The Malm ζ laminated carbonates from outcrops of the Swabian and Frankonian Alb are world-renowned for their lithographic limestone quality and for the excellent fossil preservation of the Solnhofen Facies. Although devoid of organic matter in the Solnhofen or Eichstätt quarries, due to postdepositional oxidation when uplift and carstification started in Cretaceous times already, Malm ζ sediments originally contained large amounts of organic residues of highly specific composition, suitable for organic facies reconstruction.
SUMMARY

During Jurassic times, especially within the Malm ζ stage, local depressions formed on the Eastern Bavarian Carbonate Platform that were surrounded by wall reefs. This created a unique depositional environment, where in an open-marine setting stagnant and anoxic bottom waters developed in an intra-reef depression. Anoxic conditions were stabilized below wave base by enhanced salinity in the bottom waters and establishment of a density stratification. Biomarker analysis allows to characterize palaeosalinity and redox conditions, utilizing organic sulfur compound, methylated chroman, hopanoid and saturated isoprenoid distributions. Prevention of terrigenous influx by protecting reef walls lead to iron deficiency in intra-reefal sediments causing early diagenetic sulfurization of functionalized lipids. Absence of clay-mineral catalysts and early sulfurization favored unusual steroid distribution lacking rearranged analogues but providing coexistence of saturated steranes with βαα-, ααα- and αββ-configuration, Δ13(17)-spirosterenes, unknown sterenes and steradienes, as well as mono-, di-and triaromatic steroids. Desulfurization of the polar fraction indicates that paleoenvironment reconstruction based on free hydrocarbon and heterocompound distribution was not invalidated by sulfur quenching of selected compounds. Gammacerane was found to be the only component to occur exclusively in the sulfur-bound fraction. Only minor amounts of hydrocarbons released upon desulfurization imply that free bitumen analysis is applicable for organo-facies characterization. Organic petrological investigation of organic mats revealed the presence of two different types of such structures. Comparison of organoclast fluorescence spectra with those of extracted porphyrin fractions indicate an origin of porphyrins exclusively from cyanobacterial mats whereas algal dominated mats yield no porphyrins.
Bulk organic matter contents vary between 0.1 and 15 % TOC, with no lithological control. Isotopic characterization of the kerogens gave $\delta^{13}C$ values of -25.8 to -29.5‰ and a strong negative correlation with Hydrogen Indices. Excellent quality of organic matter is revealed by HI-values ranging from 100 to 1050, with a cluster around HI-values of 600 to 700. In agreement with microscopical analysis a type II kerogen can be attributed to most samples. Extremely lipid-rich samples approaching type I-kerogen exhibit TOC-values below 2.0 %. An increase in OI-values with decreasing HI can be attributed to mixing with terrigenous OM accompanied by degradation of marine OM under more aerobic conditions in a higher energy regime.

Extract yields depend on lithology with limestones and cherts yielding <1000 ppm, marls and siliceous carbonates 2000 to 4000 ppm with several samples in the range of 5000 to 16500 ppm. Rock-Eval S1-yields indicate the same lithological control on the amount of labile OM. High abundances of extractable OM in cherts will correspond to its lipidic nature derived from siliceous algal input. Due to less carbonate dilution and higher transformation of OM by clay catalysis marls will also give higher extract yields.

Microscopical maturity assessment reveals Rb-values of 0.35 % corresponding to a vitrinite reflectivity of about 0.3 % Rr. Re-sedimented terrigenous vitrinites show high maturities ranging from 0.5 to 1.2 % Rr. Tmax-values of 400 to 410°C and PI-values <0.1 also indicate low maturity of the organic matter which is further demonstrated by extract compositions showing contents of up to 20 to 35 % asphaltenic biomacromolecules and 50 to 60 % heterocompounds.
Global distribution of biomes for the Late Jurassic (150 Ma):
Upper Jurassic global distribution of Dinosaur bone beds fits well with evaporitic sedimentation regimes in nearshore shallow platform areas. Plant fossil beds, however, show a better match with coal deposits in warm temperate coastal or cool temperate intramontane regions. The probability of Fossil Lagerstätten occurrence in these two depositional environments is high.
Solnhofen Plattenkalke
Modal sediment composition in a carbonate, chert, clay diagram.
The relationship of sulfur versus TOC in sediments, if not affected by postsedimentary diagenetic redox-fluctuations and pyrite reprecipitation, reflects the original availability of detrital iron (mainly as coatings) and reduced sulfur released by bacterial sulfate reduction and defines the “normal marine line”.

If iron as reaction partner for reduced S species is limited, S will be incorporated into labile organic matter (natural vulcanization).
The inclusion of Fe into a S/TOC diagram identifies Fe-undersaturated sediments, either due to sulfate occurrence or sulfurization of organic matter in the Malm $\zeta$ sediments.

Modal sedimentary pyrite and OM composition in a TOC,Fe,S diagram.
Rock Eval indicates highly hydrogen enriched organic matter of rather monospecific algal or cyanobacterial bloom origin. Synsedimentary oxidative trends to higher OI and lower HI values are induced by deposition below wave base.
Rock Eval despite high abundance of bitumen shows no impregnation and single sourced kerogens.
Aliphatic hydrocarbon distribution of silified limestone is dominated by long chain n-alkanes of terrigenous plant origin indicating shallow water nearshore environment. Oxic deposition is evident from low CPI, high pri/phy and low relative proportion of cyclic terpenoids.
Aliphatic hydrocarbon distribution of poorly laminated limestone is dominated by mid chain n-alkanes of aquatic macrophytes indicating shallow water nearshore environment. Suboxic deposition is evident from high pri/nC\textsubscript{17} and higher relative proportion of cyclic terpenoids.
Aliphatic hydrocarbon distribution of well laminated limestone shows n-alkanes of aquatic and land plants indicating arid hinterlands. Anoxic deposition is evident from low pri/phy, high phy/nC$_{18}$ and very high relative proportion of cyclic terpenoids as well as C$_{25}$-isoprenoids.
Sterane distributions via m/z 218: nC$_{27}$ (rodophyte) and nC$_{28}$ (prymnesiophyte) from marine algae, nC$_{29}$ from land plants or phaeophytes.
Monoaromatic sterane distributions via m/z 253 generally agrees with saturated sterane distribution but shows slightly enhanced nC\textsubscript{28} (prynnesiophyte) proportions from marine algae, easier to aromatize.
Hopane distributions via m/z 191: extended hopanes from heterotrophic bacteria and cyanophytes, deposited under anoxic regime.
Hopanes m/z 191, hopenes m/z 367: variation in side chains due to bacterial strains and sulfurization. Note different patterns for 367/191.
Crossplot of two common biomarker ratios used to assess paleosalinity. The pri/phy ratio signifies hypersalinity, whereas the chromane ratio indicates a mesosaline environment. The environment in the intra-reef deeps was only slightly hypersaline.

Open and black filled circles indicate laminated and non-laminated marls, circles filled grey represent silicified lithofacies types.
Crossplot of paleosalinity indicator MTTC-ratio vs. sulfurization indicator ITR, which indicates a specific input of halophilic sulfur bacteria. Laminated marls show indications of slightly enhanced salinity for both parameters.

Open and black filled circles indicate laminated and non-laminated marls, circles filled grey represent silicified lithofacies types.
Crossplot of paleosalinity indicators ITR and pri/phy. Both ratios respond to salinity and anoxia, which develop simultaneously in stratified intra-reef deeps.

Laminated marls show indications of slightly enhanced salinity (mesosaline) for both parameters.

Open and black filled circles indicate laminated and non-laminated marls, circles filled grey represent silicified lithofacies types.
Sulfur-bound lipids released

GC/MS total ion trace for aliphatic hydrocarbons obtained from desulphurized polar fractions of a non-laminated (M110) and a laminated marl (ML69). Filled circles represent n-alkanes, open circles and squares denote hopanes or steranes, respectively. The sulfur-bound n-alkanes predominantly derived from algal/cyanobacterial/bacterial producers as evident from the short chain length. The free n-alkanes predominantly derived from land plants and aquatic macrophytes. Eukaryotic steranes dominate in non-laminated marls, indicating more oxic conditions. Microbe/cyanobacterial hopanes in laminated marls show anoxia.
Mass fragmentograms of m/z= 191 and 217 shown for the aliphatic fraction of desulfurized polar fractions of samples ML69 and M110. Gammaecrane from bacteriovorous ciliates and C_{35} hopanes are enriched in sulfur-bound fraction. Note the low abundance of C_{28} steranes, which escape sulfurization by early aromatization to monoaromatic steroids.
Microscopical investigations of organoclats shows two populations. The lower reflectance bituminites originate from microbial mats, the higher reflecting vitrinites from land plants. Bitumen reflectance agrees well with thermal maturity by biomarkers or Rock Eval.
Microscopically identified organo-clasts from either microbial algal or cyanophyte mats in their spectral colours correlate with maltenes or rather porphyrins, respectively. Presence of two types of microbial communities is given by optical, chemical and spectral property.

Colour space after DIN 6164.
Conclusions

1. Shallow water environment with eolian input of land plants (n-alkanes) and dust but little/no riverine influx (OSC, FE/S/TOC)
2. Main producers algae and cyanophytes, some planktonic but many as benthic/ floating microbial mats (biomarker, organoclasts, colour spectra)
3. Highly preservational environment, via stratified water column with halocline/pycnocline and chemocline (biomarker, Rock Eval) caused by hydrodynamic isolation of intra-reef deeps.
5. Primary sedimentary regimes leading to Plattenkalk facies and excellent fossil preservation (biofilms) have been postsedimentary obscured by uplift and weathering. Circulating oxic waters (mangansese dendrites) have removed almost all organic matter originally responsible for laminated micrite formation.