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RESEARCH ARTICLE

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Brackish water algal reefs – facies analysis as a tool to identify palaeoenvironmental variations in Miocene deposits (Mainz-Weisenau, Germany)

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Brackish-water carbonates are far less studied than their marine or limnic counterparts. However, their association with few, specialized species enables the documentation of fine-scale changes in the depositional environment. The Cenozoic Mainz Basin (Germany) was only sporadically connected to the North Sea and the Paratethys, exposing several transitions from marine to fresh water influence. Focusing on one outcrop of the Rüssingen Formation of Mainz-Weisenau (Aquitanian, Miocene), we present a detailed analysis of the faunal and sedimentological responses to changing salinities and water depth, including algal reef growth and facies development. The deposits include allochthonous limestones surrounding an autochthonous reef complex and several smaller reef patches. The allochthonous facies is dominated by the gastropod *Hydrobia inflata*, and the reef facies is mainly made up by the green alga *Cladophorites* sp. The algal thalli are overgrown by cryptocrystalline, organic precipitations, and laminated, chemical precipitations. Locally, quiver-shaped structures of Trichoptera sp. protective cases occur. The depositional setting was a shallow, low energy, and brackish environment supersaturated by carbonate. We could not confirm a general trend of reducing salinities as reported for the Rüssingen Formation. Our results question previously reported episodic desiccation events, because apparent caliche horizons actually represent thin beds of increased *Cladophorites* growth. Set-up, distribution of the reef facies, and reef debris indicate short-time variations of temperature, salinity and water depth. We conclude that these variations are based on the geographic position at the edge of an algal reef barrier, separating the Mainz Basin from the Rhine Rift Valley.

KEYWORDS
algal reefs, brackish deposits, *Cladophorites* sp., facies development, microbial calcite precipitation

1 | INTRODUCTION

Several studies have focused on the Cenozoic Mainz Basin in mid-west Germany and its development in terms of stratigraphical and palaeoecological issues (e.g., Grimm et al., 2011; Kadolsky & Schäfer, 2011). Also the area of Mainz-Weisenau was the focus of palaeontological (e.g., Doebl et al., 1972; Försterling & Reichenbacher, 2002), and sedimentological (Schäfer, 2012) studies. It features sediments of the complete Mainz Group including the Rüssingen Formation (Aquitanian, Miocene), which is investigated here.

Kadolsky and Schäfer (2011) summarized that these sediments were deposited in a low-energy setting, under low salinity and at shallow water depth. They further mention episodic subaerial exposures deduced from root horizons and caliche as well as terrestrial input in the form of marl and low amounts of quartzes at the basin margin. They also argue that the faunal content suggests a low but variable salinity. In contrast, Rothe and Klupsch (1988) found the minerals palygorskite and sepiolite, which typically develop under evaporitic conditions. Thus, it is possible that the Mainz Basin was an inland water-body with at least episodically high evaporation rates and accordingly high salinities (Kadolsky & Schäfer, 2011). Schäfer (2014)

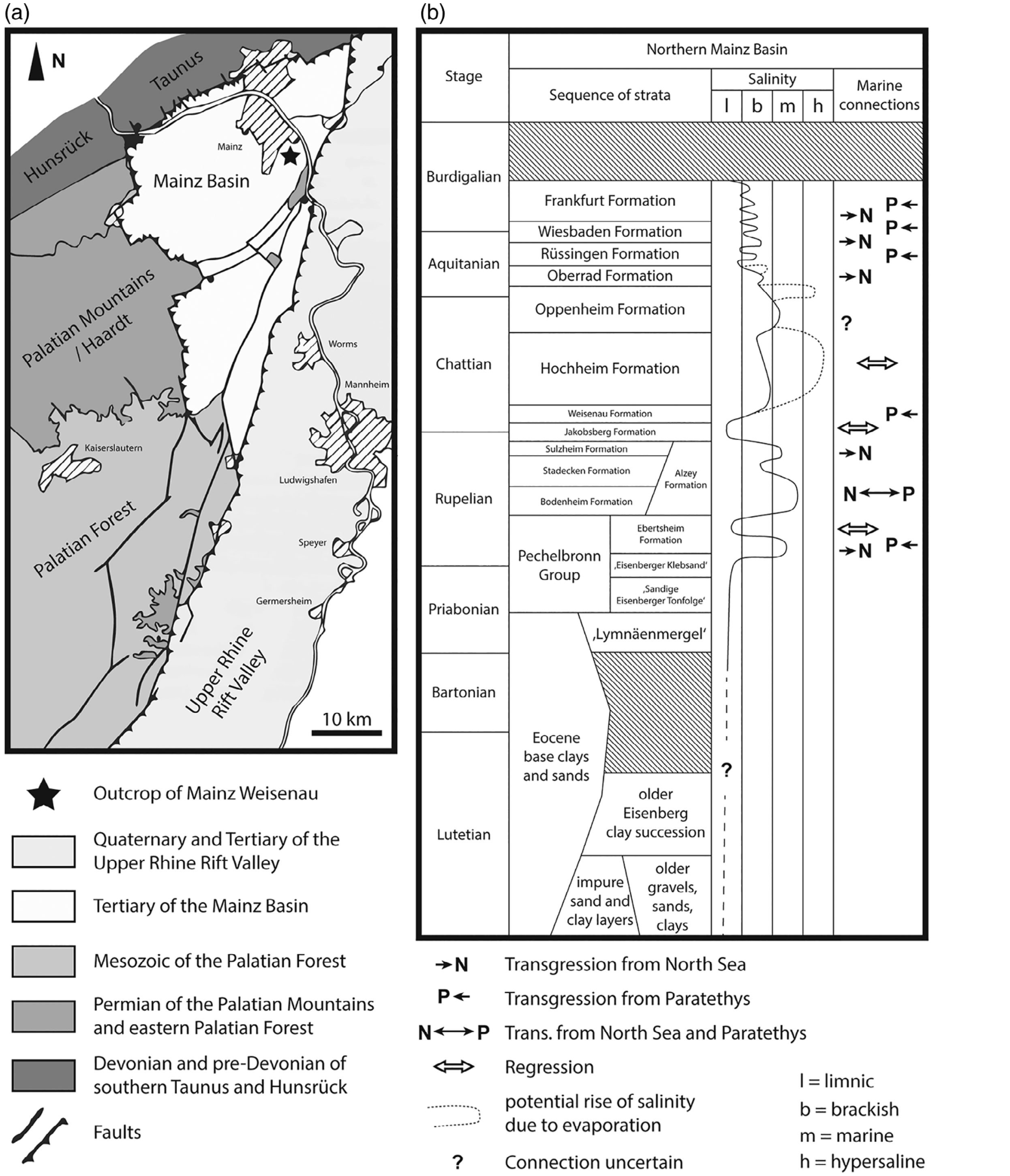

FIGURE 1 (a) Position of the outcrop Mainz-Weisenau and the geological setting of the surrounding area. (b) Stratigraphic sequence, salinity changes and marine connections of the northern Mainz Basin with the studied Rüssingen Formation (Miocene). Modified after Schäfer (2014)

suggests a general trend of shifting salinities in the long term towards brackish-limnic conditions. This shift would be interrupted by phases of increased salinities caused by weak ingressions, evaporation, freshwater influx, or varying precipitation. In this context, the interaction of fluctuating salinities and the development of an algal reef complex, which separated the shallow lagoon from the open basin, may provide information on the prevalent palaeoecology.

Comparatively little attention has been paid to brackish deposits so far. Apart from the limited number of outcrops compared to marine deposits, brackish environments often feature low biodiversity levels. In Mainz-Weisenau, the deposits are of low biodiversity and in phases monospecific, too, but they include an algal reef complex. Algal reefs in Mainz-Weisenau were first described in a doctoral thesis by Afaj (1983) and later by Kadolsky and Koch (1988), who called the structures pseudoreefs due to the absence of reef-forming metazoans. However, according to modern definitions, reefs are characterized by the constructional style and not necessarily by the presence of metazoans (Kiessling, Flügel, & Golonka, 2002; Riding, 2002), so we will use the term "reef" here. Kadolsky and Koch (1988) described the reef facies as massive limestones of columnar water plants, probably algae, growing on unspecified reef detritus. Concentric calcite encrustations form the outermost layer on most components, as known from freshwater deposits (Kadolsky & Koch, 1988). The faunal composition suggests either a prevalent brackish or a marine to hypersaline environment (Desjardins, Buatois, & Mángano, 2012); however, a distinction between these depositional environments was not made yet. Therefore, the section in Mainz-Weisenau contributes to fill this gap.

We used macro- and microfacies analysis to (a) track and analyse changes in the depositional system of the Rüssingen Formation in Mainz-Weisenau, also with regard to the spatial development of the algal reef barrier, and to (b) estimate changing salinity levels in the Mainz Basin during the deposition of the Rüssingen Formation.

2 | GEOLOGICAL SETTING

The Mainz Basin is situated between the Upper Rhine Rift Valley, the Rhenish Massif, the Palatinate Forest, and the Haardt (Figure 1a). Representing a depression within a mosaic fault complex, the Mainz Basin is not a basin sensu *strictu*, but a caved area west of the Upper Rhine Rift Valley (Grimm et al., 2011). Notwithstanding, the term Mainz Basin is historically established and will also be used in this study.

Sedimentation and development of the Mainz Basin during the Cenozoic are related to the formation of the Rhine Rift Valley. An interval of continuous sedimentation (Zechstein to Jurassic) was followed by erosive phases until the Early Eocene (Grimm et al., 2011). A first minor marine transgression is known from the southern part of the basin, the brackish Lymnäenmergel of the Upper Eocene (Figure 1b) (Schäfer, 2012). This was followed by several phases of transgression and regression from the North Sea with potential connections to the Paratethys in the south, implying changes in salinity from lacustrine to fully marine conditions (Schäfer, 2012). After further transgressions and regressions in the Rupelian and Chattian (Grimm & Grimm, 2003), the Oligocene marine transgression led to the deposition of the Weisenau Formation with the Lower Cerithienschichten (Schäfer, 2012). The calcareous Tertiary with its local lithological expression as the Mainz Group spans from the Chattian to the Burdigalian. According to Grimm and Grimm (2003) and Grimm (2005), a carbonate platform with calcareous shallow water lagoonal sediments developed. Klupsch and Rothe (1988) report caliche, dolomites, root traces, and desiccation cracks and interpret them as periodical subaerial exposes. Our study area, the quarry of Mainz-Weisenau, exposes besides other formations of the Mainz-Group, the Rüssingen Formation (Aquitanian), expressed as a sequence of calcareous to marly bedded sediments, locally with algal limestone reefs. It is characterized by the endemic gastropod and index fossil *Hydrobia inflata* (Pusch, 1837). Some layers consist almost exclusively of more or less consolidated specimens of *H. inflata*. An important correlation horizon within the whole basin is the upper *Falsocorbicula faujasii* (Deshayes, 1830) horizon. The Rüssingen Formation spreads all over the basin, with a thickness of ca. 40 m in the Mainz-Bretzenheim and ca. 17 m in the area of Mainz-Weisenau (Sonne, 1988).

3 | MATERIAL AND METHODS

Samples were taken from the Rüssingen Formation exposed in the quarry Mainz-Weisenau (49°58′30.8″N 8°18′13.1″E) near Mainz, in the mid-western part of Germany. The exact positions of the thin section samples are marked in Figure 2. We estimated the facies development by a macroscopic facies profile, and by microfacies analyses on 29 thin sections. Since the uppermost three beds were inaccessible, we could not retrieve samples from them in situ. Instead, we produced three thin sections from loose boulders clearly deriving from those beds, as they feature the upper *Falsocorbicula faujasii* horizon. Additionally, we used three thin sections from the collection of the palaeontological institute of the Friedrich-Alexander-Universität Erlangen-Nürnberg for facies analysis which come from the same outcrop. Thin sections were analysed and documented with a Zeiss AxioZoom V.16 binocular microscope. We produced the overview images with a HP Scanjet G4050 scanner and performed postprocessing with Adobe Photoshop CS6, Adobe Illustrator CS6. Classification of the samples was done according to the Dunham classification (Embry & Klovan, 1971 after Dunham, 1962).

4 | RESULTS

4.1 | General description of the profile

The analysed profile in Mainz-Weisenau has a length of 39 m and a height of c. 6 m (Figure 2). It shows bioclastic limestones with several algal reefs and seven major limestone beds, hereafter named L1 to L7 from the lowermost to the uppermost bed. The respective less-lithified beds are named M1 to M7. Visually, the section can be divided into

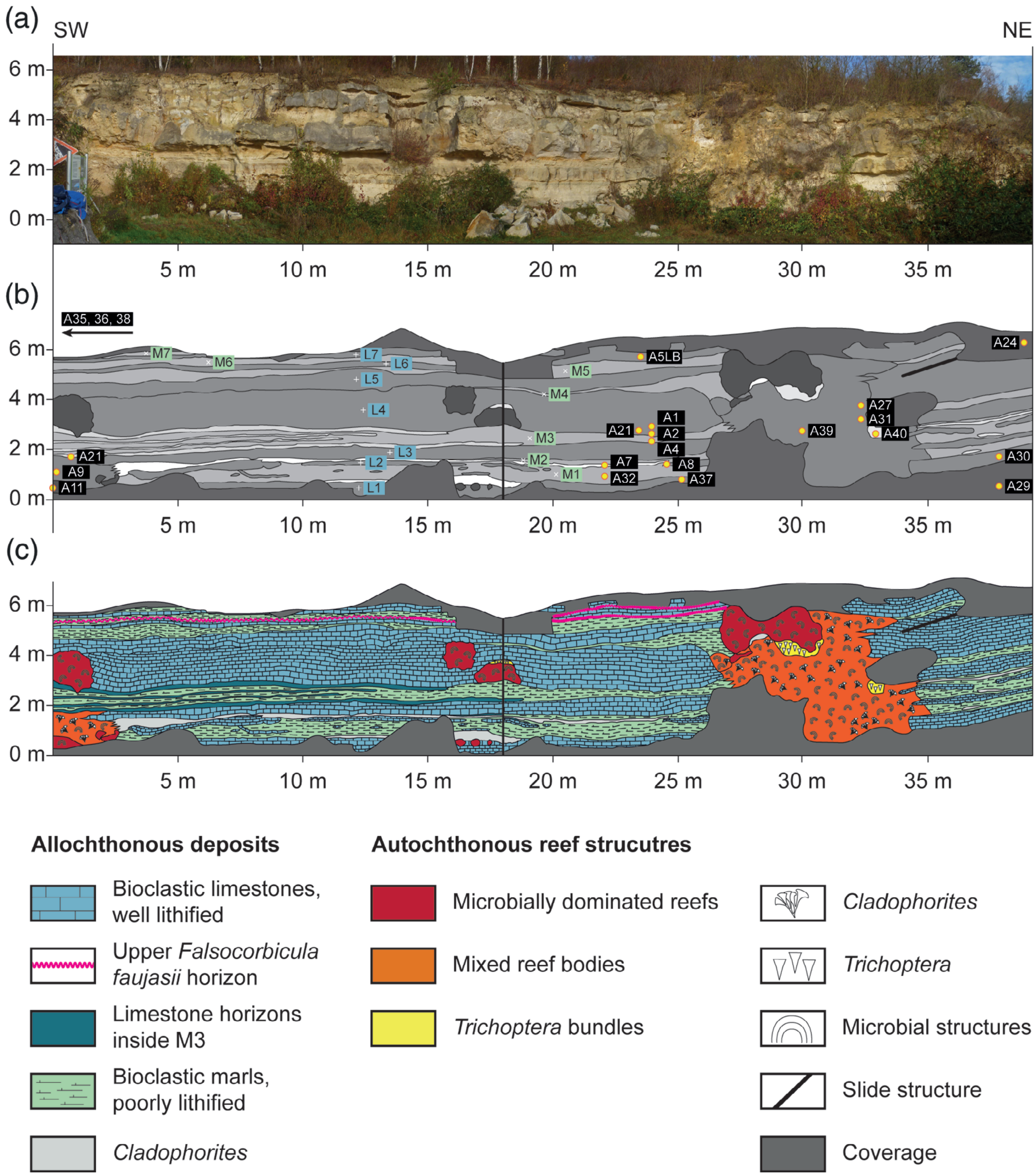

FIGURE 2 (a) Outcrop picture of the studied section in the former quarry in Mainz-Weisenau. (b) Bed labelling for limestones (L, blue colour) and marl (M, green colour), as well as sample locations (yellow dot with black label). (c) Result of the facies mapping [Colour figure can be viewed at wileyonlinelibrary.com]

reefs and surrounding deposits. A large reef complex divides the well-bedded section into a southwestern and a northeastern part. The beds on the northeastern side show a displacement of almost 1 m upwards respective to the ones on the southwestern side.

4.1.1 | Algal reefs

The largest reef complex with 8 m width and 5 m height is situated in the northeastern part of the profile, and smaller, autochthonous reefs prevail in the central and southwestern part (Figure 2a–c). While the large reef complex ranges from the oldest to the youngest bed, the smaller reefs are restricted regarding their chronological extension. Three small reefs are incorporated in limestone L4, and one reef stretches at the lowermost southwestern edge of the profile from zero meters to three meters in the length and interlocks then with the bedded area (Figure 2b,c).

Layers of poorly preserved *Cladophorites* occur in L1/M1 and L2/M2, crossing the boundary between lithified and unlithified beds. M3 comprises four horizons of reworked reef clasts. Depending on their composition and structure, we subdivided the autochthonous reefs into: (1) microbially-dominated reefs, (2) mixed reef bodies, and (3) quiver-shaped structure bundles (Figure 2c).

1. *Microbially-dominated reefs* (Figure 3a) are rigid structures of irregular cauliflower shape. They consist of finely laminated structures of up to 5 mm thickness, resembling the concentric layers of pisoids, and occasionally integrate gastropods in their structure (Figure 3b,c). In the field, we observed only fine-laminated structures, but microscopic analysis revealed that the general construction is more complex, yet similar in all the samples. The reef components have irregular roundish shapes and show some kind of concentric layering. There is no cell structure but a blotchy appearance inside them (Figure 3d). These cloudy structures are then encrusted by the finely laminated, brown, concentric layers (Figure 3e). Both structures cover other components like gastropods, ostracods, bivalves, and peloids as well (Figure 3f). All components are surrounded by a cloudy matrix which sometimes seems to agglutinate the components. Usually, the fabric is not oriented and is component supported. Because the rock is autochthonous, we identified it as a bindstone.
2. *Mixed reef bodies* (Figure 4a) consist of both (1) microbially-dominated reefs and (2) whitish, soft and crumbly deposits of algae. The algal thalli have a tubular structure and commonly grow in bunches and belong to the genus *Cladophorites*. Depending on the cut, the algae are round or elongated and hollow (Figure 4b,c). Reworked fragments of the thalli and microbially-dominated reefs are also incorporated within the algal bunches. The boundaries between *Cladophorites* and the microbially-dominated reefs are blurred. Reef growth is commonly initialized with the growth of *Cladophorites*. Locally, they are thinly encrusted by laminated dark structures, but commonly, cloudy microbial structures overgrow the green algae (Figure 4d). One sample consists only of the filamentous green algae *Cladophorites* (Figure 4e). It is partly overgrown by a cloudy

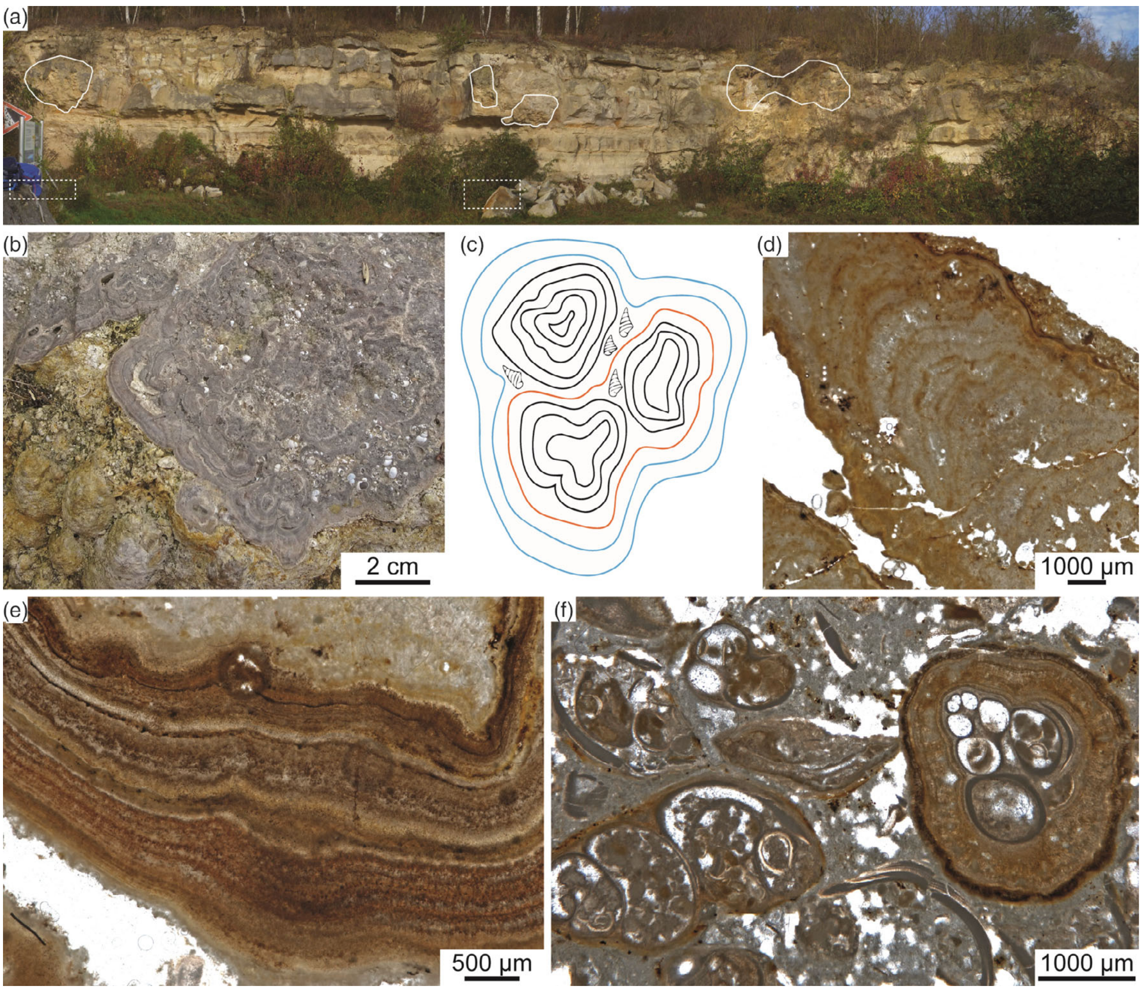

FIGURE 3 (a) Location of the microbially-dominated reefs (white circles). (b) Cauliflower-like structure of the microbially-dominated reefs. (c) Schematic drawing of the cauliflower-like structure. It consists of small microbially precipitated, laminated structures which are further overgrown by the same laminated structures and incorporate also *Hydrobia*. The black inner line is first, the red line is second, and the blue lines are the third generation of microbially precipitated layers. (d) Thin section image with alternating layers of microbial precipitates and whitish chemical precipitates. (e) Close-up view of the microbially precipitated, laminated structures. (f) The microbial structures coat a *Hydrobia* specimen [Colour figure can be viewed at wileyonlinelibrary.com]

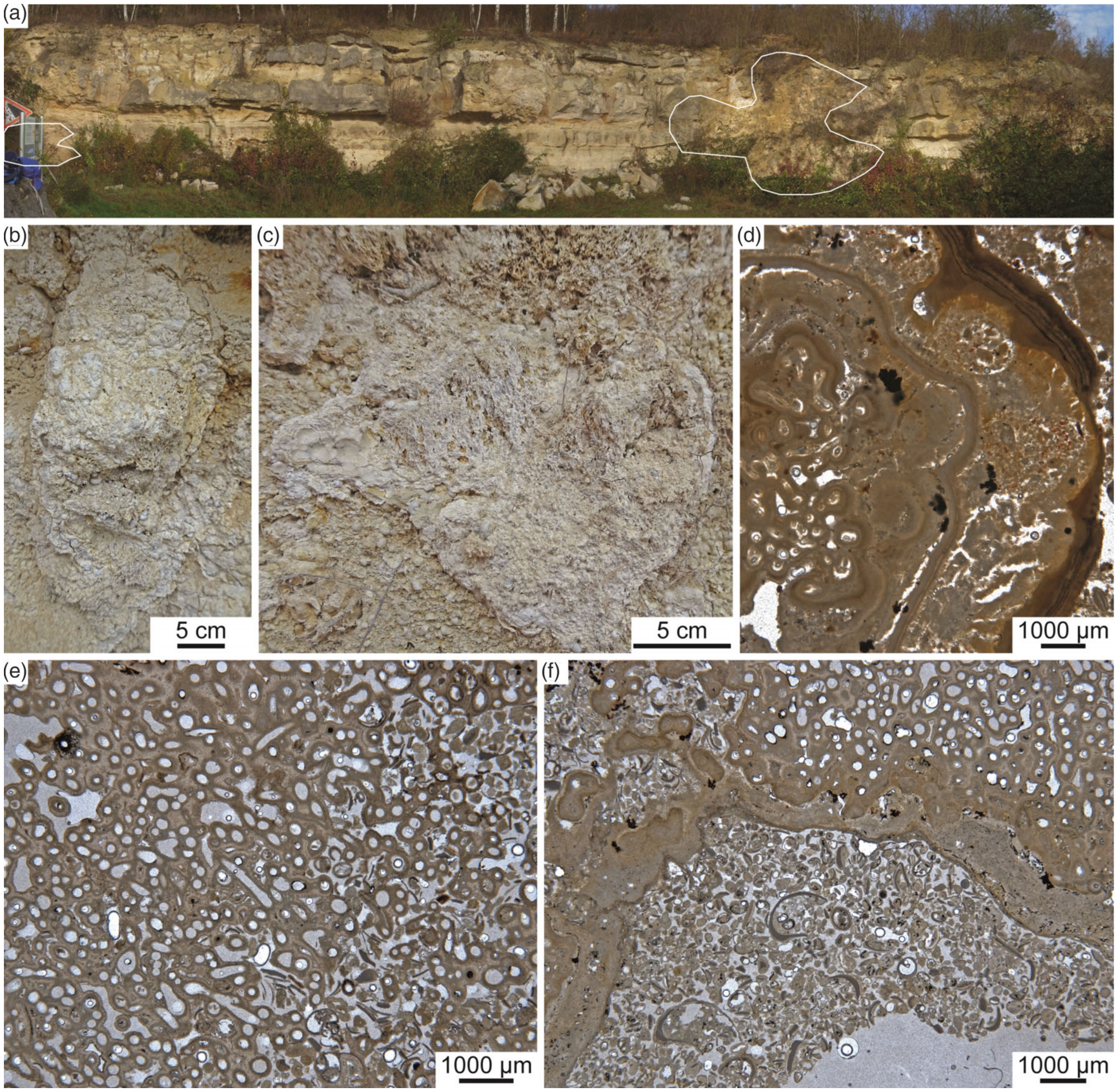

FIGURE 4 (a) Location of the mixed reefs (white circles). (b) Outcrop picture of large *Cladophorites* bunches. (c) Close-up view of freshly cut *Cladophorites* bunches displaying the tubular structure. (d) Alternately overgrown *Cladophorites* by cloudy and laminated structures of varying thickness. (e) Cross-section of a small bunch of tubular and filamentous *Cladophorites*. (f) Intercalation of gastropods or small bioclasts and *Cladophorites* with varying overgrowth of microbially and chemically precipitated laminated structures [Colour figure can be viewed at wileyonlinelibrary.com]

structure on which a laminated crust grew. Some gastropods and small bioclasts are overgrown by *Cladophorites* (Figure 4f). The frame-building fabric shows a lot of growth-framework and intraparticle pores. Therefore, it is a framestone.

3. *Quiver-shaped structures* commonly occur in bundles. They are irregularly elongated and cone to quiver-shaped (Figure 5a,b). There are two different forms, one shows the same laminated layers as the hard reef bodies (Figure 5c) and the other one agglutinates gastropods (Figure 5d) and was identified as protective cases of Trichoptera (caddisfly). Mostly, they are filled with calcite spar or laminated crusts, but some are hollow. They can reach up to 10 cm in length and are oriented with the tip of the quiver towards the ground. Rarely, isolated quivers were found as well in the allochthonous facies.

4.1.2 | Surrounding deposits

The reefs are surrounded by surrounding deposits, which we subdivided into: (1) bioclastic deposits, (2) *Cladophorites* deposits, (3) limestone horizons, and (4) the upper *Falsocorbicula faujasii* horizon.

1. *Bioclastic deposits* constitute most of the allochthonous profile compounds. Seven well-lithified limestone beds (L1–L7, Figure 2, blue coloured) alternate with seven poorly lithified beds (M1–M7, Figure 2, green coloured). Both lithologies are composed mainly of the gastropod *Hydrobia inflata*, which are about 5 mm long (Figure 6a), and differ only in terms of cementation. In thin section, the lithologies can, if at all, only be differentiated by the presence

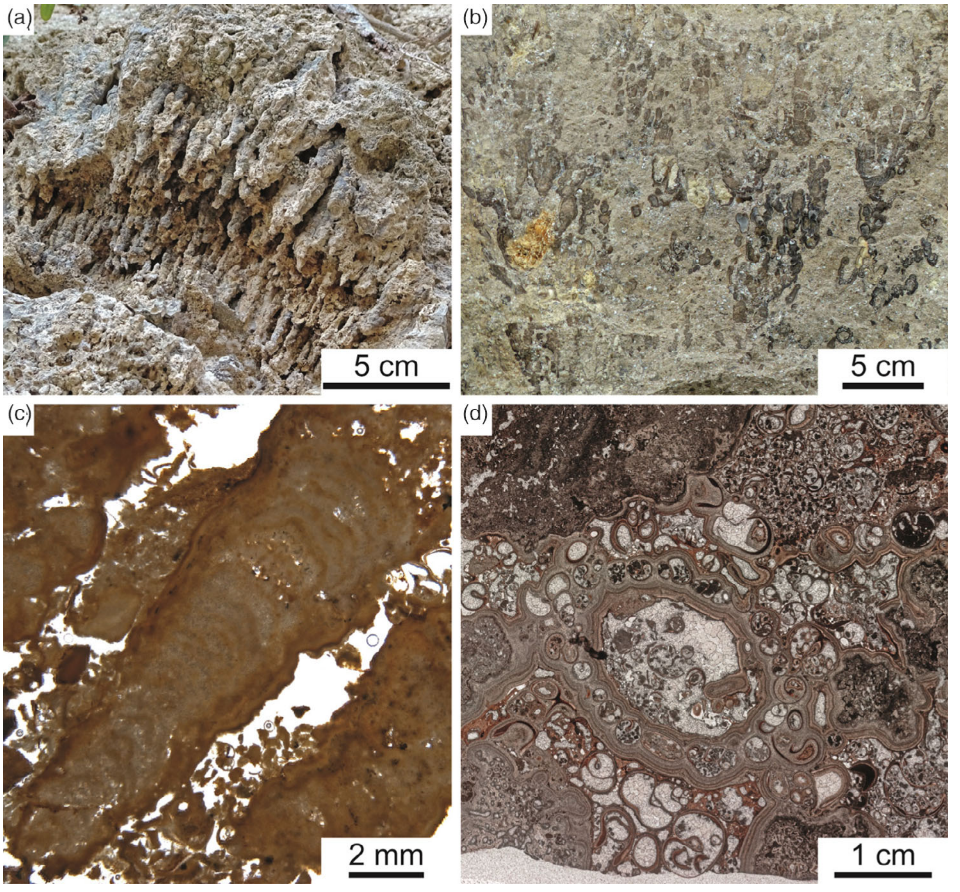

FIGURE 5 (a) Quiver-shaped structures on top of the hard reef at 18 m of the profile. (b) Quiver-shaped structures displayed at the surface of a small microbially-dominated reef in L4. (c) Thin section image of the laminated microbially precipitated form. (d) Horizontal cut of a Trichoptera protective case with agglutinated gastropods and chemically precipitated laminae, preserving the fragile structure. In thin section, it can be clearly distinguished from the microbially precipitated form in (c) [Colour figure can be viewed at wileyonlinelibrary.com]

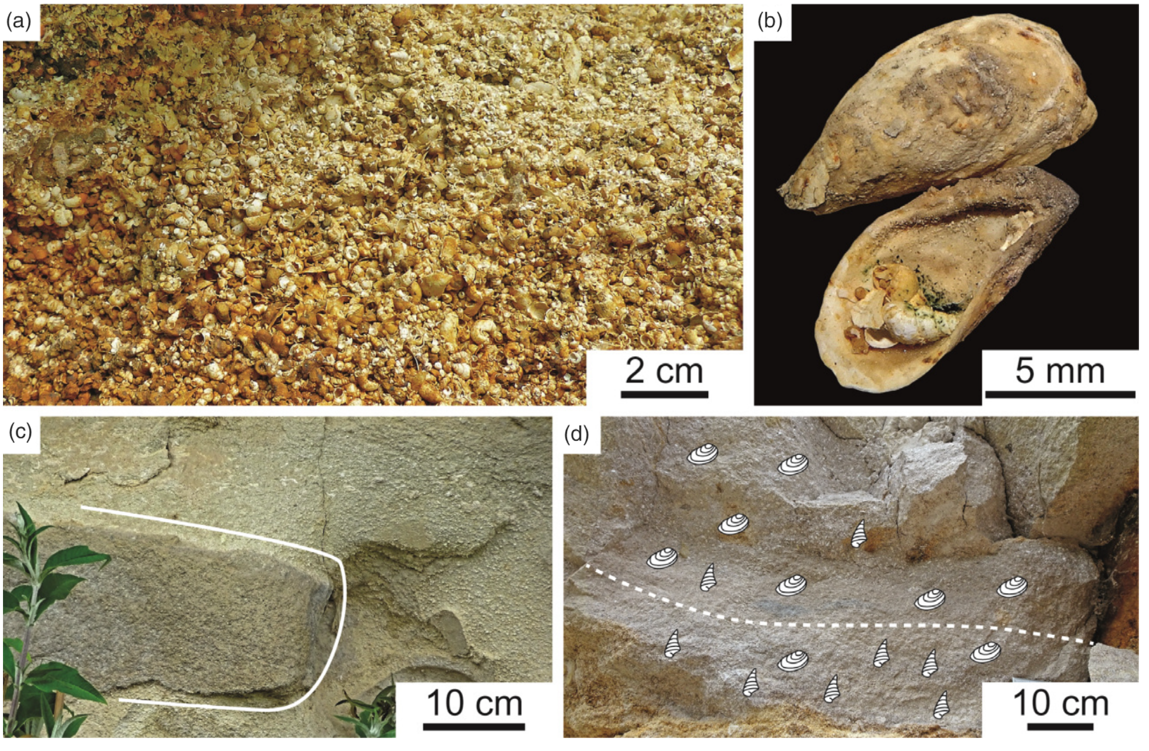

FIGURE 6 Bioclastic deposits. (a) Mass accumulation of *Hydrobia* which constitute limestones and marls. (b) The bivalve *Dreissena* is found in the uppermost section. (c) Limestone L2 is frequently interrupted. The only difference to the surrounding marl is the lack of cementation. (d) In limestone L4 bivalves occur layerwise in the *Hydrobia* accumulation [Colour figure can be viewed at wileyonlinelibrary.com]

of blocky calcite spar in L-beds. Dark laminated structures as well as cloudy structures occur occasionally in L- and M-beds. Besides *Hydrobia*, bivalves of the genera *Dreissena* and *Falsocorbicula* occur, as well as rarely terrestrial gastropods. Specimens of *Dreissena* are elongated and about 1 cm long (Figure 6b). The originally aragonitic molluscs are commonly partly dissolved and they are replaced by calcite in L-beds. Locally, reef components either reworked or built in situ, are incorporated into the beds. In thin section, ostracods, peloids with indistinct margins, as well as undeterminable bioclasts are present. The matrix is either sparitic with blocky calcite sparite, or—less abundant—blocky rim cements, or micritic with cloudy-peloidal texture. Therefore, we classified the samples as grainstones or, respectively, packstones. The pore space is developed as intra- and interparticle pores. Two beds have special features: L2 is locally disintegrated (Figure 6c), whereas all other beds can be followed through the section, and in L4, bivalves are layerwise intercalated in the otherwise pure gastropod limestone. At the lower part of L4, less bivalves (*Dreissena*) occur compared to their mass occurrence about 30 cm above the boundary (Figure 6d). We could not identify sorting, grading, or other sedimentary structures indicating transport or increased water energy.

2. *Cladophorites* deposits. The beds M1 and M2 contain very soft and crumbly layers (light grey area in Figures 2 and 7), which consist of poorly preserved *Cladophorites* specimens. The matrix around the components has a greyish-green colour.
3. *Limestone horizons inside M3*. Intercalated to the poorly lithified limestone M3 are four horizons which are darker and slightly better lithified than M3 (dark blue green area in Figures 2 and 8). Beside gastropods, they consist of components similar to those of the microbially-dominated reefs. These horizons thin out towards the north-eastern end of the profile.
4. Upper *Falsocorbicula faujasii horizon*. In the southwestern part of the profile, this horizon is located in M6, but shifts to the underlying L6 in the north-eastern part, where also a second layer of this bivalve becomes visible. One of these layers is situated at the wavy base and one is at the top of the limestone (Figure 9a,b). Between both layers, isolated bivalve specimens of 1.5–2.0 cm in length are scattered amongst the prevailing gastropod *Hydrobia* (Figure 9). They have a white to light greyish colour and a rather plain surface but show a light concentric striation. Many specimens are preserved articulated. Separated shells are mainly aligned horizontally with convexity down, but convexity up and vertical orientation also occur (Figure 9c). The bivalves are generally well preserved and scarcely broken. Some shells have geopetal fillings of cement or rarely of a peloidal matrix (Figure 9d). The matrix is mainly sparitic. We classified the horizon as grainstone.

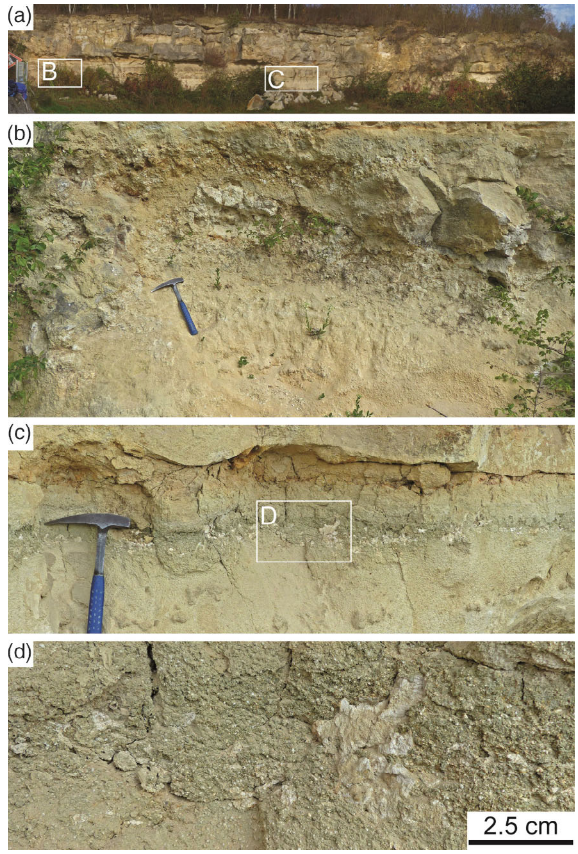

FIGURE 7 *Cladophorites*. (a) Location of the *Cladophorites* images in (b) and (c). (b) White spots are bunches of *Cladophorites* in the mixed reef. (c) Layerwise accumulation of white spots which are display in (d), the close-up view, tubular structures, though, badly preserved [Colour figure can be viewed at wileyonlinelibrary.com]

5 | DISCUSSION

During the Miocene, the study area had a similar geographic position as at present. Located in the temperate zone, the climatic conditions equalled today, yet warmer (Böhme, Bruch, & Selmeier, 2007). Therefore, the carbonates of the Mainz Basin can be classified as warm water carbonates. The section of Mainz-Weisenau is composed of several autochthonous reefs of varying size, and allochthonous limestones and more marly beds. The components in the surrounding deposits are mostly gastropods of the genus *Hydrobia*, and occasionally bivalves and ostracods (Figure 6). The bivalve *Falsocorbicula faujasii* of the homonymous horizon occurs in and above limestone L6 (Figures 2 and 9).

Low diversities but high abundances of taxa indicate either a very high salinity or a very low salinity level (Desjardins et al., 2012). Therefore, the facies was either a high salinity environment like a brine, or a brackish to freshwater environment. *Falsocorbicula faujasii* is known from brackish environments (Kadolsky, 2008). Thus, we conclude that the prevailing conditions during the deposition of bed L6 and bed M6 likely have been brackish. The other beds are characterized by mass accumulations of the gastropod *Hydrobia*. Today, *Hydrobia* occurs worldwide from freshwater to brackish or even marine environments, but is most abundant in freshwater environments (Barnes & Barnes, 1994). If the beds above and below the *Falsocorbicula* horizon were a high salinity environment, indications for evaporation or a

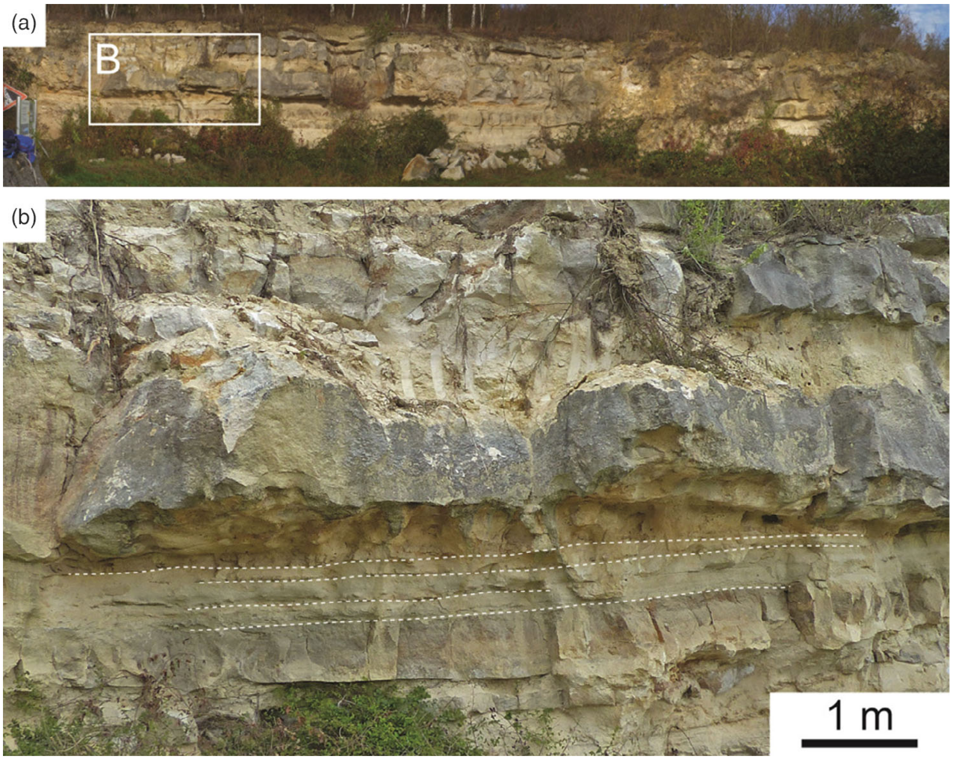

FIGURE 8 Well-lithified limestone horizons indicated by dashed white lines within the poorly lithified and depressed marl M3 [Colour figure can be viewed at wileyonlinelibrary.com]

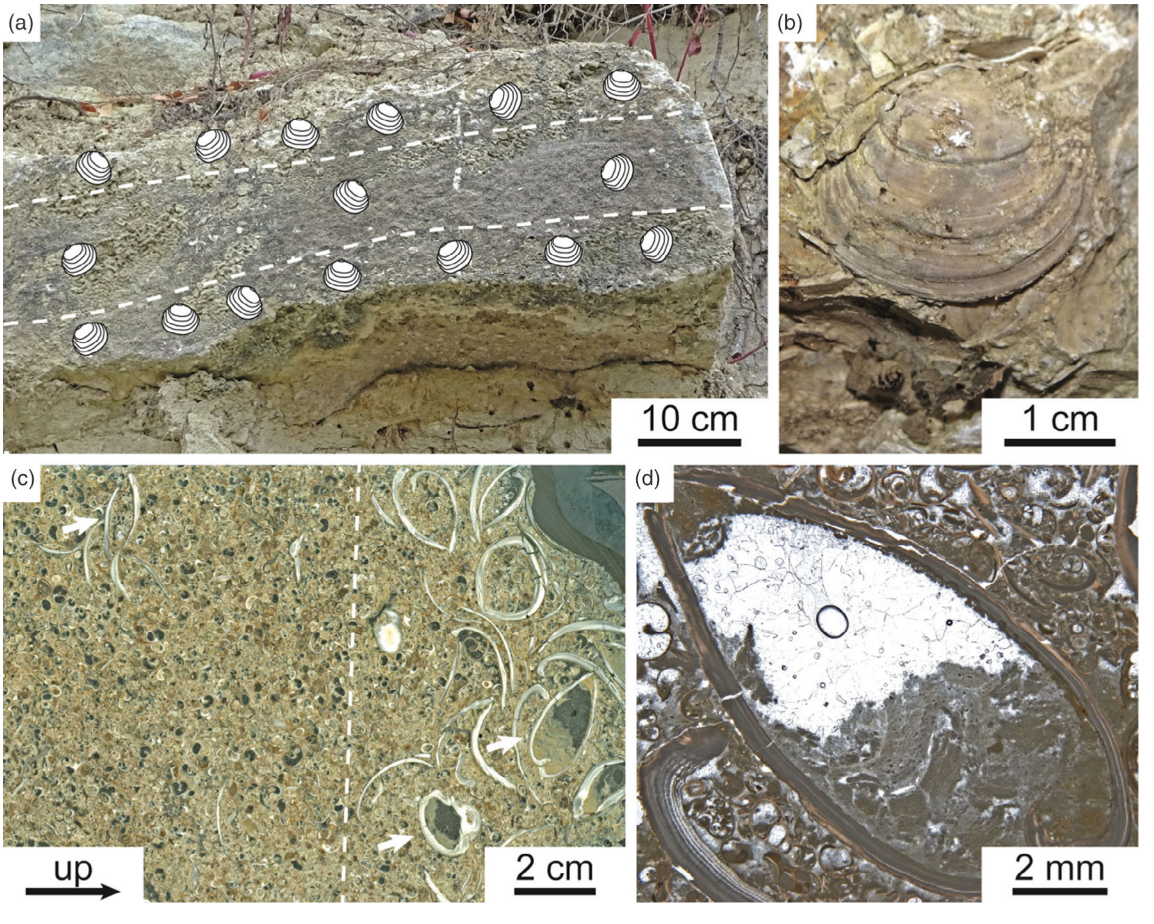

FIGURE 9 *Falsocorbicula faujasii* horizon. (a) Limestone L6 with two layers of *Falsocorbicula faujasii*. (b) One specimen within L6. (c) Polished surface of a sample of L6 displaying articulated and disarticulated specimens of *Falsocorbicula faujasii*. (d) Thin section of *Falsocorbicula faujasii*. As all other originally aragonitic component, it shows minor dissolution. The geopetal structure with sparite on top is pronounced [Colour figure can be viewed at wileyonlinelibrary.com]

transitional period of marine conditions would be expected. But, because of the absence of evaporative minerals and fully marine taxa, we follow previous studies and postulate a freshwater to brackish environment (e.g., Grimm et al., 2011; Reichenbacher, 2000; Schäfer, 2014). The occurrence of protective-cases of Trichoptera larvae (Figure 5) and the green alga *Cladophorites* (Figures 4 and 7), both of which are non-marine, further support this interpretation. Also, reports of *Cladophorites* in lake sediments from the Miocene Ries impact crater are in line with our assumption (Arp, 1995b). Therefore, the salinity was lower than during the deposition of the *Falsocorbicula* horizon, ranging between brackish to freshwater conditions. These salinity changes might have been triggered by climatic changes causing different amounts of precipitation and varying freshwater inflows, changing evaporation rates or sea-level fluctuations which could have caused short-term connections to the Mediterranean Sea (Reichenbacher, 2000).The *Cladophorites* algae dominating the reef bodies need a certain amount of sunlight to grow. Therefore, the basin was at least in some places probably shallower than 40 m (Markager & Sand-Jensen, 1992). The Trichoptera protective cases indicate phases of even shallower conditions of only a few tens of centimetres. Furthermore, washed-in land gastropods indicate close proximity to the shoreline. Following Afaj's (1983) and Schäfer's (2014) interpretation of an algal reef barrier with a shallow south-eastern lagoon to the south-west and the transition to the deeper settings in the north-east, the studied section of Mainz-Weisenau covers the transect from mid-lagoonal deposits to the beginning of the algal reef barrier. We interpret the small reefs within limestone L4 as patch reefs within the shallow lagoon, not exceeding 40 m water depth.

Kadolsky and Koch (1988) described reefs as autochthonous algal limestones which form layers or cauliflower-like aggregates. The reef facies in the outcrop of Mainz-Weisenau is very similar: the green alga *Cladophorites* is alternately overgrown by cloudy and laminated structures of varying thickness (Figure 4d), resembling pisoids (Flügel, 2004) that assemble to large complexes, often incorporating gastropods and ostracods. Contrary to the reports by Kadolsky and Koch (1988), we did not detect any reef debris at the bottom of the reefs and therefore conclude that this debris is not necessary for initial reef growth.

For the Rüssingen Formation, a general, though minor trend of reducing salinity is prospected. The results are in line with previous findings (Kadolsky & Koch, 1988; Schäfer, 2014), that only small-scale variations of salinity and sea level occur, but generally, the brackish, shallow, and low-energy deposits do not reveal changes from marine or brackish towards brackish or freshwater conditions.

Depending on the prevailing milieu, the growth and precipitation of pisoids show different patterns. Under freshwater conditions with high abundances of *Cladophorites* and Trichoptera protective cases, pisoid growth starts with chemical precipitation, while under brackish conditions, microbial crusts form the first layer (Figure 10). This indicates periodic short-time variations of the environmental conditions. The input of cold river discharge into the relatively warm basin probably led to the chemical precipitation of calcium carbonate. Therefore, intervals of increased precipitation suggest risen temperatures in the basin, probably in combination with increased freshwater supply. Rothe, Koch, and Schäfer (1997) refer also to biogenic and inorganic precipitations of calcite around *Cladophorites* specimens in Mainz-Weisenau, but they interpreted the inorganic precipitations as phases of meteoric phreatic or vadose conditions, an assumption that we could confirm by our findings for the Rüssingen Formation. For chemical and bacterial precipitation, saturated to supersaturated conditions with respect to carbonate are necessary. It is unlikely that the basin was supersaturated in terms of calcium carbonate, but reoccurring of carbonate saturation due to relatively cold river runoff into the warm basin appears plausible with the surrounding carbonate deposits.

From our perspective, the caliche-horizons reported by Rothe et al. (1997) for the Oberrad Formation and cannot be confirmed for the Rüssingen-Formation in the studied succession in Mainz-Weisenau. The horizons are not caliche but are composed of poorly preserved *Cladophorites* specimens. We therefore do not interpret the occurrence of these horizons as intervals of desiccation or emersion, but as phases of increased *Cladophorites* growth. A comparison of the

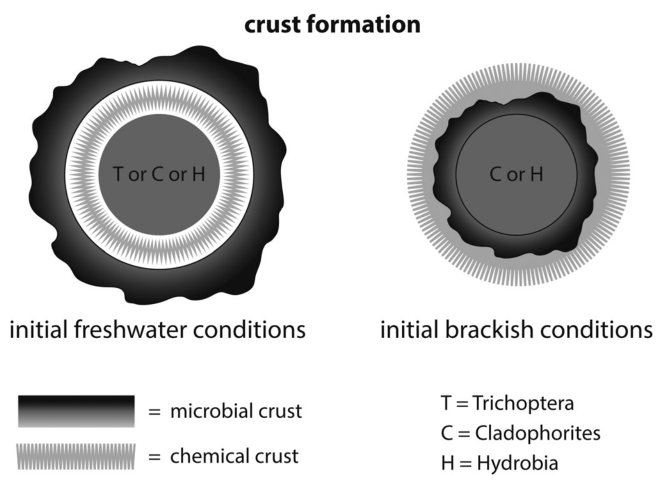

FIGURE 10 Schematic drawing of the formation of crusts around components depending on salinity and temperature. During freshwater conditions chemical precipitation is favoured, while initial growth of microbial precipitation indicates brackish conditions

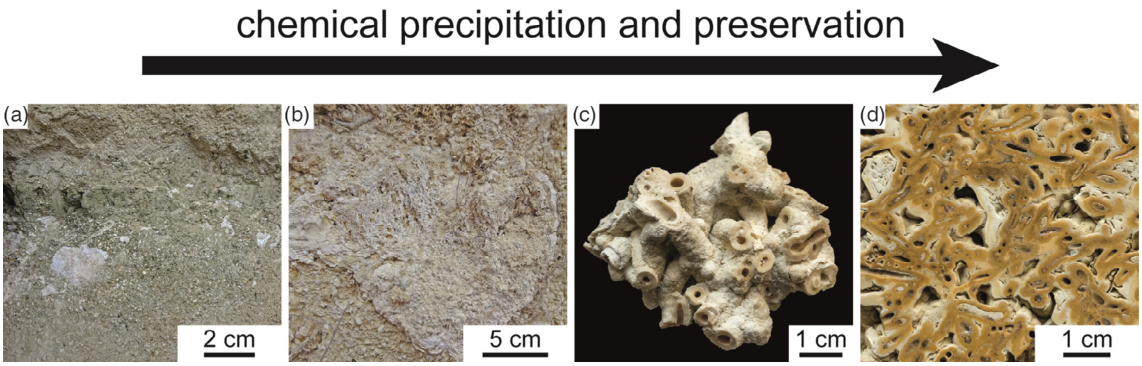

FIGURE 11 The preservation of *Cladophorites* is dependent on the intensity of chemical precipitation. (a) Shows the worst preservation of *Cladophorites* in layers which were formerly interpreted as phase of desiccation. (b) Shows better preserved *Cladophorites* in proximity to reefs. (c) shows the preservation of the tubular structure by mm-thick precipitates. In (d), the cementation around *Cladophorites* forms a solid rock [Colour figure can be viewed at wileyonlinelibrary.com]

specimens from the horizons and from the reef shows they are identical (Figure 11). Additionally, the phases of *Cladophorites* growth within the reef and the appearance of the *Cladophorites* horizons coincide (Figure 2). Furthermore, we did not observe any desiccation cracks and thus, the desiccation events reported by Grimm et al. (2011) and Schäfer (2012) for other successions in the Mainz Basin cannot be confirmed for the studied section in Mainz-Weisenau. A change in freshwater input due to changing river systems or rain intensity is much more likely. The rejection of meteoric phreatic or vadose intervals during the deposition has implications for the interpretation of the general palaeoenvironmental development. The proposed episodic desiccation or a drop of the sea level based on caliche horizons (Grimm et al., 2011; Kadolsky & Koch, 1988; Rothe et al., 1997; Schäfer, 2012) could be reconsidered also for other areas, as they clearly turned out to be thin beds of *Cladophorites* specimens in Mainz-Weisenau.

On the basis of reef propagation and the occurrences of Trichoptera protective cases, bivalves, and horizons of either small reef fragments, that is, pisoids or *Cladophorites*, we interpret small-scale variations of the environmental conditions. The occurrences of patch reefs correlate with dilatations of the large reef and horizons of *Cladophorites*, while the Trichoptera protective cases and horizons of pisoids correlate with reductions in reef expansion. Consequently, we subdivided the section into four main phases.

The first phase is dominated by large mixed reef bodies because salinity was relatively high enough to enable best conditions for the growth of reefs. The intercalation of large assemblages of fragile *Cladophorites* into the reefs point towards a sedimentation below fair-weather wave-base. The correlation of large assemblages and horizons of *Cladophorites* might indicate short intervals of increased freshwater supply, which lowered salinity and increased chemical precipitation around the algal thalli and thus increased the preservation potential of the *Cladophorites* specimens.

The second phase features horizons of pisoids, Trichoptera protective cases and a reduced extension of the large reef complex. Trichoptera indicates both, low salinity and shallow water. Terrestrial gastropods and the horizons of pisoids support our interpretation of shallow water and probably represent episodic increases in wave energy. Similar horizons with stromatolite debris are reported from the Miocene Ries impact crater where they have been interpreted as the remnants of episodic storm and flooding events as well (Arp, 1995a).

For the third phase, we assume a relative rise in salinity but still shallow water conditions. This is supported by increased growth of the large algal reef as well as of three patch reefs. The Trichoptera in the middle of this phase indicate a short-term reduction of salinity but no change in water depth. Additionally, the distinct chemical precipitations within the reefs could even indicate increased temperatures.

During the fourth phase, reef growth is reduced again. However, in contrast to the second phase, the occurrence of mainly articulated specimen of *Falsocorbicula faujasii* indicates minor to no transport of this brackish bivalve and, therefore, brackish conditions.

6 | CONCLUSIONS

Our findings suggest several small-scale variations in fresh-water supply and temperature within the depositional system of the Rüssingen Formation in Mainz-Weisenau. The general conditions were quite stable and no intense change of salinity can be confirmed for this time interval. The documented short-term variations in temperature, salinity, and water depth in combination with the findings by previous studies (Grimm et al., 2011; Reichenbacher, 2000; Schäfer, 2014) enable the interpretation of the environmental development of the Mainz-Weisenau outcrop. The variations in this restricted basin result from periodic inflow of freshwater and the occasional connection of the Mainz Basin to the nearby Rhine Graben. The location towards the northeastern edge of the basin is determined by the brackish waters which were periodically saturated in terms of calcium carbonate. Furthermore, beds similar to caliche are actually thin layers of the green alga *Cladophorites*, thus, contrasting the previous interpretation of desiccation events for other parts of the Mainz Basin. The immediate response of the sensitive reef-components in brackish deposits enables the extraction of very detailed information about small or short-term variations in climate using macro- and microfacies analyses.

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DATA AVAILABILITY STATEMENT

The data that supports the findings (fotos and results of mapping) of this study are available in the figures of this article. No other datasets were generated.

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