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Evidence for synsedimentary differential tectonic movements in a low-subsidence setting: Early Jurassic in northwestern Switzerland

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Abstract

During the Early Jurassic (lasting ~ 27 Myr) only thin deposits (mostly ca. 30–50 m) of the Staffelegg Formation accumulated in wide parts of NW Switzerland while sea-level rise was in the range of ~ 60 m. Isopach and facies patterns provide clear evidence of differential subsidence while faults that formed in the basement during the late Palaeozoic became reactivated. Orientation of many relative thickness minima and maxima follows faults constituting either the Rhenish Lineament or the North Swiss Permo-Carboniferous Trough. Such pattern is seen on the isopach maps of the Schambelen, Beggingen, Weissenstein, Frick, Fasiswald, Mt. Terri, Breitenmatt, Rickenbach, Rietheim and Gross Wolf members of the Staffelegg Formation, independently upon if the individual lithostratigraphic units are condensed or display somewhat enhanced thickness. Onto a general trend of decreasing thickness to the S, often isopach anomalies of small areal extension are superimposed. They suggest that localized strike-slip movements affected a mosaic of basement blocks. Reactivation of faults in the basement during the Early Jurassic is also evidenced by temporally enhanced hydrothermal activity as documented by chronometric ages of veins and mineral alterations.

Keywords Early Jurassic · Basement · Faults · North-Swiss Permo-Carboniferous Trough · Rhenish Lineament

1 Introduction

NW Switzerland is a classical region for research on Mesozoic sediments. Accordingly, Early Jurassic deposits are in the focus of sedimentological, palaeontological and stratigraphical investigations since the eighteenth century (Reisdorf et al. 2011 and references therein). The Early Jurassic sediments constitute the Staffelegg Formation (Reisdorf et al. 2011). They are often fossiliferous and consist predominantly of terrigenous argillaceous material, calcarenites and some intercalated phosphorite layers. These sediments accumulated in a shallow epicontinental marine setting being located at the transition between the SW part of the Swabian Basin and the SE part of the Paris Basin (Philippe et al. 1996; Jordan et al. 2008; Reisdorf et al. 2011). The palaeogeographic position is reflected by lithological and palaeontological similarities of chronostratigraphically corresponding deposits in NW Switzerland, SW Germany and E France (de Graciansky et al. 1998; Lathuiliere 2008; Schmid et al. 2008; Reisdorf et al. 2011). These Early Jurassic sediments comprise a chronostratigraphic timespan of 26.9 Myr (Ogg et al. 2016).

The Early Jurassic deposits of NW Switzerland, however, are reduced in thickness when compared to the concomitant successions in neighbouring SE Germany and E France (Fig. 1; e.g., Büchi et al. 1965; Bachmann et al. 1987; Lathuiliere 2008; Rupf and Nitsch 2008). In NW Switzerland, the thickness of the Early Jurassic Staffelegg Formation varies between ~ 25 and ~ 100 m (Müller et al. 1984; Reisdorf et al. 2011). However, two distinct trends in the regional thickness pattern of Early Jurassic sediments are evident: (i) the thickness of the entire Early Jurassic deposits decreases from ~ 100 m in E France to ~ 25 m in NW Switzerland; (ii) from N to S thickness decreases in SW Germany from 90 to 40 m to about 25 m in NW Switzerland (Reisdorf et al. 2011). A numerically high-resolution isopach map of the Early Jurassic deposits

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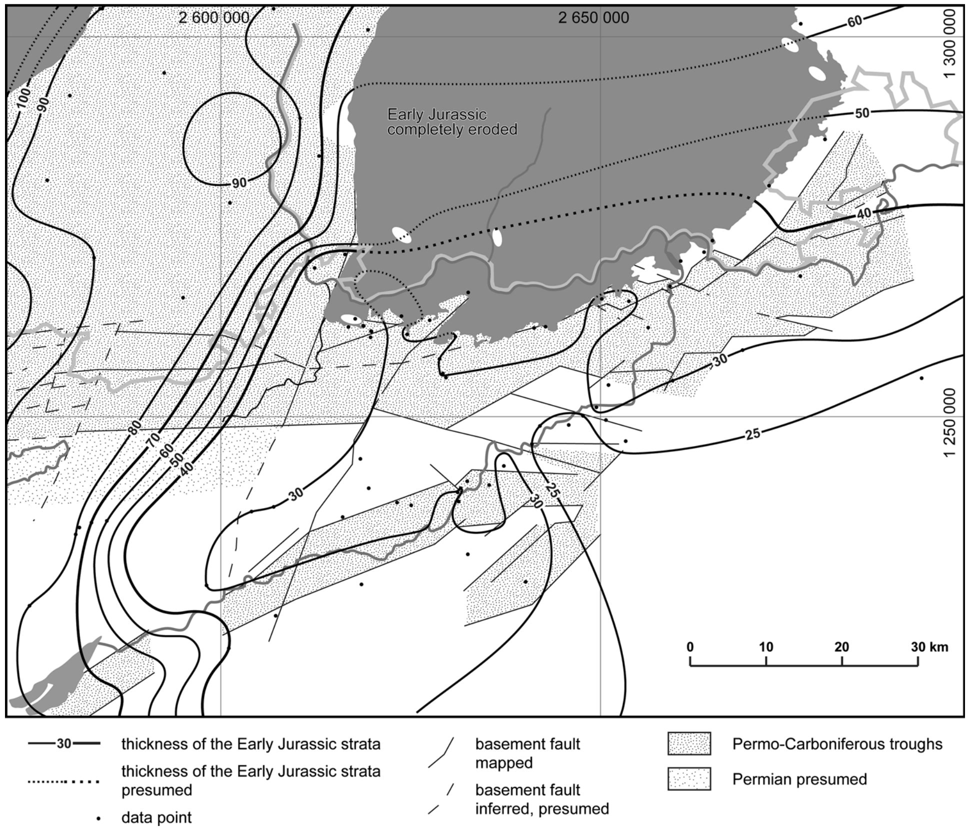


Fig. 1 Palinspastically restored isopach map of the Early Jurassic in NW Switzerland and adjacent parts of France and Germany (modified after Reisdorf et al. 2011). Contrary to Reisdorf et al. (2011: Fig. 6), the thickness of the basal part of the Opalinus-Ton/Opalinuston Formation (Torulosum subzone, Late Toarcian) is now included

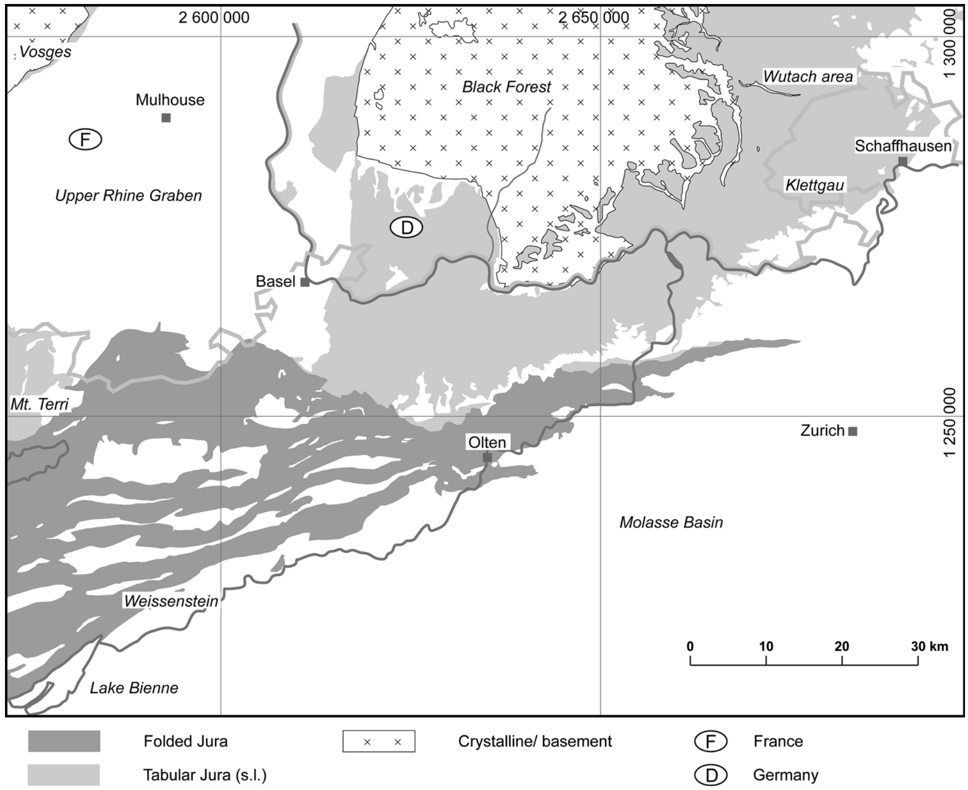
in NW Switzerland does not show considerable variations in thickness within the mentioned trends (cf., Müller et al. 1984; Bitterli 1992; Reisdorf et al. 2011).

Compared to the chronostratigraphic timespan of 26.9 Myr (Ogg et al. 2016) the low thickness implies an in-average very low net-sedimentation rate of only 0.93–3.72 m/Myr that definitely could have been affected by erosion. These sedimention rates are two to three orders of magnitude smaller than those that have been calculated for the full marine Middle and Late Jurassic deposits of NW Switzerland (Wetzel et al. 2003). The low sedimention rates are even intriguing for an epicontinental marine depositional environment, because they are very similar to sedimentation rates of deep sea-sediments in the rock record (cf., Scholle et al. 1983; Füchtbauer 1988). Therefore, it appears that the basin part in NW Switzerland underwent low subsidence. Furthermore, the relatively uniform facies distribution is not suggestive of differential subsidence. Consequently, the accommodation space might have been provided mainly by eustatic sea-level changes (e.g., Brandt 1985; Einsele 1985; Philippe et al. 1996). Thus, the Early Jurassic has been classified as a period of "tectonic quiescence" in NW Switzerland (e.g., Vonderschmitt 1942; Wagner 1953; Laubscher 1986; Thury et al. 1994). In contrast, detailed sedimentological studies during the last decades provided convincing evidence that at least the southern part of the Central European Epicontinental Basin recurrently experienced phases of considerable differential tectonic subsidence during the Middle and Late Jurassic that modulated sediment-accumulation and affected facies patterns (e.g., Wetzel et al. 1993; Burkhalter 1996; Gonzalez and Wetzel 1996; Wetzel 2000; Allenbach 2002; Wetzel and Allia 2003; Wetzel et al. 2003; Jank et al. 2006). The obvious influence of differential tectonic subsidence on the Middle and Late Jurassic deposits in NW Switzerland leads to the question if the Early Jurassic represents a phase of "tectonic quiescence" or if uniform thickness pattern only obliterates such tectonic effects. It is the purpose of the present study, to analyse thickness and facies pattern in detail and to decipher if and how much the slowly formed lithostratigraphic units of the Early Jurassic Staffelegg Formation were affected by tectonic movements.

2 Study area and geological setting

The study area is located in NW Switzerland and extends into the adjacent regions of E France and SW Germany (Fig. 2). With respect to this study, four tectonic domains are distinguished, Tabular Jura, Folded Jura, Black Forest and Vosges (representing the exhumed Palaeozoic

Fig. 2 Geological overview of the study area, situated in NW Switzerland, SW Germany and E France



basement), and the Cenozoic Upper Rhine Graben that, however, has late Palaeozoic preceding structural elements.

The Palaeozoic crystalline basement is dissected by numerous faults that formed during the late Palaeozoic, in particular when a mega-shear zone developed at the end of the Variscan orogeny between the Ural and the Appalachians (Arthaud and Matte 1977). Numerous basins, grabens, and half-grabens developed, including the so-called "Burgundy Trough" and the "North-Swiss Permo-Carboniferous Trough" including the so-called "Constance-Frick Trough", "Olten Trough" and "Klettgau Trough" (Fig. 3; Diebold 1988; Ménard and Molnar 1988; Ziegler 1990; von Raumer 1998). In the southernmost Upper Rhine Graben area, a narrow horst occurs that separates the Burgundy and Constance-Frick Trough (Ustaszewski et al. 2005). A large part of the Burgundy Trough terminates to the E at the NE–SW to N–S-trending so-called "Wehra–Zeininger fault zone" (e.g., Gonzalez 1990; Ustaszewski et al. 2005; Grimmer et al. 2017). Furthermore, at the position of the future Upper Rhine Graben, a roughly N–S-trending fault system comprising the so-called "Rhenish Lineament" established at the end of Variscan orogeny (Boigk and Schöneich 1974; Krohe 1996; Grimmer et al. 2017). The Rhenish Lineament and similarly aligned faults such as the so-called "Caquerelle Fault" continue S of the southern border of the modern Upper Rhine Graben (Liniger 1967; Nussbaum et al. 2017).

These late Palaeozoic tectonic structures are preferentially oriented exhibiting three main strike-directions (Fig. 3; e.g., Einsele and Schönenberg 1964; Wetzel 2008; Geyer et al. 2011): (i) NW–SE ("Herzynian"; 120°–130°), (ii) ENE–WSW ("Erzgebirgian"; 70°–80°), and (iii) NNE–SSW ("Rhenish"; 10°–20°).

In the study area and to the South underneath the Molasse Basin, these basement structures are fairly well known from seismic records (e.g., Diebold et al. 1991; NAGRA 2008; Naef and Madritsch 2014). In contrast, in the Black Forest and the Vosges, corresponding tectonic structures are exposed (e.g., Metz 1977; Zeh 2008 and references therein; Geyer et al. 2011). Depending on the stress field, these tectonic structures became recurrently reactivated during the Mesozoic and Cenozoic as evidenced by vein mineralization and alteration of minerals (e.g., Wernicke and Lippolt 1997; Wetzel et al. 2003; Edel et al. 2007; Staude et al. 2012; Pfaff et al. 2009; Brockamp et al. 2015; Burisch et al. 2016; Walter et al. 2017).

After the Variscan orogeny and late Palaeozoic fault-tectonic phase, during the Triassic wide parts of Central Europe subsided and peneplanation took place. First, terrestrial sediments accumulated until the Middle Triassic, when marine transgression commenced and a shallow epicontinental sea formed (e.g., Feist-Burkhardt et al. 2008; Geyer et al. 2011). In the study area, mainly carbonates, marls and up to ~ 100 m thick evaporites formed

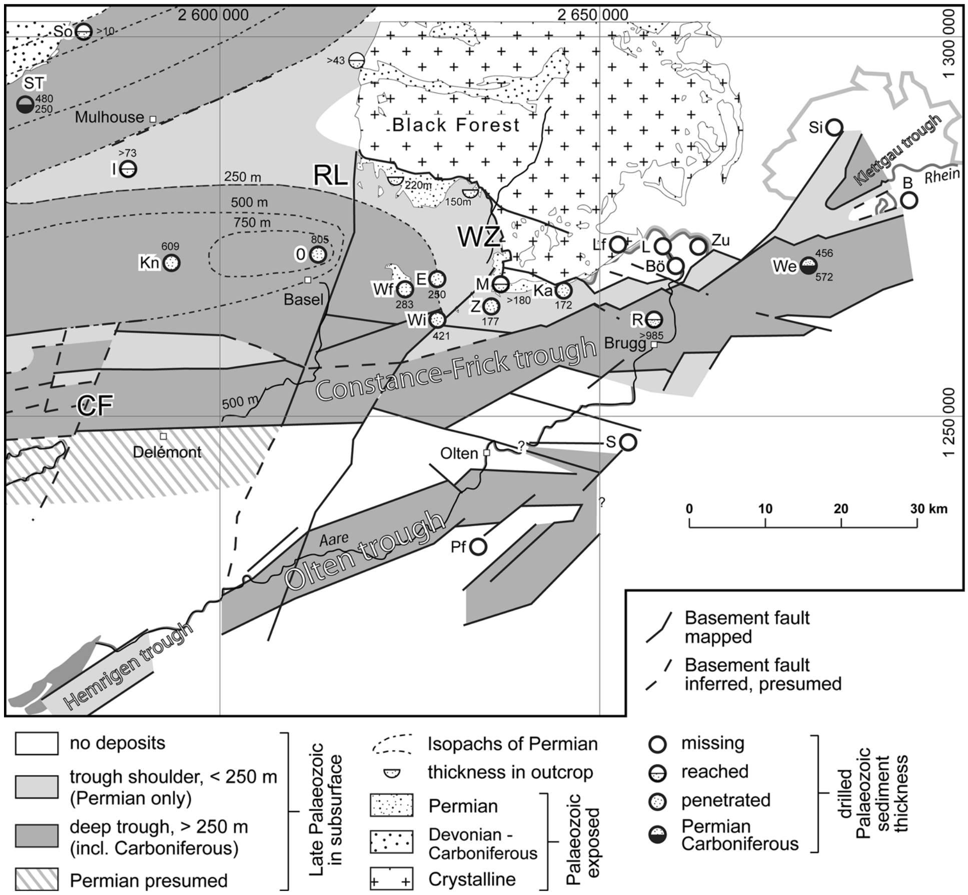


Fig. 3 Known Permo-Carboniferous troughs and faults in NW Switzerland and adjacent parts of France and Germany; modified after Wetzel (2008, but see slightly different interpretation of seismic data by Naef and Madritsch 2014). Abbreviations: CF Caquerelle Fault, RL Rhenish Lineament, WZ Wehra–Zeininger fault zone, B Benken (NAGRA 2001), Bö Böttstein (NAGRA 1985), Bi Bisel (unpublished), Bx Buix (Schmidt et al. 1924), E Engerfelden (Ryf 1984), I Illfurth (unpublished), K Kaisten (NAGRA 1991), Kn Knorrinque (unpublished), L Leuggern (Peters et al. 1989), Lf Laufenburg (Heusser 1926), M Mumpf (Schmassmann and Bayramgil 1946), O Otterbach (Häring 2002), Pf Pfaffnau (Büchi et al. 1965), R Riniken (Matter et al. 1987), S Schafisheim (Matter et al. 1988a), Si Siblingen (NAGRA 1993), So Soultz (unpublished), ST south of Thann (Fluck et al. 1980), We Weiach (Matter et al. 1988b), Wf Weiherfeld (Schmassmann and Bayramgil 1946), Wi Wintersingen (Schmassmann and Bayramgil 1946), Z Zuzgen (Schmassmann and Bayramgil 1946), Zu Zurzach (Cadisch 1956)

under restricted marine conditions (e.g., Philippe et al. 1996; Jordan 2016; Pietsch et al. 2016).

During the Late Triassic (Keuper), continental and marine-marginal conditions repeatedly alternated in the study area (e.g., Jordan 2008; Geyer et al. 2011; Jordan et al. 2016). Furthermore, during the Late Triassic sediment accumulation was recurrently interrupted for prolonged periods of time as evidenced by paleosols of various maturity and regional as well as basin-wide unconformities (e.g., Etzold and Schweizer 2005; Nitsch et al. 2005). Consequently, net-sedimentation rates were rather low being in the range of 7–9 m/Myr (Nitsch et al. 2005). During the Early Jurassic, sedimentation rates further decreased in NW-Switzerland to 0.93–3.72 m/Myr for this period as a whole (see above). In fact, from Early Triassic to Early Jurassic subsidence shows a roughly exponential decrease (e.g., Loup 1992; Wetzel et al. 2003).

For the latest Triassic (Rhaetian) in the study area, three regional and basin-wide unconformities have been recognized (e.g., Etzold and Schweizer 2005; Nitsch et al. 2005). The Rhaetian sediments formed in an estuarine to (marginal-)marine setting close to sea-level as evidenced by stagnant pore water and dolomite layers (Beutler and Nitsch 2005; Geyer et al. 2011; Fischer et al. 2012; Jordan et al. 2016; Schneebeli-Hermann et al. 2018). In spite of the long time span of the Rhaetian (4.7 Myr; Ogg et al. 2016), the sediment record is rather incomplete while widely affected by erosion in a roughly N–S trending area (e.g., Etzold and Schweizer 2005 and references therein; Reisdorf et al. 2011; Jordan et al. 2016). The uppermost unconformity developed at the latest during the transgression in Early Jurassic times (e.g., Hallam 2001; Etzold and Schweizer 2005; Reisdorf et al. 2011 and references therein).

The Jurassic transgression is related to the disintegration of Pangea as well as the opening of the Tethys to the South and of the North Atlantic to the West (e.g., Ziegler 1990; Stollhofen et al. 2008). Thereafter throughout the Jurassic, an epicontinental sea covered major parts of central Europe (Central European Epeiric Sea; e.g., Ziegler 1990; Smith et al. 2004; Pieńkowski et al. 2008). However, to the East, the southern part of the basin was bounded by the Bohemian Massif and to the South by the Alemannic Land (Fig. 4; e.g., Stoll-Steffan 1987; Loup 1993; Jordan et al. 2008; Geyer et al. 2011). The latter was quite close to the study area (e.g., Jordan et al. 2008). During the Early Jurassic, the study area was situated in the boreal realm at latitude of approximately 35° to 40°N (Ziegler 1988; Edel 1997; Smith et al. 2004).

Independent on lithology and strata arrangement, the Early Jurassic deposits of NW Switzerland, SW Germany and E France show numerous correlative erosional unconformities and reworking horizons (Bessereau and Guillocheau 1994; de Graciansky et al. 1998; Bloos et al. 2005; Reisdorf et al. 2011; STG 2016). In the thin Early Jurassic deposits of NW Switzerland, erosional unconformities are more clearly developed and they erode stratigraphically deeper than in adjacent areas towards the W, N, or E, which are characterised by thicker sediments (Fig. 5).

Distinct facies changes over short distance occur in NW Switzerland and lithostratigraphic units exhibit pronounced facies variations. This is in particular true for the Sinemurian deposits in the Folded Jura and to the south in the Molasse Basin (Reisdorf et al. 2011).

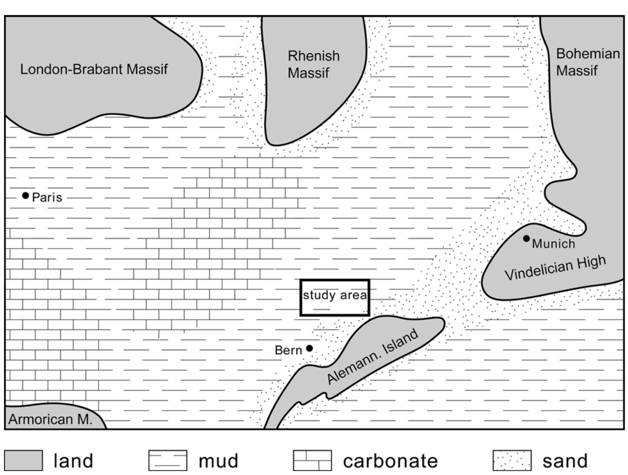


Fig. 4 Paleogeographic map for the Early Jurassic in NW Switzerland and adjacent parts of France and Germany. The study area was covered by shallow epicontinental sea (modified after Ziegler 1990; Wetzel and Reisdorf 2007)

3 Materials and methods

The deposits studied almost completely cover the Early Jurassic. Since no chronometric age data are available the time frame is based on biostratigraphic data, which are correlated with the Jurassic Time Scale of Ogg et al. (2016). The biostratigraphic sub-division of the Early Jurassic follows the European standard ammonite biostratigraphy, which distinguishes Boreal and Tethyan ammonite zonation (e.g., de Graciansky et al. 1998; Pieńkowski et al. 2008). For this study, the ammonite zonation of the Boreal realm is utilised (e.g., de Graciansky et al. 1998; Pieńkowski et al. 2008). For the onset of the Early Jurassic, there is a difference of ~ 0.3 Myr between Boreal (201.4 Ma) and Tethyan realm (~ 201.1 Ma), while the boundary between the Early and Middle Jurassic is bio- and chronostratigraphically consistent in the Boreal and Tethyan ammonite zonation (Cresta et al. 2001; Hillebrandt et al. 2013; Ogg et al. 2016). The Torulosum subzone, previously attributed by many authors to the Middle Jurassic Opalinum zone, belongs to the Aalensis zone and, therefore, represents the latest Early Jurassic (Schmid et al. 2008; Feist-Burkhardt and Pross 2010; Reisdorf et al. 2014). The Early–Middle Jurassic boundary is dated to an age of 174.2 Ma (Ogg et al. 2016).

The age of lithostratigraphic units is given in chronostratigraphic terminology (e.g., "Early" instead of "Lower") following the recommendation of the Swiss Committee of Stratigraphy (Remane et al. 2005). The lithostratigraphic classification follows the nomenclature used in the E and SE of France, SE Germany and NW Switzerland (Fig. 5). Lithostratigraphic boundaries do not coincide, but in rare cases are approximate to chronostratigraphic boundaries (e.g., stages and substages; de Graciansky et al. 1998; Bloos et al. 2005; Reisdorf et al. 2011; Morard et al. 2014). Marker beds of the Hettangian and Early Sinemurian (Hallau Bed, Schleitheim Bed, Gächlingen Bed, Oolithenbank, Kupferfelsbank; Fig. 5) as well as the topmost interval of the Early Pliensbachian comprising Trasadingen Bed, Davoei-Bank and Banc à Davoei was used for the preparation of isopach maps (see below).

Isopach maps show the spatial thickness distribution of sedimentary bodies. In combination with additional data morphology of the depositional area as well as subsidence pattern can be deciphered (e.g., Wetzel et al. 1993; Wetzel and Allia 2003; Allenbach and Wetzel 2006). The isopach maps comprise facies variations within the lithostratigraphic units. Delimitation of the facies changes are shown in the respective maps.

The isopach maps of the study are based on ca. 1700 published and unpublished thickness data (for details see

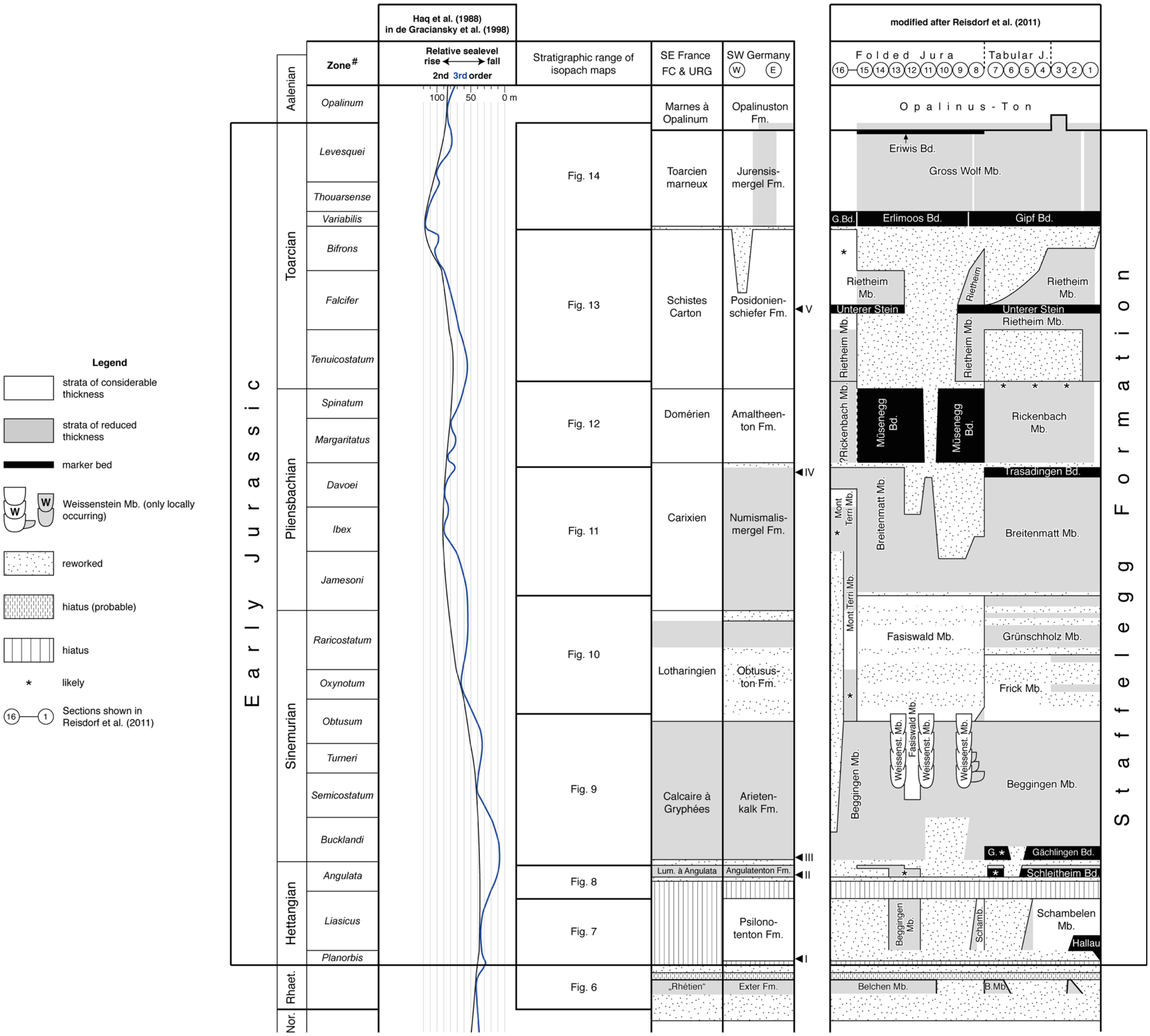


Fig. 5 Early Jurassic biostratigraphy and lithostratigraphy of NW Switzerland and adjacent parts of SW Germany and E France as well as eustatic sea-level change during this period of time (compiled from Haq et al. 1988 and Reisdorf et al. 2011; modified). Note the stratigraphic range of the isopach maps. Due to the partly complex stratigraphic architecture of the Early Jurassic deposits in a few cases simplifications are required in the assignment of lithostratigraphic units: (i) despite of its wide chronostratigraphical range, the Weissenstein Member is included in only one isopach map; (ii) the thickness values for the Mt. Terri Member based on the biostratigraphic data available are incorporated into two isopach maps. *B.Mb* Belchen Member, *E* East of the Black Forest, *FC* France Comté, *Fm.* Formation, *G.* Gächlingen Bed, *G.Bd.* Gipf Bed?, *Lum.* Lumachelle, *Mb.* Member, *Nor.* Norian, *Rhaet.* Rhaetian, *Schamb.* Schambelen Member, *Tabular J.* Tabular Jura, *URG* Upper Rhine Graben, *W* West of the Black Forest, # = zones sensu Dean et al. (1961), sensu Bloos (1979) and sensu Schlegelmilch (1992); I = Psilonotenbank (e.g., Bloos et al. 2005; Etzold et al. 2010); II = Oolithenbank (e.g., Schloz 1972; Bloos et al. 2005; Schmid et al. 2008); III = Kupferfelsbank (e.g., LGRB 2004; Schmid et al. 2008); IV = Davoei-Bank (e.g., Schlatter 1991); V = Unterer Stein (e.g., Urlichs 1977; Röhl and Schmid-Röhl 2005)

online supplemental material). No references to data points are given in the description and captions of the isopach maps, but they are provided in the online supplemental material. Locations or geographic domains are given in today's terms, even if they might not have existed during the Early Jurassic, such as the Black Forest, Tabular and Folded Jura or Upper Rhine Graben. Isopachs were drawn by linear interpolation between data points. Compensating for the increasing shorting of the Folded Jura to the west, data points today situated within the Folded Jura were palinspastically restored by counterclockwise rotation around a point at the eastern tip of the Folded Jura at the Lägern by 7°–8° to locate them at their original position during deposition (see Laubscher 1965, 1986; Kempf et al. 1998).

The depositional water depth was estimated. For the Central European Epicontinental Basin the fair-weather wave base has been stated to have been located in ~ 5–10 m and the storm wave base at ~ 30 m (Einsele 1985; Brandt 1985; Wetzel and Allia 2003). Furthermore empirical values gained from forensic and marine biological studies imply a water depth range of up to > 50 m (Reisdorf et al. 2012 and references therein).

To decipher effects of synsedimentary subsidence, besides sea-level changes and depositional water depth, the initial sediment thickness needs to be known. Therefore actual thickness is multiplied with so-called "decompaction factor" (e.g., Einsele 2000) that is at the given overburden 2 for mudstone, 1.6 for sandstone and 1.5 for limestone. The thickness of the individual lithostratigraphic units in compacted and decompacted state are listed in Tables 1, 2, 3.

4 Isopach maps

Based on the biostratigraphic framework the isopach maps have a resolution of approximately one sub-stage. The isopach maps form the base to unravel subsidence pattern and to decipher related facies changes.

4.1 Belchen Member (Rhaetian, Late Triassic)

For the Rhaetian, the sandstone and the mudstone facies have not been distinguished in the isopach map (Fig. 6). Three areas can be recognised from E to W:

- In the East sediments up to 2.4 m are found (this occurrence is not clearly demarcated because of lacking data).
- South of the Black Forest, no Rhaetian sediments are preserved.
- West of the Black Forest sediments reach a thickness up to 10 m.

Due to the abundant outcrops and their spatial distribution in the western part of the study area, the thickness pattern can be more differentiated than towards the east. Three localised relative thickness maxima are evident from section and well data: (i) in the centre of the Upper Rhine Graben, (ii) SW of the Black Forest in a narrow area in the Tabular Jura (Dinkelberg) and the Upper Rhine Graben, and (iii) in the Molasse Basin south of the Folded Jura (well Pfaffnau). Except for these relative maxima in thickness, the Rhaetian sediments are ~ 5 m thick.

4.2 Schambelen Member and base of the Beggingen Member (Early Hettangian, Early Jurassic)

The Beggingen Member has a diachronous base, and, hence, is addressed separately for the Early and Late Hettangian as well as the Sinemurian. Early Hettangian sediments occur within two-thirds of the study area (Fig. 7). Because of the low number of data points around the Black Forest, the thickness pattern is subjected to some uncertainty there. South of the Black Forest a distinct isopach pattern is documented by the 1-m line that trends N–S, but in the south of the study area, it becomes ENE–WSW directed and thus, parallel to the limit of the Early Hettangian deposits. Deposits < 1 m thick constitute an irregularly demarcated area.

South of today's Black Forest between Brugg and Schafisheim a pronounced W–E directed increase in thickness culminates in a regional thickness maximum of ~ 9 m. From there, thickness decreases to the east to > 4 m. Due to the lack of data it cannot be proven whether the W–E trending thickness gradient continues in the southern part of the study area. Another regional thickness maximum of ~ 9 m is located in the Wutach area east the Black Forest (Wutach area). It is N–S-oriented. These two depocenters are aligned in Rhenish direction.

4.3 Base of the Beggingen Member (Late Hettangian)

In NW Switzerland, SW Germany and SE France, the late Hettangian is characterized by deposits of low thickness (Contini 1984; Geyer et al. 2003, 2011; Reisdorf et al. 2011). In wide parts, thickness is > 2 m (Fig. 8). In the southern part, no sediments of this age are present in an elongated W–E to SW–NE trending area. The overlying deposits indicate reworking at their base (Reisdorf et al. 2011). Another, but small area lacking Late Hettangian sediments is located SW of the Black Forest near Arisdorf. Isopachs are roughly E–W oriented while thickness tends to decrease southward. At the eastern limit of the study area, a W–E oriented trend of increasing thicknesses is seen.

4.4 Beggingen Member and Weissenstein Member (Early Sinemurian–early Late Sinemurian)

These Early Sinemurian–early Late Sinemurian sediments cover for the first time in the Early Jurassic the study area entirely (Fig. 9). Narrowly spaced and interfingering

Table 1 Thickness of lithostratigraphic units of the Latest Triassic and Early Jurassic in NW Switzerland

Formation (Fm.)/Member (Mb.)	Thickness compacted [m]	Thickness decompacted [m]	Sedimentation Rate [m/Myr]compacted sediment	Sedimentation Rate [m/Myr] decompacted sediment	Decompaction Factor	Ammonite Zone	Age [Myr]	Duration [Myr]
Gross Wolf Mb. and lower part Opalinus–Ton	0.4–42.9	0.9–85.8	0.1–10.7	0.9–85.8	2	Variabilis–Aalensis	178.2–174.2	4
Rietheim Mb.	0–19.5	0–39.0	0–3.6	0–39.0	2	Tenuicostatum–Bifrons	183.6–178.2	5.4
Rickenbach Mb./Breitenmatt Mb. (only Müsenegg Bd.)	0–c. 3.0	0–6.0	0–0.6	0–6	2	Margaritatus–Tenuicostatum	188.3–183.6	4.7
Breitenmatt Mb. (excl. Müsenegg Bd.)/upper part Mt. Terri Mb.	0.5–c. 9.5	0.8–14.3	0.2– > 3.5	0.8–14.3	1.5	Jamesoni–Davoei	191.0–188.3	2.7
Frick Mb. & Grünschholz Mb./Fasiswald Mb./lower part Mt. Terri Mb.	0?; 2.5–27.0	0?; 5.0–54.0	0?; 0.6–6.9	0?, 5.0–54.0	2	Obtusum–Jamesoni	194.9–191.0	3.9
upper part Beggingen Mb. and Weissenstein Mb.	1.5–24.4	2.3–36.6	0.33–5.4	2.3–36.6	1.5	Bucklandi–Obtusum	199.4–194.9	4.5
lower part Beggingen Mb.	0–c. 3.0	0–4.5	0–4.3	0–4.5	1.5	Angulata	200.1–199.4	0.7
Schambelen Mb./base Beggingen Mb.	0–9.1	0–18.1	0–9.1	0–18.1	2	Planorbis–Liasicus	201.1–200.1	1
Belchen Mb. (Klettgau Fm.)	0–7.0 (10.0?)	0–11.2 (16.0?)	0–0.8 (1.2?)	0–11.2 (16)	1.6	/	209.6–201.1 (205.8–201.1)	8.5 (4.7)

Table 2 Thickness of lithostratigraphic units of the Latest Triassic and Early Jurassic in E France and SW Germany (today's Upper Rhine Graben)

Formation (Fm.)	Thickness compacted [m]	Thickness decompacted [m]	Sedimentation Rate [m/Myr] compacted sediment	Sedimentation Rate [m/Myr] decompacted sediment	Decompaction Factor	Ammonite Zone	Age [Myr]	Duration [Myr]
Jurensismergel Fm. and Opalinuston Fm.	3.0–39.0	6.0–78.0	0.7–9.8	1.5–19.5	2	Variabilis–Aalensis	178.2–174.2	4
Posidonienschiefer Fm.	3.0?–12.0	6.0–24.0	0.6–2.2	1.1–4.4	2	Tenuicostatum–Bifrons	183.6–178.2	5.4
Amaltheenton Fm.	3.5–c. 30.0	7.0–60.0	0.7–6.4	1.5–12.8	2	Margaritatus–Tenuicostatum	188.3–183.6	4.7
Numismalismergel Fm.	c. 0.7–c. 25.0	1.3–50.0	0.2–9.3	0.5–18.5	2	Jamesoni–Davoei	191.0–188.3	2.7
Obtususton Fm.	22.0–30.7	44.0–61.4	5.6–7.9	11.3–15.7	2	Obtusum–Jamesoni	194.9–191.0	3.9
Arietenkalk Fm.	<3.0– > 5.0	<4.5– > 7.5	0.7–1.1	1.0–1.7	1.5	Bucklandi–Obtusum	199.4–194.9	4.5
Angulatenton Fm.	c. 0.5–2.5	0.8–3.8	0.7–3.6	1.1–5.4	1.5	Angulata	200.1–199.4	0.7
Psilonotenton Fm.	0	0	0	0	2	Planorbis–Liasicus	201.1–200.1	1
Early Jurassic	40.0–90.0	/	1.5–3.3	/	/	Planorbis–Aalensis	201.1–174.2	27
Exter Fm.	2.0–10.0	3.2–16.0	0.2–1.2	0.4–1.9	1.6	/	209.6–201.1 (205.8–201.1)	8.5 (4.7)

Table 3 Thicknesses of lithostratigraphic units of the Latest Triassic and Early Jurassic in SW Germany

Formation (Fm.)	Thickness compacted [m]	Thickness decompacted [m]	Sedimentation Rate [m/Myr] compacted sediment	Sedimentation Rate [m/Myr] decompacted sediment	Decompaction Factor	Ammonite Zone	Age [Myr]	Duration [Myr]
Jurensismergel Fm. and Opalinuston Fm.	1.8–8.0	3.6–16.0	0.5–2.0	0.9–4.0	2	Variabilis–Aalensis	178.2–174.2	4
Posidonienschiefer Fm.	1.7–12.4	3.3–24.9	0.3–2.3	0.6–4.6	2	Tenuicostatum–Bifrons	183.6–178.2	5.4
Amaltheenton Fm.	1.6–10.2	3.1–20.4	0.3–2.2	0.7–4.3	2	Margaritatus–Tenuicostatum	188.3–183.6	4.7
Numismalismergel Fm.	0.7–3.0	1.4–6.0	0.3–1.1	0.5–2.2	2	Jamesoni–Davoei	191.0–188.3	2.7
Obtususton Fm.	15.0–25.0	30.0–50.0	3.9–6.4	5.9–12.8	2	Obtusum–Jamesoni	194.9–191.0	3.9
Arietenkalk Fm.	2.6–c. 6.0	3.9–9.0	0.6–1.3	0.9–1.2	1.5	Bucklandi–Obtusum	199.4–194.9	4.5
Angulatenton Fm.	0.4–2.0	0.6–3.0	0.6–2.9	0.9–4.3	1.5	Angulata	200.1–199.4	0.7
Psilonotenton Fm.	0–9.1	0–18.2	0–9.1	0–18.2	2	Planorbis–Liasicus	201.1–200.1	1
Early Jurassic	36.0–c. 65.0	/	1.3–2.4	/	/	Planorbis–Aalensis	201.1–174.2	27
Exter Fm.	0–8.5	0–13.6	0–1.0	0–1.6	1.6	/	209.6–201.1 (205.8–201.1)	8.5 (4.7)

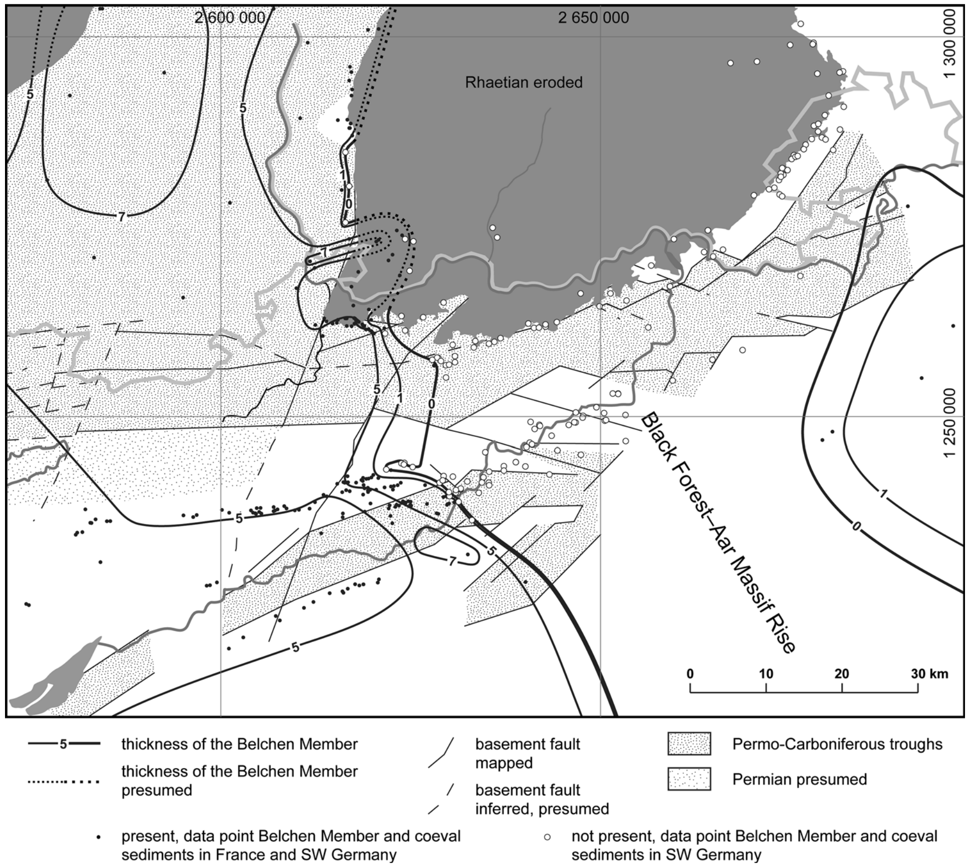


Fig. 6 Palinspastically restored isopach map of the Belchen Member (Klettgau Formation), Exter Formation and Argilies et grés rhétiens or „Rhétien", respectively; Rhaetian (Late Triassic). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)

different facies lead to a more complexly structured isopach pattern in the southern part than in the northern part.

The isopach map comprises mainly condensed arenitic limestone (Lithofacies A) and calcareous sandstone and sandy limestone (Lithofacies B). Lithofacies A dominates the Beggingen Member, while the Weissenstein Member mainly constitutes Lithofacies B. Addressing both lithostratigraphic units separately reveals considerable thickness differences between them.

The isopach map of Lithofacies A shows two domains. In the N, higher thickness of 3 to > 5 m tending to increase to the N occur on both sides of the Black Forest (Wutach area and Upper Rhine Graben) than at its immediate margin, where thickness is between 2 and 3 m. Because of the low number and poor quality of data in the Upper Rhine Graben area, the course of isopachs is rather uncertain. S of the Black Forest, but presumably also to the S of the Upper Rhine Graben, Lithofacies A still exhibits low thickness. In the southern part of study area, Lithofacies A reaches ∼ 5 m thickness only in the SW (Weissenstein area). Thickness tends to decrease from ∼ 5 to > 1 m from S to N. In the SE, however, several local minima (< 1 m) and maxima (> 4 m) follow a SW-NE orientation superimposed on a background value of > 1 m.

The Weissenstein Member (Lithofacies B) is restricted to the southern part of the study area; its thickness decreases from S to N. Isopachs > 5 m are tongue-shaped and S–N-directed. Several maxima > 5 m and up to 22.5 m thick occur. Because of the facies interfingering (see above), the isopachs of the Weissenstein Member overlap those of Lithofacies A. The thickness maxima of the Weissenstein Member coincide with those of the Beggingen Member only in the SW of the study area (Weissenstein area).

4.5 Frick Member, Grünschholz Member, Fasiswald Member and basal part of the Mt. Terri Member (early Late Sinemurian–Early Pliensbachian)

These members are summarised in one isopach map. In the NW of the study area, a wide, N–S oriented depocenter (≥ 25 m) is developed, which is largely limited to the today's Upper Rhine Graben (Fig. 10). In the borehole Sierenz, the largest thickness of ∼ 30 m occurs. Towards the E, thickness decreases markedly and in the Klettgau area near Beggingen, it reaches a minimum of 9 m.

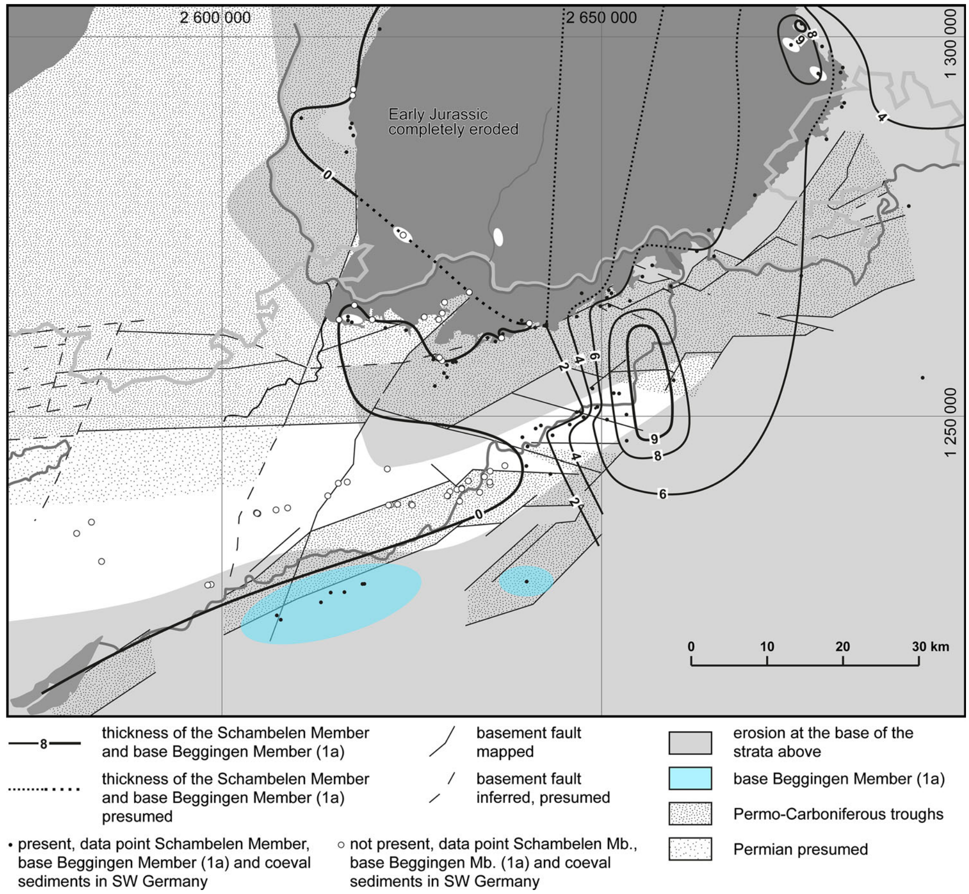


Fig. 7 Palinspastically restored isopach map of the Schambelen Member and base of the Beggingen Member (Staffelegg Formation), Psilonotenton Formation; Early Hettangian (Early Jurassic). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)

South of the Upper Rhine Graben and the Black Forest, deposits are 15–20 m thick. This thickness decreases from N to S to < 10 m in the southernmost part of the study area matching the general trend that, however, is opposed by two local thickness maxima > 15 m. They are aligned in NE–SW direction and exhibit thicknesses ∼ 19 m and ∼ 25–27 m, respectively. In the Mt. Terri region thickness strongly decreases as the basal Mt. Terri Member thins from ∼ 10 m to 0 m over a short distance (Fig. 10; Reisdorf et al. 2011).

4.6 Breitenmatt Member and upper part of the Mt. Terri Member (early Pliensbachian)

The thickness pattern of the early Pliensbachian shows a subdivision of the study area into two parts. In the W, the deposits are rather thick (> 5 to > 10 m) compared to the E, covering 80% of the area, where they are only up to 3 m thick (Fig. 11). The boundary between both domains roughly follows the eastern boundary of the Upper Rhine Graben. Thicknesses of ∼ 10 m occur S of the Upper Rhine Graben (Reisdorf et al. 2011). The predominantly low thickness in the E shows an overall trend of decreasing thickness from > 3 m in the N to > 1 m in the S. This trend is superimposed by two thickness minima < 1 m, one located W of the Black Forest is directed N–S, while the other one S of the Black Forest is oriented E–W. However, the small thickness does not exclude that the pattern is affected by uncertainties when evaluating lithology and thickness.

4.7 Rickenbach Member and Müsenegg Bed (Late Pliensbachian–earliest Toarcian)

The thickness of Late Pliensbachian–earliest Toarcian deposits decrease from N to S (Fig. 12). A depocenter is present on each side of the Black Forest while the sedimentary cover has been removed by erosion. In the east thickness is significantly smaller (∼ 6 to ∼ 10 m) than in the west where ∼ 6 to ∼ 30 m sediments occur in the Upper Rhine Graben. South of these depocenters, thickness decreases with a steep gradient to < 3 m, while further south thickness is < 1 m. Locally, Late Pliensbachian to earliest Toarcian sediments are even absent.

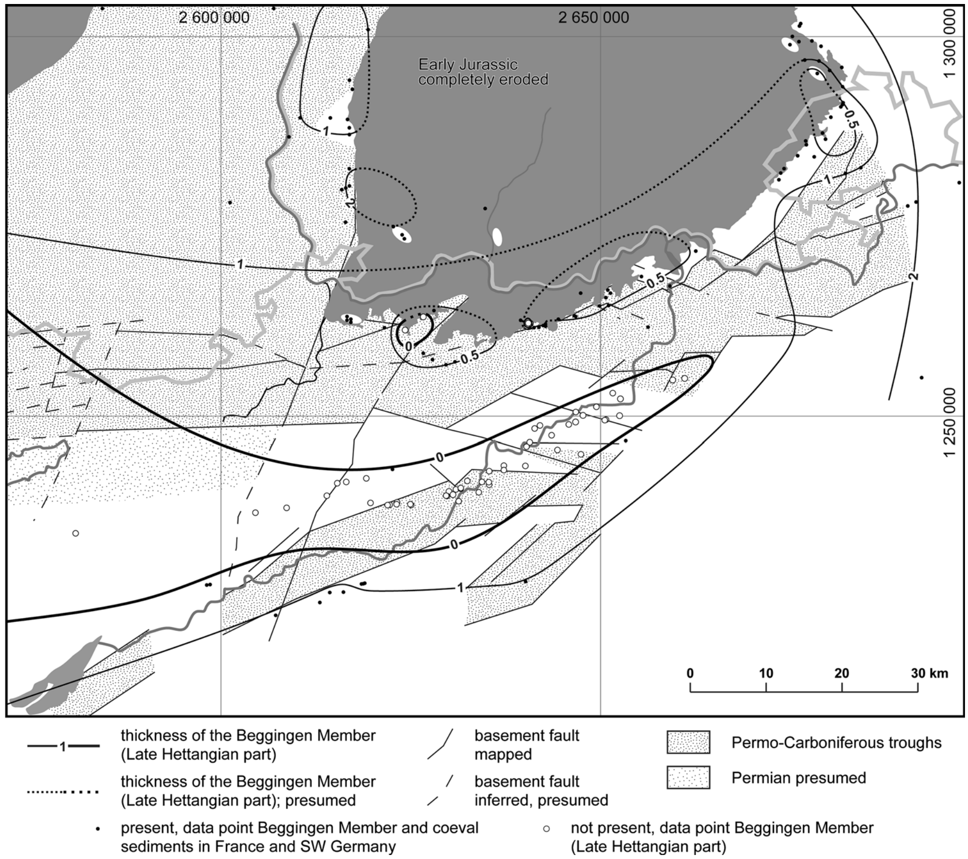


Fig. 8 Palinspastically restored isopach map of the Base Beggingen Member (Staffelegg Formation), Angulatenton Formation, Lumachelle à Angulata; Late Hettangian. Permo-Carboniferous troughs and faults simplified after Wetzel (2008)

4.8 Rietheim Member (early Toarcian)

The isopach map of the early Toarcian is accentuated by two depocenters and two thickness minima (Fig. 13). The depocenters are located E and W of the Black Forest (see above). The eastern maximum is oriented N–S and its thickness varies between 7 and 12 m. The depocenter in the W covers the area of the Upper Rhine Graben, there containing 9–12 m sediments, and continuing to the S to reach a maximum of ~ 19 m.

In contrast, early Toarcian deposits S and E of the Black Forest are thinning from N to S and finally wedge out and hence, constituting an N–S-oriented, large, low-thickness area (< 3 m). Directly W of the Black Forest, a minimum (1.5 to ~ 3 m) occurs on a small area between Ballrechten and Badenweiler; it is N–S oriented and shows a steep thickness gradient.

4.9 Gross Wolf Member of the Staffelegg Formation and basal part of the Opalinus-Ton (Late Toarcian)

Thickness values around < 1 to 3 m widely occur, the lowest values in the S (Fig. 14). However, four depocenters occur, two in the E and two in the W. The eastern ones reach moderate values of ~ 6 m and 8 m, respectively. The depocenter in the NE (Wutach area) is small and N–S oriented (Fischer 1964). The other one covers a larger area and exhibits an ENE–WSW elongation.

Compared to the remaining part of the study area, the two western depocenters exibit thicknesses one to two orders of magnitude larger, in the eastern Upper Rhine Graben area up to ~ 39 m (continuing to the N). To the S thickness decreases over a short distance to ~ 5 m. Sediments in the SW of the study area (Mt. Terri area) reach ~ 43 m thickness (cf. Hostettler et al. 2017). South- and eastwards, thickness decreases over short distance according data of Glauser (1936). Towards the N, however, the thickness decreases over a distance of about 40 km to 10 m.

5 Interpretation and discussion

5.1 Bathymetry

5.1.1 Schambelen Member

The Schambelen Member is predominantly composed of marly terrigenous mudstone containing a fully marine fauna (Jordan 1983; Haldimann 2005). The local occurrence and lamination present in some intervals as well as

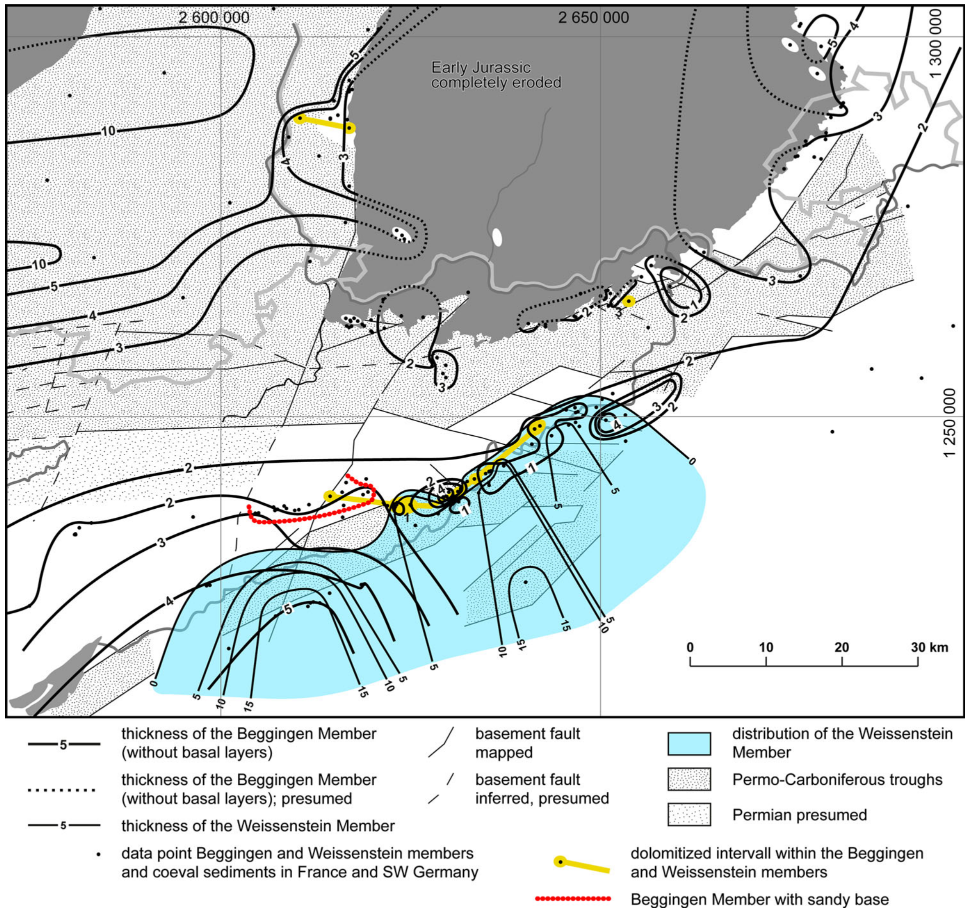


Fig. 9 Palinspastically restored isopach map of the Beggingen and Weissenstein members (Staffelegg Formation), Arietenkalk Formation, Calcaire à Gryphées; Early Sinemurian–early Late Sinemurian. Permo-Carboniferous troughs and faults simplified after Wetzel (2008)

occasional tempestitic layers implies deposition in an open, but temporarily restricted lagoonal setting not fully connected to the open sea (Wetzel et al. 1993; Meyer and Furrer 1995). A depositional water depth of < 10–15 m is assumed while small areal extent and short fetch restricts the build-up of large storm waves. Coastal sediments of the same age are not present in the study area. The overlying silty to fine sandy bioturbated mudstone and abundant coquinas suggest that these sediments formed around the fair-weather wavebase ($\sim$ 10 m).

5.1.2 Beggingen Member

At the base of the Beggingen Member several up to 1.3 m thick reworking horizons are marked by coquinas containing *Cardinia* and/or *Plagiostoma* and occasionally iron ooids (Reisdorf et al. 2011; cf. Seilacher 1982; Einsele 1985). They are interpreted to have formed within the range of fair-weather waves (5–10 m; Fürsich 1995; Wetzel 2000). These open marine deposits may contain fossils reworked from underneath (Reisdorf et al. 2011).

Overlying calcarenites are rich in reworked phosphoritized moulds of invertebrates and phosphatic pebbles. Intercalated are marls with abundant *Gryphaea*, often still in life position, and phosphatic concretions. These deposits likely accumulated both below (marls) and above (arenite) fair-weather wavebase (< 10–15 m; Wetzel 2000). The local occurrence of a thin layer with dolomite at the top of the Beggingen Member (Buser 1952: 62), and other dolomitization phenomena may point to localized short-term emergence (Wetzel et al. 1993; Fig. 9).

5.1.3 Weissenstein Member

The interfingering of rather clean calcareous sandstones and sandy limestones of the Weissenstein Member with the Beggingen Member within a small area suggests sediment accumulation around fair-weather wavebase ($\pm$ 10 m). Localized dolomitization in the Weissenstein Member could document short-term emergence or temporary inflow of freshwater (Jordan 1983; Wetzel et al. 1993).

5.1.4 Frick Member

The uniform and locally sandy terrigenous mudstones, rarely exhibit primary sedimentary structures, such as

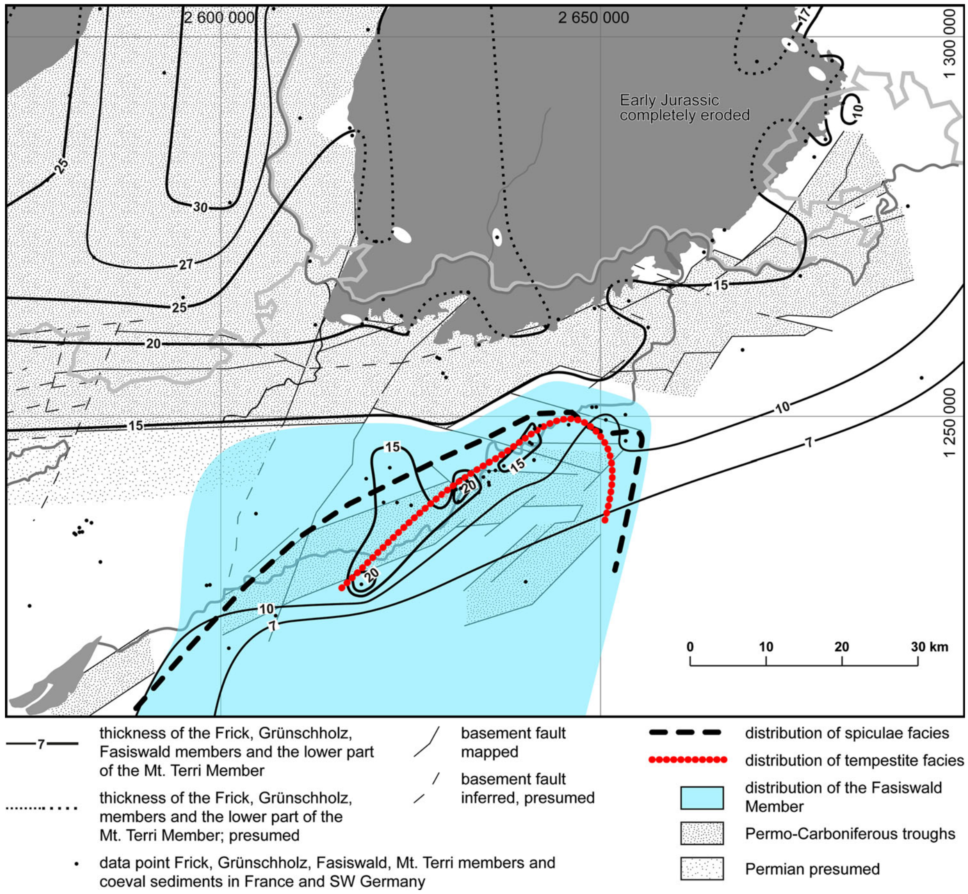


Fig. 10 Palinspastically restored isopach map of the Frick, Grünschholz, Fasiswald members and basal part of the Mt. Terri Member as well as the Obtusus Formation and Lotharingien (early Late Sinemurian–Early Pliensbachian). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)

bedding planes or small-scale ripples (NAGRA 1989). Therefore, in analogy to the Opalinus-Ton a depositional water depth at or below storm wavebase or somewhat below is assumed (± 30 m; cf. Wetzel and Allia 2003).

5.1.5 Grünschholz Member and Fasiswald Member

Conspicuous layers of bioclasts including encrinites and *Gryphaea*-conglomerates are suggestive of a depositional water depth between fair-weather and storm wavebase (10 to < 30 m). Tempestites are restricted to the southern part of the study area (Fig. 10). Similarly, spicules of siliceous sponges within the Fasiswald Member imply a water depth between 15 and 30 m (cf. Brunton and Dixon 1994). Similar faunal content and sedimentary facies of the Grünschholz Member suggest a similar bathymetry (20 to < 30 m).

5.1.6 Mt. Terri Member

Terrigenous mudstone and marl of this member display characteristics very similar to Frick Member (and tempestites have not been observed; Reisdorf et al. 2011). Consequently, a depositional water depth below storm wavebase (> 30–40 m) is assumed.

5.1.7 Breitenmatt Member (including Müsenegg Bed)

The strongly condensed marl intervals and phosphoritic, predominantly concretionary limestones are rich in belemnites and gryphaeid oysters and accumulated around fair-weather wavebase (< 10–15 m). Evidence for shallow water depth are reworked belemnites and phosphoritized moulds of invertebrates such as *Gryphaea* as well as phosphatic pebbles (Wetzel et al. 1993; Wetzel and Reisdorf 2007; cf. Sahagian et al. 1996; Arp and Schulbert 2010).

5.1.8 Rickenbach Member

The condensed glauconitic, phosphoritic, highly fossiliferous, belemnite-rich marls are indicators for deposition below fair-weather wavebase, but within the range of storm wavebase (20–30 m; cf. Futterer 1978; Brandt 1985; Doyle and Macdonald 1993).

5.1.9 Rietheim Member

For these bituminous, predominantly thinly bedded terrigenous mud- and siltstones, a depositional water depth of >

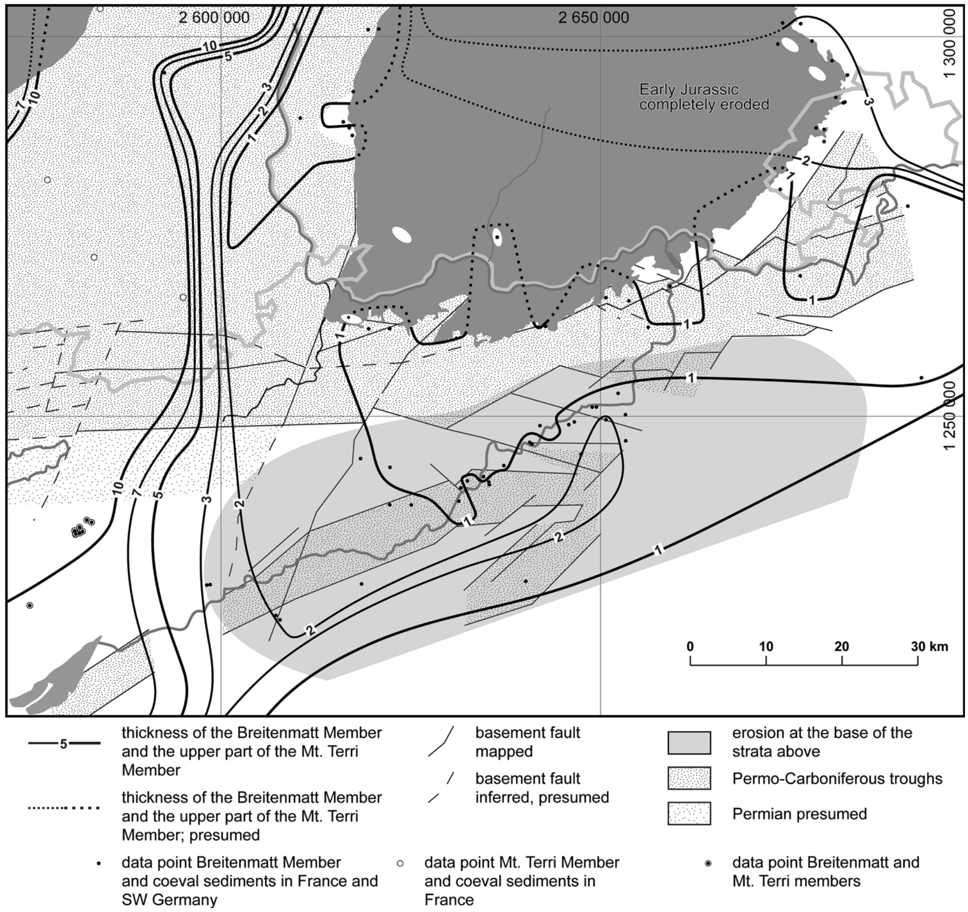


Fig. 11 Palinspastically restored isopach map of Breitenmatt Member and upper part of the Mt. Terri Member as well as the Numismalismergel Formation and the Carixien (early Pliensbachian). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)

60 m is assumed based on the *post mortem* fate of ichthyosaurs (Reisdorf et al. 2012).

5.1.10 Gross Wolf Member

The Gipf Bed and the Erlimoos Bed representing the basal layers of the Gross Wolf Member rest on an erosional unconformity. Numerous reworking features in combination with iron ooids and/or stromatolites and sponges in these marker beds indicate a depositional water depth around the fair-weather wavebase (5 to > 10 m; cf. Rieber 1973; Böhm and Brachert 1993; Brunton and Dixon 1994). For the grey phosphoritic marl and concretionary marly limestone strata further up a water depth below storm wave base is assumed (Jordan 1983). Tempestites (encrinites) are known from this member exclusively from the Unterer Hauenstein area (Wetzel, unpubl.). A bathymetry of ~ 30 m is, thus, suggested.

5.1.11 Base of the Opalinus-Ton

Reworking at the base of the Opalinus-Ton is only evident in the southernmost study area (NAGRA 1992). Sedimentological features imply a depositional water depth at or below storm wavebase (± 30 m; Wetzel and Allia 2003). Otherwise for the uniform terrigenous mudstone in NW Switzerland, deposition at or below the storm wavebase in 30–50 m water depth is assumed (Wetzel and Allia 2003).

5.2 Isopach maps

5.2.1 Belchen Member

The facies of the preserved Rhaetian deposits imply a deposition in a brackish-estuarine to shallow-marine setting that was controlled by local topography as indicated by the isopach pattern (cf. Altmann 1965; Geyer et al. 2011; Jordan et al. 2016 and references therein). In the west, the limit of the Belchen Member as well as coeval sediments in France and SW Germany coincide with the Rhenish Lineament and the Wehra–Zeininger fault zone (Figs. 3, 6). The N–S oriented thickness maximum coincides with the central Upper Rhine Graben and the ENE–WSW trending depocentre between the Rhenish lineament and the Wehra–Zeininger fault zone implies an alignment with Palaeozoic tectonic structures in

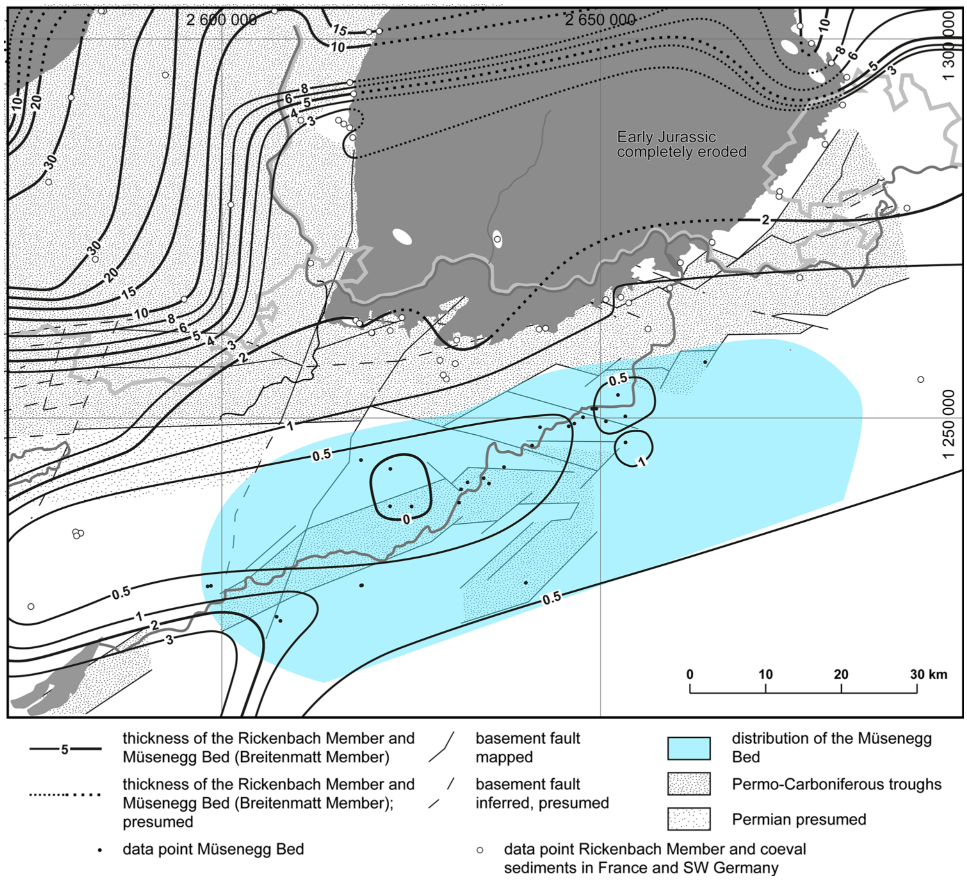


Fig. 12 Palinspastically restored isopach map of the Rickenbach Member and Müsenegg Bed (Breitenmatt Member) as well as the Amaltheenton Formation and Domérien (Late Pliensbachian–earliest Toarcian). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)

the basement that became reactivated. Evidently, not only during the Jurassic (cf., Burkhalter 1996; Wetzel et al. 2003), also pre-Jurassic sedimentation was affected by differential subsidence. Already de Lapparent (1887) and Pfannenstiel (1932) envisaged this possibility, however, for an area a little bit farther N.

5.2.2 Staffelegg Formation

Synsedimentary subsidence during the Early Jurassic has already postulated by Einsele (1985), Wildi et al. (1989), Loup (1992, 1993) and Wetzel et al. (1993, 2003). However, these authors did not address the subsidence pattern and aspects of differential subsidence in detail. In fact isopach maps and spatial distribution of the facies of the various lithologic units imply that the area was affected by differential subsidence that changed with time (see below).

5.2.3 Schambelen Member

The depocentre between Brugg and Schafisheim ($\sim$ 9 m) and that in the Wutach area ($\sim$ 9 m) appear of being located along a Rhenish striking axis that crosses two throughs in the basement, the Constance-Frick Trough and the eastern extension of the Olten Trough, and continues into the so-called "Swabian Depression" of Einsele and Schönenberg (1964; Figs. 3, 7). This axis coincides with faults transecting the graben structures, for instance in the area of Brugg or forming the southern limp of the Olten Trough (Fig. 3). However, in the area of the "Swabian Depression" no tectonic faults are known so far (cf. Murawski 1960; Geyer et al. 2011), but seismic investigations have not been carried out. The "Swabian Depression" strikes NNE–SSW from Stuttgart to Constance and is already documented in the sedimentary record during the Triassic (Einsele and Schönenberg 1964; Krimmel 1980). Therefore, a tectonic origin of this structure is not unlikely.

5.2.4 Beggingen Member

The strongly condensed Late Hettangian sediments at the base (> 0–2 m) display no distinct depocentres (Fig. 8). Still, isopachs of this member reveal an ENE–WSW trend south of the Black Forest that coincides with the strike of the Constance-Frick Trough and the Olten Trough. Further up, the Early Sinemurian to early Late Sinemurian condensed deposits of the Beggingen Member show only weakly developed N–S to E–W trending depocentres (Fig. 9). Thickness differences of > 3 m are indicative of

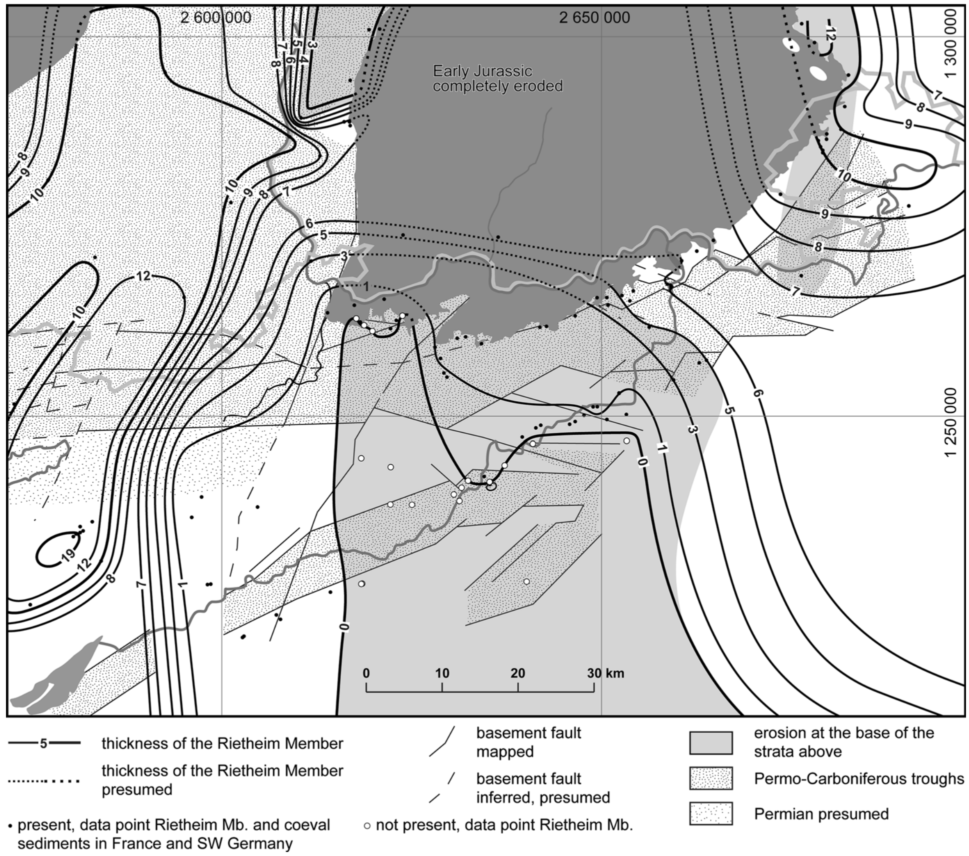


Fig. 13 Palinspastically restored isopach map of the Rietheim Member, Posidonienschiefer Formation and schistes carton (early Toarcian). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)

enlarged subsidence as seen in the Wutach area for that no Palaeozoic faults are known (see above).

In the Upper Rhine Graben area thickness reaches relative maxima ($\sim$ 10 m) being roughly E–W oriented, but they are delimited by the 3-m-isopach having an overall NNE–SSW orientation. In an area between the Rhenish Lineament and the Werra-Zeiniger fault zone SW of the Black Forest, the isopach pattern shows a E–W trend and thus, corresponds to that of Permo-Carboniferous faults underneath (cf. McCann et al. 2006).

The thickness maximum $\sim$ 5 m of the Beggingen Member in the Weissenstein area occurs above the eastern tip of the southern boundary faults of the Olten Trough (cf. Madritsch et al. 2008). Local occurrences of the Beggingen Member being 3–5 m thick are situated above the Olten Trough and continue along the ENE–WSW striking southern margin of the Constance-Frick Trough. However, while located above several faults, they could have been reactivated simultaneously or subsidence of the Early Jurassic seafloor was affected by Triassic salt underneath (Wetzel et al. 2003).

5.2.5 Weissenstein Member

The S–N- to SSE–NNW oriented tongue-shaped and thinning occurrence of sandy deposits of the Weissenstein Member suggests sediment delivery from the Alemannic Land (Fig. 9; e.g., Trümpy 1980; Wetzel et al. 1993). However, even if sediment input appears to be reflected by this pattern, sediments only become part of the rock record below base level. The northern limit of the Weissenstein Member shows an overall ENE–WSW trend that disappears above the Olten Trough. Thickness up to 22.5 m reflects significant subsidence. Enhanced subsidence at this time is also recorded further to the SW in the well Altishofen (Fischer and Luterbacher 1963; Büchi et al. 1965).

Dolomite-bearing intervals within the Beggingen and Weissenstein members appear along an ENE–WSW direction adjacent to the northern boundary fault of the Olten Trough. Dolomite was encountered where these two lithostratigraphic units show reduced thickness. Dolomitisation very likely resulted from emergence of this area (Wetzel et al. 1993). This constellation is interpreted as evidence for differential subsidence related to a reactivated Paleozoic fault zone.

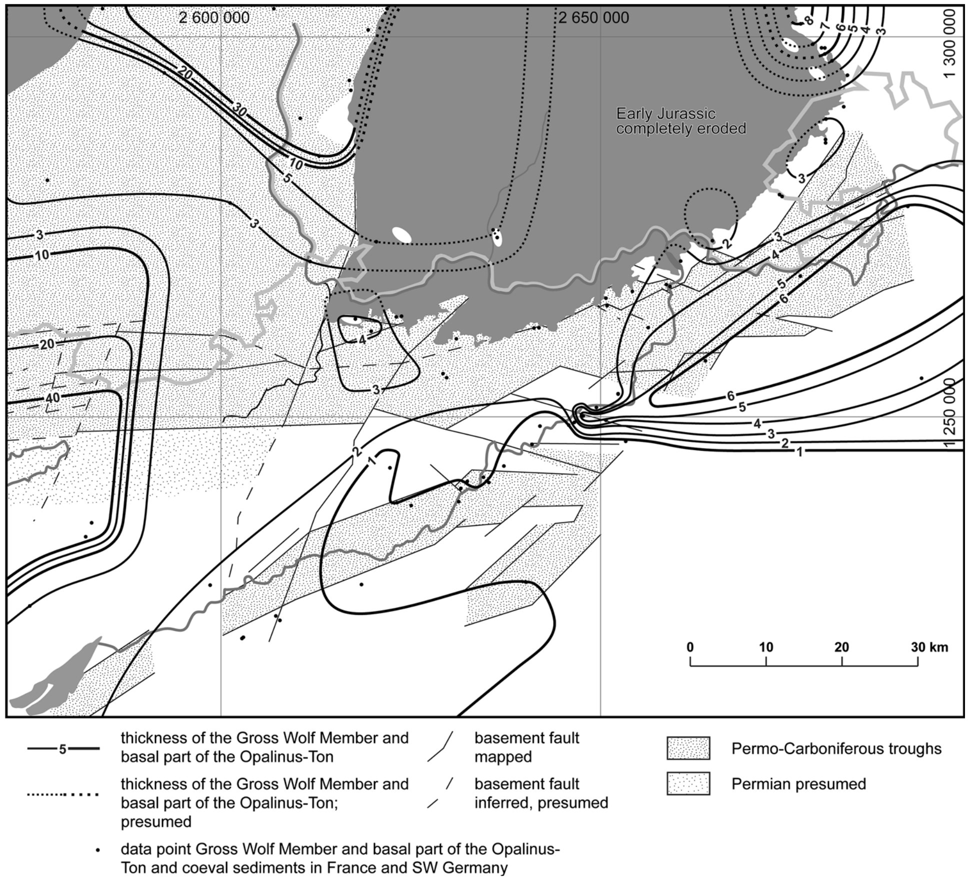


Fig. 14 Palinspastically restored isopach map of the Gross Wolf Member (Staffelegg Formation) and basal part of the Opalinus-Ton, the Jurensismergel Formation and basal part of the Opalinuston Formation as well as Toarcien marneux and basal part of the marnes à opalinum (Late Toarcian). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)

5.2.6 Frick Member, Grünscholz Member, Fasiswald Member and lower part of the Mt. Terri Member

Subsidence in the Upper Rhine Graben area started to increase during the Early Sinemurian and continued during the Late Sinemurian to Early Pliensbachian, while the area east of the Wehra-Zeininger fault zone slowly subsided. In the Klettgau area, low thickness ($\sim$ 10 m) documents slow subsidence ($\sim {}^{1}/_{3}$ compared to the adjacent area) close to the boundary of the Constance-Frick Trough (Figs. 3, 10). Only $\sim$ 5 km further S sediment thickness increases above the Constance-Frick Trough to $\sim$ 15 m. As general trend, the Late Sinemurian–Early Pliensbachian strata record higher subsidence above the Constance-Frick Trough than in adjacent areas without Palaeozoic fault systems (cf. Wetzel 2008: Fig. 10.36). This overall trend is also evident above the Olten Trough, where roughly two ENE–WSW trending thickness maxima occur. Therefore, Sinemurian–Early Pliensbachian isopach pattern was modulated by Permo-Carboniferous Troughs as well as the Rhenish Lineament and the Wehra-Zeininger fault system.

5.2.7 Breitenmatt Member and upper part of the Mt. Terri Member

The subsidence pattern changed significantly during the early Pliensbachian. In the area of the Upper Rhine Graben a domain still shows enhanced subsidence, but the depocentre shifted towards W (Figs. 10, 11). In spite of the westward shift, the NNE–SSW-trend retained. Its western limit extended close to the Rhenish-trending Lubine-Lalaye-Baden–Baden fault zone (Echtler and Chauvet 1992). Thus, subsidence did not accelerate along the Rhenish Lineament and the Wehra-Zeininger fault zone.

Southward of the Lubine-Lalaye-Baden–Baden fault zone sediment accumulation increased during the early Pliensbachian for the first time within the area of the Upper Rhine Graben and into an area where presumably a continuation of the Permo-Carboniferous trough system is situated (cf. Ustaszewski et al. 2005; Madritsch et al. 2008). In the remaining area, including that above the Constance-Frick and Olten troughs subsidence was slow (Fig. 11).

5.2.8 Rickenbach Member and Müsenegg Bed

During the Late Plienbachian to earliest Toarcian, the previous subsidence pattern is largely retained. Above the Permo-Carboniferous troughs subsidence is low, while subsidence increased within the central part of the Upper Rhine Graben (Figs. 11, 12). E of the Black Forest a N–S-trending depocentre occurs in the Wutach area.

5.2.9 Rietheim Member

The spatial arrangement of early Toarcian depocentres resembles that of the Pliensbachian in the Wutach and Upper Rhine Graben area, but not outside (Figs. 11, 12, 13). These depocentres are aligned in Rhenish direction. The southward shift of the depocentre in the Upper Rhine Graben towards the Mt. Terri-area marks, however, a considerable change. As during the early Pliensbachian, the area west of the Rhenish Lineament and its southern continuation shows enhanced subsidence (Figs. 11, 13). Late Paleozoic sediments of yet unknown thickness may occur underneath (Figs. 3, 13).

The isopach map also shows two N–S-trending thickness minima (< 3 m). The large minimum extends from the Black Forest towards the south and crosses the Olten Trough and the Constance-Frick Trough. In the north, the narrow minimum runs roughly along the Rhenish Lineament. The sediments show signs of reworking that probably happened during the sea-level low-stand of the Variabilis Zone (Knitter and Ohmert 1983; Einsele 1985; Kuhn and Etter 1994). Therefore, these minima resulted from erosion that occurred at least partly in vicinity to the mentioned tectonic structures (Fig. 13).

5.2.10 Gross Wolf Member and basis of Opalinus-Ton

Areas of high and low subsidence subsisted with some modifications during the Late Toarcian such as depocentres in the Upper Rhine Graben and the Wutach area (Figs. 13, 14). The erosive relief formed during the early Variabilis Zone in the Upper Rhine Graben area was levelled out during the late Variabilis Zone (Knitter and Ohmert 1983; Einsele 1985; Riegraf 1985).

Thereafter, during the Aalensis Zone, subsidence increased significantly in the area around Freiburg and at Mt. Terri (Wetzel and Allia 2003; Reisdorf et al. 2016; Hostettler et al. 2017). Due to missing high resolution biostratigraphic data, it remains unclear whether rather high subsidence prevailed in the area between Mt. Terri and the Upper Rhine Graben or whether two separate depocentres existed, separated by a slowly subsiding domain (as shown in Fig. 14).

Apart from the areas of enhanced subsidence during the Late Toarcian, subsidence increased locally above Permo-Carboniferous fault systems, but in some areas data are too sparse. In the eastern part of the study area increased subsidence resulted in an ENE–WSW isopach trend.

5.3 General aspects of sediment thickness distribution

The lithostratigraphic units shown in the isopach maps formed within a particular, but rather narrow range of depositional water depth, while their facies characteristics and faunal contents are quite uniform for each unit. The individual isopach maps document the effect of the emergent Alemannic Land in the S expressed mainly by the overall southward decreasing thickness. This trend is, however, not exclusively caused by reduced sediment accumulation. In particular, the mudstone-dominated units (Schambelen Member, Frick Member, Fasiswald Member and Rietheim Member) are increasingly erosively truncated towards the south (cf. Riegraf 1985; Brandt 1986; Bloos 1990; Kuhn and Etter 1994). Furthermore, synchronous lithostratigraphic units adjacent and distant to the Alemannic Land differ in facies and infinger, in particular the Sinemurian to Early Pliensbachian lithostratigraphic units (Figs. 9, 10).

Different facies and, thus, lithostratigraphic units formed during the same time (Fig. 5). Synchronous units, however, differ only little, about ± 5 m in their depositional water depth except the Mt. Terri and Breitenmatt Member for which a bathymetric difference of ~ 15 m is estimated. Synchronous units exhibit an overall trend of decreasing thickness southward that is superimposed by positive and negative deviations discussed below.

Except the condensed Pliensbachian strata (Breitenmatt and Rickenbach Member), the thickness of the stratigraphic units of the Staffelegg Formation exceeds the eustatic sea-level rise during the corresponding period (Fig. 5; Table 1). The Pliensbachian strata in SE Germany and E France are even thicker than the concomitant eustatic sea-level rise. Therefore, additional accommodation space must have been provided by subsidence and hence, isopach maps reflect the subsidence pattern.

5.3.1 Early Jurassic transgression surface

The relief of the depositional area at the onset of the Jurassic transgression might have influenced the isopach patterns of the basal Early Jurassic strata. They rest on the Klettgau Formation, in particular the Belchen or the Gruhalde Member (see above; Reisdorf et al. 2011; Jordan et al. 2016). Where the Belchen Member was eroded or did not form, the Klettgau Formation shows reduced thickness (Figs. 6, 7; Jordan et al. 2016). The particular N–S-trending zone south of the Black Forest has been called "Black Forest-Aar Massif Rise" (e.g., Trümpy 1980; Wetzel et al. 1993; Jordan et al. 2008; Fig. 6). However, the morphology of this domain in Late Rhaetian and Early Jurassic times is not really known (Schneebeli-Hermann et al. 2018; see also Trunkó 1998). Furthermore the reason for missing Rhaetian deposits, non-deposition or later erosion, remains speculative (Altmann 1965; Aepler 1974; Etzold and Schweizer 2005). Similarly, original thickness and amount of erosion of the Belchen Member remains unknown (cf. Etzold and Schweizer 2005; Nitsch et al. 2005).

The western boundaries of the overlying Early Hettangian Schambelen Member and Beggingen Member coincide with the area of reduced thickness of the Klettgau Formation implying the presence of a positive relief (Fig. 7; Jordan et al. 2016). Similarly, the thickness of the Schambelen Member decreases eastward where the thickness of the Klettgau Formation increases. In contrast, the two depocentres of the Schambelen Member are located where no Rhaetian sediments are present (any longer) and the Klettgau Formation exhibits the lowest thickness (> 20 to 40 m). This pattern suggests that a negative relief became filled suggestive of relief inversion. However, the Schambelen Member accumulated in rather uniform water depths of 5–10 m and, therefore, at the onset of the Early Jurassic transgression very likely a low-relief coastal plain was flooded. Because of the fine-grained nature of both Belchen and Schambelen Member, layers consisting of reworked material are highly unlikely to occur. However, considering the mentioned topography of the boundary between both members, erosion occurred in the time span between Belchen and Schambelen Member or when the Schambelen Member started to form (Figs. 5, 7; Reisdorf et al. 2011; Schneebeli-Hermann et al. 2018). In contrast, the Beggingen Member that accumulated in < 10–15 m water depth commonly exhibits reworked material at the base and hence, documents erosion of the substrate.

5.3.2 Transgression direction of the Jurassic Sea

The direction of Jurassic transgression is recorded by the oldest Jurassic sediments preserved in NW Switzerland, E France and SW Germany (see Debrand-Passard 1980, 1984a, b; Mégnien and Mégnien 1980; Wetzel et al. 1993; Geyer et al. 2011). The earliest Early Jurassic sediments are reported from Kleiner Heuberg near Balingen (SW Germany, ~ 50 km N of Switzerland; earliest Planorbis zone; Altmann 1965; Bloos 1999; Bloos and Page 2000). Slightly younger sediments of the Planorbis zone occur somewhat to the SW (Altmann 1965; Krimmel 1980; Schlatter 1983) and continue to the S to NW Switzerland (Hallau Bed of the Schambelen Member; Planorbis zone; Fig. 5; Schlatter 1983; Reisdorf et al. 2011). Therefore, transgression of the Jurassic Sea in the study area was SW-directed (see Wetzel et al. 1993; Geyer et al. 2011).

5.4 Isopach pattern, basement structures and stress field

The isopach patterns of the studied strata shows recurrently conspicuous spatial relation to Paleozoic fault systems in the basement. Relative isopach minima and maxim are superimposed on a general trend of southward decreasing thickness. Pronounced depocentres and areas of reduced thickness showing these Palaeozoic preferential strike directions, however, indicate that in many instances only parts of the Palaeozoic faults became reactivated (see above).

The recurrently preferred orientations of isopach anomalies suggest causal relationship to the tectonic stress field during the Early Jurassic that was characterized by a NW–SE extensional regime while rifting affected the Tethyan and the North Atlantic realm (Ziegler 1990; Philippe et al. 1996; Scheck-Wenderoth et al. 2008). This extensional regime has had the potential to reactive at least parts of the Palaeozoic tectonic structures forming part of the Rhenish Lineament, the Wehra-Zeininger fault zone and the Permo-Carboniferous trough system.

All these faults appear to have dissected the basement into a block-mosaic (Diebold and Naef 1990). Differential movements between individual blocks very likely occurred during strike-slip movements in the mentioned stress regime (see Reicherter and Reinecker 2008; Lenoir et al. 2014). For instance, conjugate fault systems may result in small-scale pull-apart basins parallel to trough axis and induce small-scale subsidence domains as recorded by the Early Sinemurian strata in NW Switzerland (Figs. 3, 9). Differential subsidence within the basement related to block rotation or strike-slip movements, however, are very likely transformed into flexural movement on the seafloor while affected by ductile deforming Triassic salt (e.g., Wetzel et al. 2003).

The patterns of the individual isopach maps imply a slight change of the stress field during the Early Jurassic. For instance, the youngest Sinemurian sediments in the area of the Upper Rhine Graben show an increase in thickness towards W that is superimposed on the above mentioned N–S trend (see above, Fig. 10). Since the late Sinemurian N–S-trending, large-scale depocentres prevail along the Rhenish Lineament and similarly oriented faults. However, the depocentres repeatedly shifted towards or away from the center of the Upper Rhine Graben (Figs. 7, 8, 9, 10, 11, 12, 13, 14), but also beyond its borders to the S to the Mt. Terri area. The depocentre located in the southern extension of the Upper Rhine Graben between the

Rhenish Lineament and Caquerelle Fault implies a southward continuation of the Burgundy Trough extending beyond its known boundaries (Figs. 3, 11, 13, 14). A similar result was obtained for the Late Oxfordian to Late Kimmeridgian Reuchenette Formation (Jank et al. 2006: Fig. 17).

The isopach patterns of Early Jurassic strata can be interpreted as the result of a sequential brittle reactivation of faults dissecting the basement. This also applies to significant thickness minima that are located in the area of the Upper Rhine Graben (Figs. 11, 13). In particular, in the Courtemautruy section in the Mt. Terri area a hiatus comprises the period from the latest Early Sinemurian to the early Pliensbachian (Turneri to Ibex zone) due to erosion (Reisdorf et al. 2011), while in sections in $\sim$ 500 m distance during this period $\sim$ 10 m thick sediments accumulated (e.g., section Les Salins; see Reisdorf et al. 2011).

5.5 Thermal effects of extension

Effects of approximate NW–SE extensional stresses increased at the beginning of the Middle Jurassic and continued at varying intensity until the Late Jurassic causing considerable differential subsidence in relation to Palaeozoic faults in the basement (Philippe et al. 1996; Wetzel et al. 2003). Many of these deposits are characterized by significant facies changes and large thickness (Wetzel et al. 2003). Furthermore, lithospheric extension during the Late Triassic and Early Jurassic led to heating of the basement and subsequent thermal subsidence (Timar-Geng et al. 2004; Scheck-Wenderoth et al. 2008). In addition, extensional stresses resulted in hydrothermal activity recorded by vein mineralizations and mineral alterations. Many veins outcropping or drilled in the Vosges and Black Forest area were chronometrically dated. They reveal a Rhaetian to Early Jurassic age. However, the age spectra are often wide and, therefore, they cannot be ascribed to distinct pulses of fault reactivation (Wetzel et al. 2003 and references therein; Timar-Geng et al. 2004; Baatartsogt et al. 2007; Edel et al. 2007).

For some of the dated veins, the orientation is documented having E–W to WNW–ESE strike directions in the southern Black Forest (Werner et al. 2002), as well as NW–SE in the central Black Forest (Bonhomme et al. 1983; Werner et al. 2002). These data support that Paleozoic fault systems in the basement of NW Switzerland and adjacent areas became reactivated during the Jurassic. Chronometric age data giving a narrow spectrum document hydrothermal activity during the Rhaetian in the Black Forest (Wernicke and Lippolt 1995; Staude et al. 2012), and during the Hettangian (Wernicke and Lippolt 1995; Brander 2000), Sinemurian (Werner et al. 2002), Pliensbachian (Lippolt et al. 1986; Werner et al. 2002) as well as during the Toarcian (Mertz et al. 1991; Wernicke and Lippolt 1994; Pfaff et al. 2009). In particular fault systems became reactived that are oriented similar to the North-Swiss Permo-Carboniferous Trough.

6 Summary and conclusions

For sediment successions of considerable thickness in epicontinental basins, the effects of synsedimentary tectonic movements have been recurrently demonstrated, while rather thin deposits were subordinately studied. The Early Jurassic strata in NW Switzerland are rather thin, commonly $<$ 50 m and accumulated in shallow water $<$ 50–60 m deep, but nonetheless the influence of synsedimentary differential subsidence can deciphered by using isopach maps covering time spans of $<$ 6 Myr.

The Palaeozoic basement has been structured at the end of the Variscan orogeny by faults systems being mainly NNE–SSW and NW–SE oriented. They dissect the basement resulting in a mosaic of blocks. Therefore, in response to the stress field small-scale tectonic movements may take place along such fault systems, in particular in an extensional stress field, for instance during the Jurassic, when the Tethys and the North Atlantic Ocean opened. The reactivation of these Palaeozoic fault systems since the Latest Triassic is documented by Rhaetian and Early Jurassic strata that exhibit a variable and complex lithostratigraphic architecture and distinct thickness changes. Because of the in-average low sedimentation rate these changes are often of low magnitude. In many instances, facies and isopach pattern spatially coincide with faults in the basement. The spatial relationships suggest that movements within the basement affected the seafloor above. However, ductile deformation of Triassic salt very likely led to flexural deformation of the Early Jurassic seafloor.

In NW Switzerland and adjacent areas, synsedimentary tectonic activity is particularly obvious in vicinity to the Rhenish Lineament. Displacement along normal faults provided accommodation space for comparatively thick deposits since the Sinemurian. Furthermore, reactivation of faults belonging to the North-Swiss Permo-Carboniferous Trough system is expressed by isopachs displaying a roughly ENE–WSW trend. The individual segments, Constance-Frick Trough, Olten Trough and Klettgau Trough, are reflected in case of activity by isopach patterns at a stratigraphic resolution of a sub-stage. Small-scale isopach anomalies occur above the trough axis. They are suggestive of strike-slip movements along the complex fault systems within the basement.

Chronometric age data of hydrothermal veins and mineral alterations within the basement as well as in the Mesozoic sediment cover document tectonic movements during the Early Jurassic and, hence, support the above sedimentological indications of synsedimentary tectonics.

Isopach maps are not only suitable for the detection of synsedimentary tectonics, but they are also an effective tool to indicate and localise activity of fault systems. Even if the tectonic movements are small during the Early Jurassic. This period should no longer considered as a time of "tectonic quiescence" in NW Switzerland, E France and SW Germany.

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