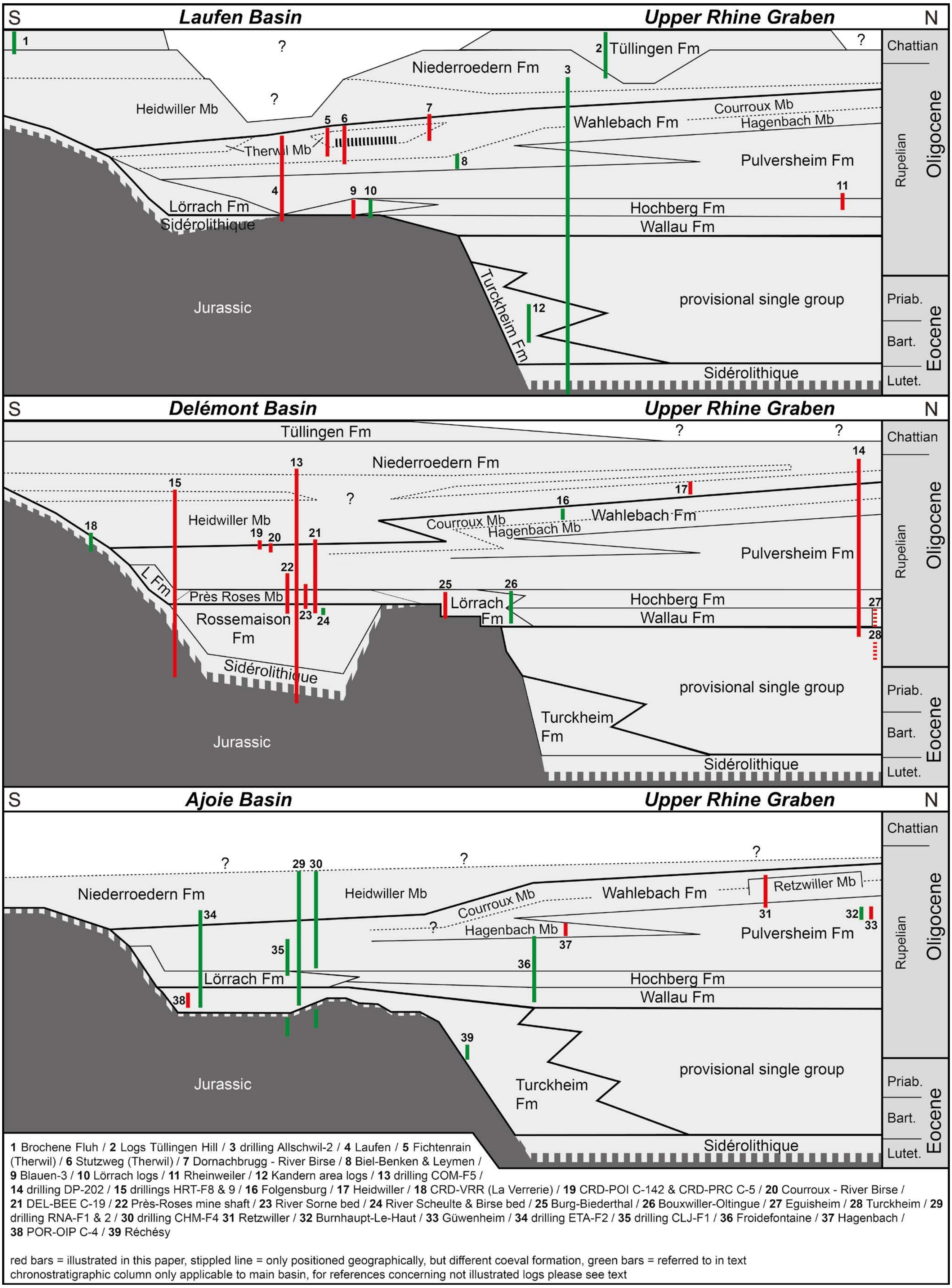


Fig. 45 - Stratigraphic extension and approximate geographic position of discussed and illustrated outcrop sections and drill logs.

aries, as is the case with the Alsace Group and the "Untere Süsswassermolasse" and their respective formations. These units share lithological characteristics and partially represent synonyms historically established in their respective basins. While the formations below the Pulversheim Fm can unambiguously be limited to the tectonosedimentary context of the URG, from the Pulversheim Fm onward only the separate tectonic attribution remains valid. Hence we propose to use the position of the forebulge as provisional limit until the nomenclatorial issues are resolved.

Further issues arise from the uncertain official status of many of these lithological units (as of 2017; see online resources of the Swiss and German stratigraphic commissions; strati.ch, litholex.bgr.de) partly due to old and insufficient definitions or delayed updates. Consequently a comprehensive definitive precedence and validity of names remains unsolved.

9 Summary and outlook

Fig. 40 shows a compilation of relevant current lithostratigraphic schemes for the URG and the Mainz Basin in relation to the revised framework of the research area (Fig. 44). Since we are dealing with ideas developed in different countries / states, partly confined by superordinate lithostratigraphic requirements (e.g. LGRB, Swisstopo), different points of view concerning the status and the naming of individual units are unavoidable. Our reasoning concerning status changes and naming differences has been outlined for the individual units described above. Here we will summarize the most important changes and their impact on recent frameworks of adjacent areas:

The Rossemaison Fm ("Gelberde", "Terre jaune"), Turckheim Fm ("Steingang", "conglomérats côtier"), Pulversheim Fm ("Melettaschichten", "Couches à Mélettes"), Wahlebach Fm (partim "Cyrenenmergel", "Marnes à Cyrènes", partim "Elsässer Molasse", "Molasse alsacienne") and the Heidwiller Mb (partim "Elsässer Molasse", "Molasse alsacienne") required renaming, status changes and/or emendation due to lack of revision, ambiguous definition and confusing nomenclature.

The Hochberg and Wallau Subfms were defined based on type sections in the Mainz Basin far to the north. Due to an ambiguous definition of the Wallau-Hochberg Fm boundary partly based on inconclusive and (bio)stratigraphically not valid benthic foraminifera assemblages an emendation based on clear sedimentological evidence was required to adapt both lithostratigraphic units to the southern URG. On the occasion of the emendation we raise both subformations to formation status since they represent units of sufficient extent and thickness to be distinctly recognizable in the field and in drill cores. Correspondingly the formerly superordinate Bodenheim Fm is rendered superfluous in the URG.

Based on the recent interpretation of the sedimentary sequence in Roussé (2006) the Rosenberg Subfm in the URG sensu Grimm et al. (2011b) is reintegrated as lowermost part in the Pulversheim Fm ("Melettaschichten").

The Lörrach Fm sensu LGRB (2011a,b) is adapted for all former "Meeressand" deposits and is considered coeval to the similar Alzey Fm in the Mainz Basin and the northern URG.

While the affiliation of the "Calcaire delémontien" to the Tüllingen Fm is still discussed in Grimm et al. (2011b), we merge the former with the latter.

The choice of a type section / locality pending, the Schliengen Fm sensu LGRB (2011) may be adapted for the not renamed "Sidérolithique" in the northern Jura and the southern URG.

While LGRB (2011) attributes the entire Cenozoic succession to a single group (Oberrheingraben-Tertiär), Grimm (2005) and Grimm et al. (2011b) endorse the use of the Oberrhein Group (Turckheim Fm and Sidérolithique) and the Stockstadt Group (including the Froidefontaine-, Elsass- und Worms Subgroup).

In our opinion the "Oberrheingraben-Tertiär" is too restricted, relegating combinations of complex lithological background to e.g. a single Froidefontaine-Formation (LGRB 2011), whereas Grimm et al. (2011b) either group formations of entirely different sedimentological and tectonical background (Oberrhein Group) or subgroups of highly diverse depositional environments (Stockstadt Group). To emend these inconsistencies we dissolve the Oberrhein Group, raise the Froidefontaine and Elsass Subgroup to group status and suspend the Stockstadt Group (which may be raised to supergroup status). The Froidefontaine Group now comprises sediments influenced by marine processes, whereas the Alsace Group is characterised by fluviatile and lacustrine depositional environments. We also propose a provisional group combining the Pechelbronn and Haguenau Groups.

A high-resolution analysis of heavy mineral suites in context of the sedimentary and micropalaeontological development of the Froidefontaine Group based on several drill cores would provide more precise information on the onset of the sediment provenance change in the Late Rupelian.

Future correlations with the Swiss Molasse Basin need to incorporated in the revised lithostratigraphic units of the URG. This revision and official approval is a work in progress conducted by the Swiss Stratigraphic Committee. As stated above, difficulties remain unavoidable when trying to find a common denominator and to overcome the respective requirements in different administrative units or scientific notions.

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