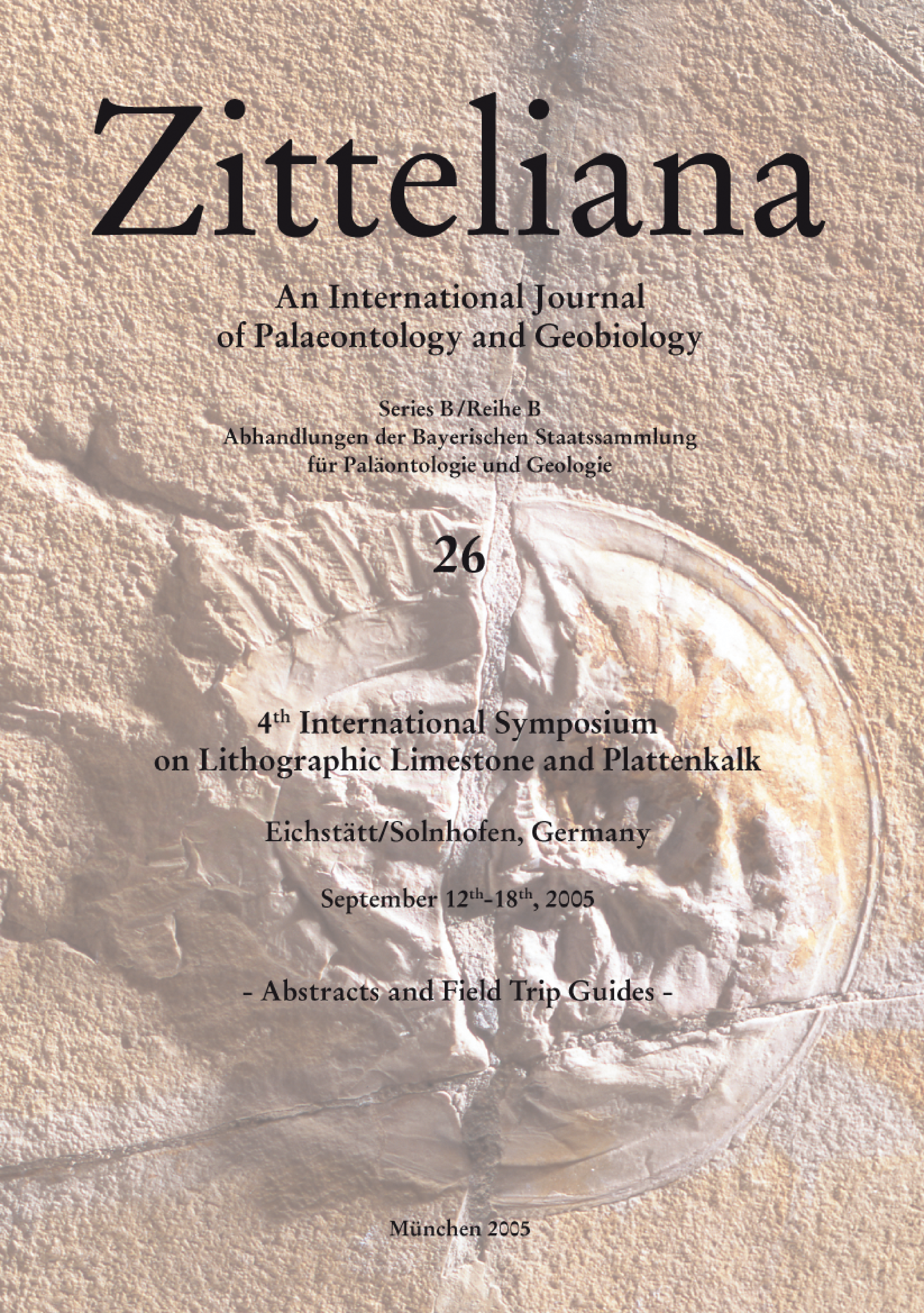

Zitteliana

An International Journal
of Palaeontology and Geobiology

Series B/Reihe B
Abhandlungen der Bayerischen Staatssammlung
für Paläontologie und Geologie

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Organised by

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Jura-Museum, Eichstätt

Martin Röper
Bürgermeister-Müller-Museum, Solnhofen

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and GeoBio-Center LMU

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Umschlagbild: *Mesolimulus walchi* Desmarest; Pfeilschwanzkrebs mit Fährte; Lower Tithonian, Solnhofen (BSPG AS I 944).

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CONTENTS/INHALT

Zitteliana	B 26	96 Seiten	München, 05.09.2005	ISSN 1612-4138

ABSTRACTS

Zitteliana	B 26	96 Seiten	München, 05.09.2005	ISSN 1612-4138

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Stratigraphy and Palaeoenvironments of the Upper Jurassic of Southern Germany – A Review

By
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Abstract

The Upper Jurassic of Southern Germany, mainly comprising the Swabian and Franconian Alb, is briefly characterised. Several open questions regarding litho- and biostratigraphic correlations and the depositional environment of the siliceous sponge facies are shortly discussed.

Kurzfassung

Der Oberjura von Süddeutschland, der im Wesentlichen die Schwäbische und Fränkische Alb umfasst, wird kurz charakterisiert. Einige offene Fragen in Bezug auf litho- und biostratigraphische Korrelationen und den Ablagerungsraum der Kieselschwamm-Fazies werden kurz diskutiert.

Keywords

Upper Jurassic; Southern Germany; stratigraphy; reef facies; palaeoenvironment; palaeogegography

1. Introduction

In the Late Jurassic, Southern Germany was part of the north-western Tethyan shelf. In outcrop, the marine epicontinental sediments are forming the Swabian and the Franconian Alb and their forelands. For field guides with outcrop descriptions, refer to Geyer & Gwinner (1984) for the Swabian Alb and the 'Wanderungen in die Erdgeschichte' series covering many areas of the Franconian Alb (Meyer & Schmidt-Kaler 1990b, 1991, 1992, 1995, Schmidt-Kaler 1991, Schmidt-Kaler et al. 1992, Meyer et al. 1994, Kaulich et al. 2000, Mäuser et al. 2002).

The Upper Jurassic of Southern Germany is a classical area of geological and palaeontological research. However, this does not mean that the Jurassic of Southern Germany has been conclusively studied and interpreted. In contrary, there exist several open questions on stratigraphical problems and correlations as well as on sedimentological and palaeogeographical interpretations that are lively discussed, as is shown here.

The correlation between the Swabian and the Franconian realm is being complicated by the fact that both areas have been investigated separately until today by the referring federal institutions. This separation is increased by different facies developments and by the Ries impact crater which formed in the Miocene, now separating Swabia from Franconia. Concerning stratigraphy, the traditional subdivision of Quenstedt (1856/58) of each series into 6 subunits (alpha, beta, gamma, delta, epsilon, zeta), which has been used for a long time, has led to some confusion, i.e. regarding the correlation between Baden-Württemberg and Bavaria, since these originally lithostratigraphic units have often been misunderstood as bio- or chronostratigraphic units which they are not. Therefore, these formerly popular names are omitted here in favour of the now officially defined formations following international standards (Fig. 1, 2) (Villinger & Fleck 1995; Deutsche Stratigraphische Subkommission 2002; see also Zeiss 1977).

For a discussion of the sequence stratigraphic interpretation of the southern German Upper Jurassic, see Schmid et al. (submitted).

2. Upper Jurassic succession and facies

In contrast to the Lower and Middle Jurassic where dark clays predominate, the Upper Jurassic of Southern Germany is characterised by a succession of light-coloured limestones and marls (400-600 m), indicating mostly well-oxygenated water. In the Late Jurassic, Southern Germany was covered by an epicontinental sea, being part of the northern Tethys shelf (Fig. 1). It was bordered by the Bohemian Land in the east and by the Rhenish Land in the northwest, two landmasses separated by the Hessian Seaway connecting the Tethyan with the Boreal

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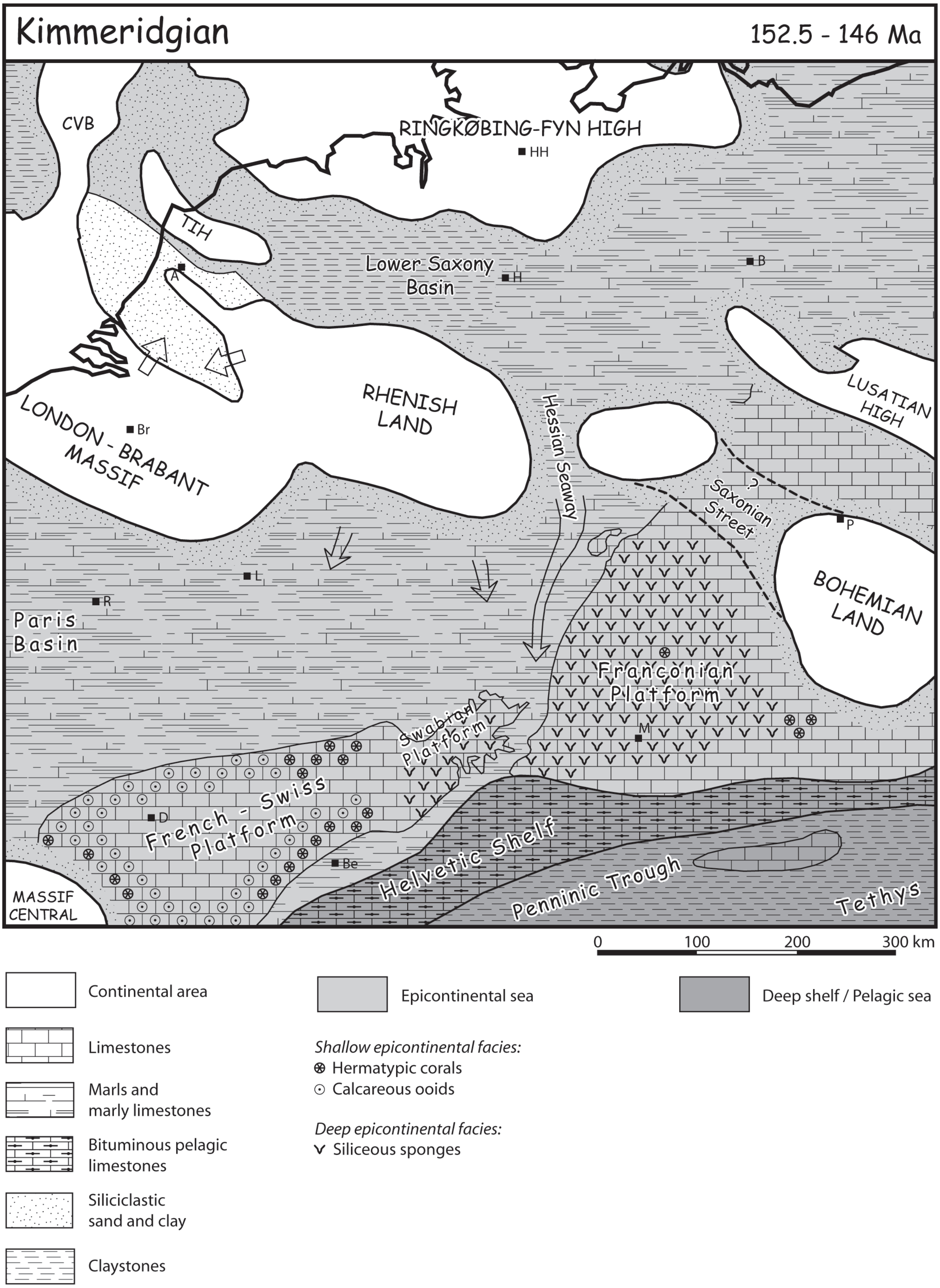

Figure 1: Kimmeridgian palaeogeography and general facies distribution of Southern Germany and adjacent areas. CVB – Cleaver Bank High, TIH – Texel-Ijsselmeer High; A – Amsterdam, B – Berlin, Be – Bern, Br – Brussels, D – Dijon, HH – Hamburg, H – Hannover, L – Luxemburg, M – Munich, P – Prague, R – Reims. Combined and modified after Gwinner (1976), Meyer (1981), Meyer & Schmidt-Kaler 1989, P.A. Ziegler (1990) and Dercourt et al. (2000).

realm. In the latest Jurassic, the Hessian Seaway was closed at times by the continous land barrier of the London-Brabant-Rhenish-Bohemian Land, resulting in a stronger Tethyan influence. Towards the west, the adjacent platform facies of the Paris Basin and the Swiss Jura partly reaches the southern German realm in the Upper Rhine area. In the southwest, the shelf facies drops gradually towards the pelagic facies of the Helvetian Basin (Schilt Fm and Quinten Fm; cf. Schneider 1962, Lupu 1972, Bertleff et al. 1988, Meyer & Schmidt-Kaler 1990a), while the transition in the southeast towards the pelagic facies of the eastern alpine Hochstegen Marble (Kiessling 1992, Kiessling & Zeiss 1992) is not accessible.

A reefal facies established in the Middle Oxfordian, being part of an extensive facies belt characterised by frequent siliceous sponge reefs spanning the northern Tethys shelf. Coral reefs, however, are also present, expanding towards the end of the Late Jurassic and thus mirroring the overall shallowing sea-level trend. The climate remained warm, but became more arid. The fine-grained siliciclastics were transported from the north, while the micritic mud was probably derived from the shallow-water carbonate platform of the Swiss Jura (B. Ziegler 1987, Selg & Wagenplast 1990, Geyer & Gwinner 1991, Meyer & Schmidt-Kaler 1989, 1996, Pittet et al. 2000, Leinfelder et al. 2002).

2.1 Lower Oxfordian

In Southern Germany, the base of the Upper Jurassic is formed by the **Glaukonitsandmergel Member**, a condensed section with a very reduced thickness (0.3-5 m). The dark glauconitic marls, which may contain detrital quartz, represent the uppermost part of the Ornatenton Formation and thus of the 'Braunjura' facies. Early Oxfordian age is indicated by ammonites of the Mariae or Cordatum zones (Zeiss 1955, Munk & Zeiss 1985). Riegraf (1987a, b) described planktonic foraminifera from this member and from the lowermost Impressamergel Fm (see below).

At the eastern side of the Upper Rhine Graben, the Upper Jurassic begins within the **Kandern Formation** (ca. 85 m). The Lower Oxfordian part of this formation consists of marly clays with numerous calcareous concretions, a facies also known as 'Terrain à chailles' of the 'Rauracian' facies development (Geyer & Gwinner 1991, Geyer et al. 2003).

2.2 Middle to Upper Oxfordian of the Upper Rhine Graben area

The Middle Oxfordian marks the beginning of the 'Weißjura' facies, being characterised by light-coloured limestones and marls. In contrast to the facies dominated by siliceous sponges and cephalopods otherwise prevailing in the Oxfordian of Southern Germany (see below), the Upper Rhine Graben area differs markedly by showing the same shallow-water coral facies as it is developed in the adjacent carbonate platforms of the Swiss Jura and NE France (Geyer & Gwinner 1991, Meyer & Schmidt-Kaler 1989, 1990a).

The Middle Oxfordian **Korallenkalk Formation** (ca. 60 m) with a variety of corals, brachiopods, echinoderms and ooids is

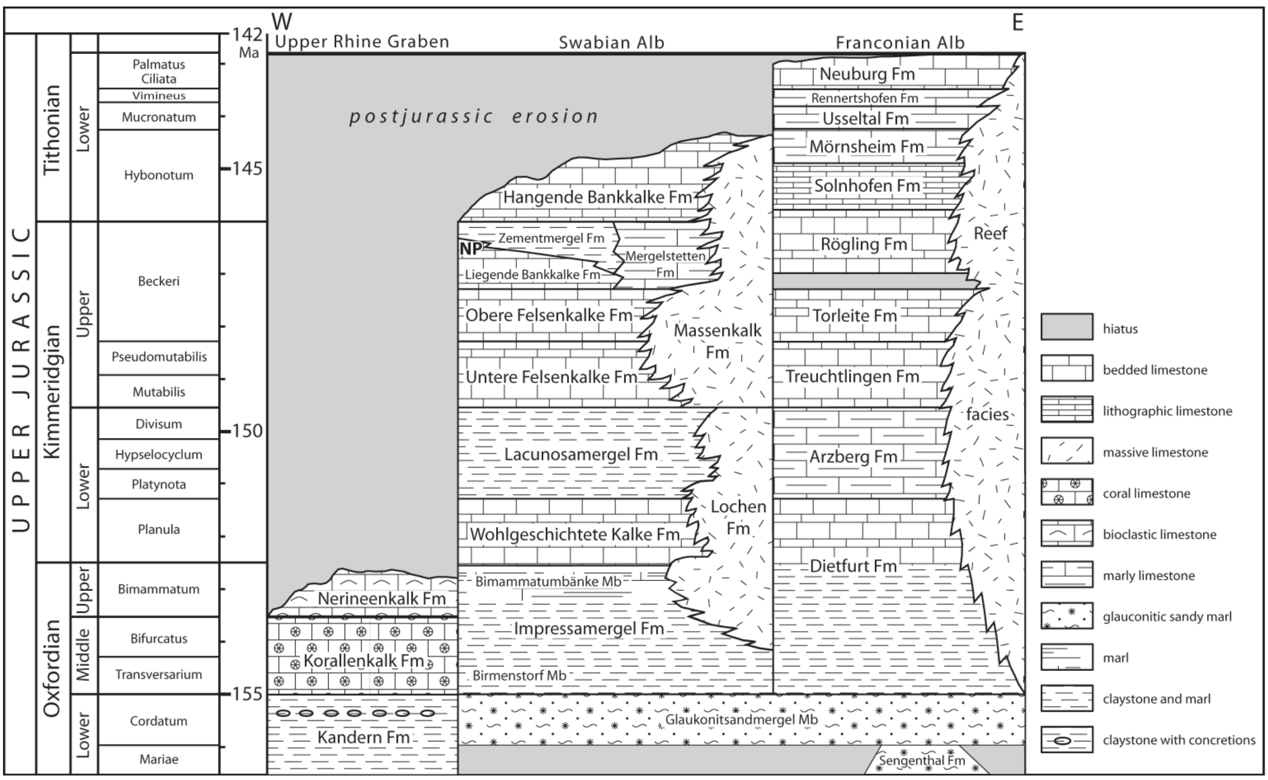

Figure 2: Stratigraphy and facies of the Upper Jurassic of Southern Germany (modified from Schmid et al., submitted). Formations, correlation and time scale modified from Deutsche Stratigraphische Subkommission (2002) and Bloos et al. (in press). Note different stratigraphic position of the Nusplingen Plattenkalk (NP) and the Solnhofen Lithographic Limestones with an age difference of ca. 500,000 a (Dietl & Schweigert 1999).

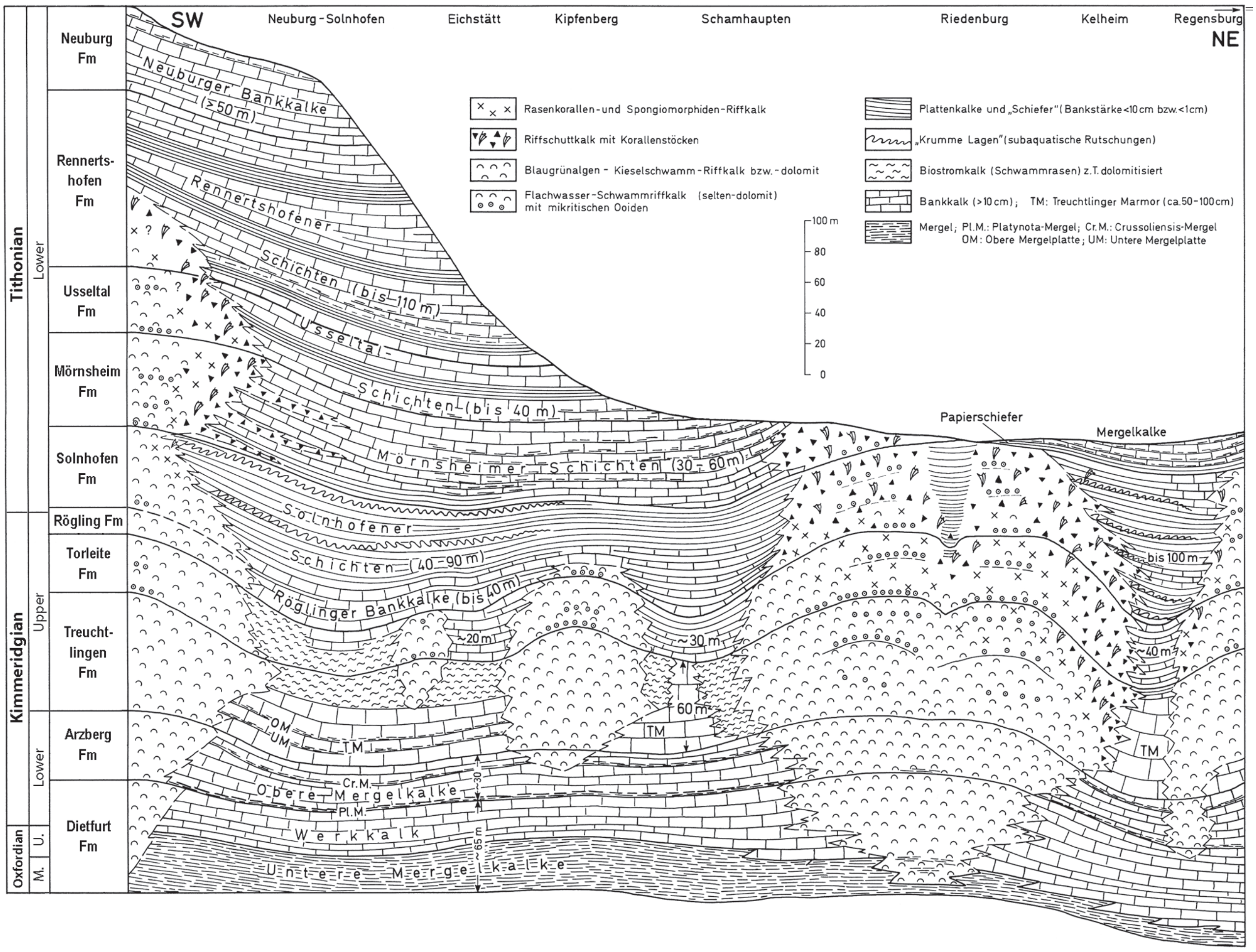

Figure 3: Lithostratigraphy and lateral facies variations of the Upper Jurassic of the Southern Franconian Alb (modified from Meyer & Schmidt-Kaler 1996). The Lower Oxfordian Glaukonitsandmergel Mb (see Fig. 1) is not shown here. Please note that Formation names (after Deutsche Stratigraphische Subkommission 2002 and Bloos et al., in press) refer only to the bedded facies, not to the massive reefal facies.

well exposed at the Isteiner Klotz near Basel (Geyer & Gwinner 1991, Geyer et al. 2003). The Korallenkalk is followed by the Upper Oxfordian **Nerineenkalk Formation** (>16 m) with abundant gastropods in the higher part. Younger Jurassic deposits in this area were eroded in post-Jurassic times (Geyer & Gwinner 1991).

2.3 Late Jurassic reefal facies (massive limestones) (Oxfordian to Tithonian)

Starting already in the early Late Jurassic, a reefal facies dominated by siliceous sponges established on the southern German part of the northern Tethys shelf (Leinfelder et al. 2002), being characterised by massive fabrics in contrast to the otherwise bedded limestones and marls (Fig. 2, 3). Starting with small and isolated patch-reefs, the reefal facies extended through time to form large and continuous reef complexes in the Middle and Upper Kimmeridgian (Gwinner 1976, Meyer & Schmidt-Kaler 1989, 1990a). The main reef builders were siliceous sponges (both hexactinellids and lithistids), actually owing their reef-building capacity to the intergrowth with thrombolitic to stromatolitic microbial crusts (cf. Schrammen 1924, Aldinger 1961, Leinfelder et al. 1993, 1994, 1996, Schmid 1996, Krautter 1997, Leinfelder 2001). In general, these reefs can be classified as siliceous sponge-microbialite reef mounds. Hermatypic corals do only appear within the reefal facies diachronously from the late Kimmeridgian onwards to become increasingly abundant towards the Tithonian. This trend is interpreted by most authors as mirroring a general shallowing trend on the northern Tethys shelf where the siliceous sponge reefs represent a deeper ramp setting with a range of approximately 50-150 m water depth (B. Ziegler 1967, Gygi & Persoz 1987, Selg & Wagenplast 1990, Leinfelder 1993, Leinfelder et al. 1994, 1996, 2002, Werner et al. 1994, Schmid 1996, Krautter 1997, Pittet & Mattioli 2002; see also discussion in Keupp et al. 1990). Contrasting this 'classic' bathymetric model, there exist ideas suspecting a shallow-water origin of the siliceous sponge facies of the higher part of the Upper Jurassic (Kott 1989, Koch 2000; Koch & Weiss, this volume). Such interpretation though would place siliceous sponge-dominated facies and hermatypic corals in the same bathymetric position, and thus would require a controlling factor other than bathymetry to explain the separation of both facies. Although water temperature and nutrient control might be considered as likely candidates, it would be hard to explain significant temperature or nutrient gradients in such a hypothetic large levelled-out shallow-water platform. Moreover, the adjacent bedded cephalopod facies as described here totally lacks any unequivocal shallow-water features such as dasycladacean algae or thick cross-bedded oolitic grainstones, features occurring amply in genuine shallow-water facies, e.g. in the neighbouring Swiss Jura and Upper Rhine area (see above), or in Iberia (LEINFELDER et al. 1994, 1996). The optimum habitat of the pervasive ammonites is also generally considered to be positioned in waters deeper than about 50 m (B. ZIEGLER 1967, GYGI 1999). In addition, the so-called tuberoids which represent a special type of intraclasts, namely disintegrated pieces of microbial crusts and/or siliceous sponges, are not generated by wave action and reworking, but formed in situ, as was already recognized by FRITZ (1958) and ALDINGER (1961) and is also indicated by their occurrence which is restricted to the closest vicinity of the reefs.

The Recent hexactinellid sponge reefs on the western Canadian shelf (KRAUTTER et al. 2001) and their environment, though exhibiting some differences, rather support the traditional bathymetric model. Conversely, several features previously thought to indicate shallow-water conditions have proven to be not diagnostic: rarely occurring gypsum pseudomorphs (KOCH & SCHWEIZER 1986) can be produced by sulfur-oxidizing bacteria (EHRLICH 1990), and the interpretation of *Tubiphytes* as a special oncoid type (KOTT 1989) has been shown to be erroneous (for discussion see SCHMID 1996, HENSSEL et al. 2002). However, the origin of allochem-type particles within the sponge mounds has not yet been shown convincingly. We assume that these particles comprise both deeper-water generated microbial particles and shallow-water derived sands swept into deeper parts of the shelf where they became incorporated and stabilised within microbial mounds (cf. LEINFELDER et al. 1996). In this context, the interpretation of the massive siliceous sponge facies of the Molasse subsurface as 'shallow-water sponge limestones with ooids' (MEYER & SCHMIDT-KALER 1990a, 1996) seems also highly questionable since shallow-water indicators other than ooid-type particles are again absent. However, since this interpretation is based on isolated boreholes and exact timelines are not available from the massive limestone facies, this problem must remain unresolved at the moment.

In the Swabian Alb, the **Lochen Formation** (up to >200 m) represents the older reefal facies of the Late Jurassic, spanning the Oxfordian to the lower Kimmeridgian (Fig. 2). In the surroundings of the reefs a small-sized fauna occurs ('Lochen facies', GEYER & GWINNER 1984). The main faunal elements are siliceous sponges, certain ammonites, brachiopods and echinoderms. Benthic foraminiferal associations from bedded and massive facies can be distinguished (WAGENPLAST 1972, SCHMALZRIEDT 1991). The reefal facies starts with small and isolated patch-reefs in the Middle Oxfordian, expanding through time. Mound development is frequently complex, with small mounds clustering to form larger buildups (SCHMID et al. 2001). This facies is mostly restricted to the western and middle Swabian Alb, being separated from the reefal facies of Bavaria in the east by a basinal structure, the 'Swabian Marl Basin' (MEYER & SCHMIDT-KALER 1989, 1990a).

The Lochen Fm of the Swabian Alb is continued by the **Massenkalk Formation** (up to > 300 m), also representing a reefal facies with massive fabrics. Unlike the older reefal facies, however, the Massenkalk Fm comprises large reef complexes where either siliceous sponges or corals prevail. In Franconia, no formation name has yet been defined for an equivalent massive **reef facies** (e.g., FLÜGEL & STEIGER 1981, BRACHERT 1986, LANG 1989). There it starts already at the beginning of the Middle Oxfordian when sedimentation switches from glauconitic condensation to the marls of the lower Dietfurt Fm (see below). While the Swabian reef facies starts more patchy to form a more or less continuous reef area in the middle to upper Kimmeridgian, the reef facies of the Franconian Alb appears to be characterised from the beginning by distinct reef-facies tracts, partly prevailing throughout the Late Jurassic (cf. MEYER & SCHMIDT-KALER 1989, 1990a), although this interpretation is partly derived from isolated borehole correlation.

Contrary to what the established term 'reef facies' might suggest, these limestones do not represent massive reefs with metazoan frameworks. Actually, the term 'reef facies' as we continue to use comprises all kinds of reefal sediments including mound-type reefs and peri-reef carbonate sands. This has to be emphasised since there is an ongoing debate as to the nature of this facies, including the question whether the term 'reef' should be used here at all. After KOCH et al. (1994), the majority of the referring sediments should represent a peloid-lithoclast-ooid sand facies rather than true reefs, often containing ooid-type particles. According to this model, true reefs do occur within this facies, but are only small-sized and of subordinate importance within the sand piles. On the other hand, as MEYER (1994: 52) has already pointed out, the referring sediments are often stabilised by stromatolitic or thrombolitic microbial crusts (SLADKY 2005), resulting in a synsedimentary hardened reef-like sand bodies which may form steep margins, a feature that can not be formed by loose sand piles anyway. However, the term 'reef facies' or 'massive limestone' should only be used in a descriptive, summarizing term that comprises a large variety of facies types. If and to what degree these facies types should be addressed as reefal has to be decided in each case. Another debated question is whether the micritic parts of the earlier mounds represent hard automicrites related to activity or decay of microbial matter or rather baffled and trapped accumulations of soft allochthonous mud. As to the Southern German Upper Jurassic mounds, there are indications for both (LEINFELDER & KEUPP 1995, SCHMID et al. 2001), but their mutual proportions and growth/accumulation patterns have not been clarified so far.

2.4 Middle Oxfordian to lower Kimmeridgian

To continue in stratigraphical order, the typical Upper Jurassic light-coloured facies starts in the Swabian Alb with the **Impressamergel Formation** (25-125 m; formerly 'Weißjura alpha'), a succession of light grey marls with intercalated limestones that increase in number towards the top (Bimammatum-bänke Mb). Besides the brachiopods, ammonites of the Plicatilis and Bifurcatum Zones are widespread. Radiolarian and planktonic foraminiferal faunas, found in the Swabian and Franconian Alb (RIEGRAF 1987b), indicate pelagic influence and not too shallow water-depths. Towards the SW of Swabia, a special facies with siliceous sponge biostromes is developed in the lowermost part of the formation (Birmenstorf Mb). The Impressamergel Fm forms the very base of the steep slope of the Swabian Alb and thus is mostly covered by debris (GEYER & GWINNER 1984). The deposition of clays, being transported from the Rhenish landmass towards the southeast, also reached the western part of Bavaria, forming the marly lower part of the **Dietfurt Formation** (35-65 m; formerly 'Weißjura alpha'). In eastern Bavaria, a broad belt rich in siliceous sponge reef facies ('Franconian main reef tract') trending from north to south developed and persisted until the Early Tithonian (MEYER & SCHMIDT-KALER 1989).

The Impressamergel Fm is overlain by the **Wohlgeschichtete Kalke Formation** (10-150 m; formerly 'Weißjura beta'). It represents a homogeneous succession of regularly bedded limestones with a bank thickness of 10-60 cm, separated by thin marl layers; thus, it may even resemble an artificial wall in outcrop. The Wohlgeschichtete Kalke Fm forms the steep slope of the Swabian Alb, mainly in the western part (GEYER & GWINNER 1984). Ammonites are the predominant faunal element, representing the Planula Zone (for discussion concerning the Oxfordian-Kimmeridgian boundary see Schweigert & Callomon 1997). Siliceous sponges (see below) may form small biostromes or patch reefs within the bedded cephalopod facies. This facies is continued in Bavaria in the upper part of the **Dietfurt Fm** (see above; formerly 'Weißjura beta'), where the Ries-Wiesent reef-facies tract begins to develop, separating the Bavarian from the Swabian realm (MEYER & SCHMIDT-KALER 1989). In the upper part of the formation, a mainly Tethyan radiolarian fauna with few Boreal elements was found on the southern Franconian Alb, probably indicating deep neritic (?50 m) conditions (KIESSLING 1997).

The **Lacunosamergel Formation** (10-75 m; formerly 'Weißjura gamma'), being intercalated between two limestone successions, is mostly covered by debris; thus, good outcrops are scarce. The bedding planes of the grey marls sometimes show glauconitic veneers, indicating frequent condensation in a deep-ramp environment; ammonites of the Platynota, Hypselocyclum and Divisum zones are widespread. Within the bedded facies a special type of patch-reefs occurs, the so-called 'Lacunosastotzen'. Here, the main reef builders were rhynchonellid brachiopods largely substituting siliceous sponges (GEYER & GWINNER 1984). Siliceous sponges were more abundant in the adjacent massive reef facies (see above), but these patch-reefs presumably grew in still deeper water. This peculiar reef type is time equivalent with the development of pure microbialites and microbialite-rich reefs in SW-Europe, which is interpreted by LEINFELDER (2001) as a time-slice dependant exceptional, transgressive environmental setting rich in nutrients and a predisposition for local or widespread dysoxic environments. Recently, the Lacunosamergel Fm has been newly studied in detail and subdivided by SCHICK (2004a-c).

Towards the east, beyond the Ries-Wiesent reef-facies tract, the facies changes to more calcareous deposits of the **Arzberg Formation** (25-40 m; formerly 'Weißjura gamma'). This formation contains several lithostratigraphic marker horizons such as the Crussoliensis-Mergel (Fig. 3; MEYER & SCHMIDT-KALER 1989).

2.5 Upper Kimmeridgian

The **Untere Felsenkalke Formation** (20-60 m; formerly 'Weißjura delta') forms the steep slope in most parts of the Swabian Alb. Since the massive limestone facies predominates for this time slice (Mutabilis/Pseudomutabilis Zone), bedded lime-stones are not very widespread, but nevertheless present. In the upper part of the Untere Felsenkalke Fm, a characteristic glauconitic marker bed ('Glaukonitbank') occurs, indicating longer periods of non-deposition probably related to a transgressive phase; however, there are no signs of biostratigraphic condensation. Otherwise, the Untere Felsenkalke Fm is characterised by bedded cephalopod-bearing limestones with only thin or lacking marl layers. Both the limestone portion and the bedding thickness are highest in the upper part, with limestone beds up to 150 cm thick (GEYER & GWINNER 1984). In the Bavarian realm, a large platform consisting of thick-bedded carbonates developed, thus characterising the **Treuchtlingen Formation** (up to 60 m; formerly 'Weißjura delta'). In contrast to all other bedded carbonates described here, this formation is characterised by a succession of thick beds with an average thickness of 1 m (KOTT 1989, MEYER & SCHMIDT-KALER 1990b, 1996). These beds represent a succession of biostromes formed by siliceous sponges and thrombolites, interrupted by micritic sediment layers (HENSSEL et al. 2002); bioherms are only locally developed. Considering the fauna predominated by siliceous sponges and cephalopods, and the lack of unequivocal shallow-water elements, this platform can be assigned to an average water depth just below storm wave base (MEYER & SCHMIDT-KALER 1990a, SELG & WAGENPLAST 1990), contrasting the shallow-water interpretation of KOTT (1989) as discussed above. Such bathymetric interpretation is further corroborated by the sessile foraminifer *Tubiphytes morronensis* which is found throughout the Upper Jurassic, but whose bright white tests occur in rock-forming abundance here. Since the test thickness of this special foraminifer depends on light and thus water depth, it can be used as a palaeobathymetric indicator (SCHMID 1996). This time slice also marks the first occurrences of hermatypic corals in the Upper Jurassic of Southern Germany in SE Franconia (outside the Upper Rhine area, see above).

From the Northern Franconian Alb (Wattendorf), the oldest known lithographic limestones (see below) in the Upper Jurassic are reported by FÜRSICH et al. (this volume), dated by SCHWEIGERT (this volume) as Pseudomutabilis Zone.

Similar to the underlying formation, the Swabian **Obere Felsenkalke Formation** (10-40 m; formerly 'Weißjura epsilon') representing bedded limestones is not very widespread, being mostly replaced by massive limestones of the Massenkalk Fm. The light-coloured limestone beds with a mean thickness of 10-40 cm yield chert nodules in abundance and do not exhibit marl partitions as in many other formations. They contain mainly ammonites of the early Beckeri Zone, belemnites, and bivalves (GEYER & GWINNER 1984). The Bavarian equivalent is the **Torleite Formation** (20-40 m; formerly 'Weißjura epsilon'), marking a period of distinct shallowing and coeval expanding coral facies. Though the reefal morphology gets more levelled out, several basins remain within the platform (MEYER & SCHMIDT-KALER 1989, 1996).

The **Liegende Bankkalke Formation** (10-150 m; formerly 'Weißjura zeta 1') is a succession of bedded limestones and marls with a medium bed thickness; chert nodules occur locally. Ammonites indicate the late Beckeri Zone. In the vicinity of the massive limestone facies, breccias and slumps are common (GEYER & GWINNER 1984). This formation is restricted to the western and middle Swabian Alb. The lower boundary is marked by a discontinuity, possibly of tectonic origin (SCHWEIGERT 1995, SCHWEIGERT & FRANZ 2004).

Within this formation, there locally occur laminated limestones (in particular the **Nusplingen Plattenkalk**, resembling the famous Solnhofen Lithographic Limestones of Franconia (see below) in some respects, but differing in others, i.e. in its older age and the occurrence of calcareous turbidites (ZÜGEL et al. 1998, DIETL & SCHWEIGERT 1999). In the coeval Massenkalk Fm, corals become abundant like in the Arnegg reef representing a shallowing-up succession from siliceous-sponge to coral facies (PAULSEN 1964, LATERNSER 2001) or in the famous silicified coral faunas of Nattheim and Gerstettten (GEYER & GWINNER 1984, REIFF 1988).

The **Zementmergel Formation** (up to 170 m; formerly 'Weißjura zeta 2') is a marl-dominated formation, being deposited in depressions and sometimes interfingering with the siliceous sponge or coral reef buildups, respectively (GEYER & GWINNER 1984). There exist lateral transitions into both reef facies types depending on the position on the former palaeorelief; coral debris beds occur locally. The boundary between the Liegende Bankkalke Fm and the Zementmergel Fm is a strongly diachronous facies boundary (PAWELLEK 2001, SCHWEIGERT & FRANZ 2004) (Fig. 2). The intercalation of limestones within this formation makes the positioning of partial sections rather difficult (SCHWEIGERT 1995, SCHWEIGERT & FRANZ 2004). Towards the eastern Swabian Alb, a clear distinction between the Liegende Bankkalke Formation and the Zementmergel Fm is impossible, and sometimes the succession may even start with marls directly above the Obere Felsenkalke Fm, which in this case was often misinterpreted as Liegende Bankkalke Fm. Thus, the **Mergelstetten Formation** (up to > 120 m) has been erected, replacing the Liegende Bankkalke Fm and the Zementmergel Fm in the eastern Swabian Alb (SCHWEIGERT & FRANZ 2004). It consists of bioturbated thin-bedded marly limestones with marl layers poor in macrofossils; breccias and slumps occur mainly in its lower part. Both base and top of the formation are marked by discontinuity surfaces (SCHWEIGERT & FRANZ 2004).

The Brenztaltrümmerkalk Mb, a bioclastic and oolitic limestone with shallow-water components (e.g., dasycladaceans, nerineids, diceratids, corals), is also restricted to the eastern Swabian Alb (not figured in the stratigraphic chart; to be positioned between the Mergelstetten Fm and the Massenkalk Fm from which the shallow-water components derived) (REIFF 1958, GEYER & GWINNER 1984, SCHWEIGERT & VALLON 2005).

In SE Germany, the **Rögling Formation** (up to 40 m; formerly 'Weißjura zeta 1') represents the bedded facies of northern Bavaria which was deposited in the basins between the reefal areas that prevailed in the south (MEYER & SCHMIDT-KALER 1989). The boundary between the Beckeri and Hybonotum zones and hence the Kimmeridigian-Tithonian boundary lies within the Rögling Fm (GROISS et al. 2000). It has to be pointed out that the stratigraphical correlation which was used until recently correlated the Swabian Zementmergel Fm ('Weißjura zeta 2' according to the Quenstedt nomenclature) with the Franconian Solnhofen Fm (also assigned as 'zeta 2'; see below) (MEYER & SCHMIDT-KALER, 1989, 1990a). Following new biostratigraphic results concerning the ammonite faunas (SCHWEIGERT 1993, 1998, 2000, SCHWEIGERT et al. 1996), the DEUTSCHE STRATIGRAPHISCHE SUBKOMMISSION (2002) has accepted the new correlation as presented here (Fig. 2). It has to be conceded that the new correlation, consequently following the ammonite biostratigraphy, leads to a less well-fitting lithostratigraphic correlation as compared to the older one (GALL et al. 1977, MEYER & SCHMIDT-KALER 1989, 1990a), especially for correlating the Mergelstetten Fm (120 m) with the Rögling Fm (40 m). In this respect, a 20 cm thick, brick-red marl layer at the base of the Rögling Fm becomes important, marking a distinct hiatus after a regional tectonic event (Fig. 2) (SCHWEIGERT 1993, SCHWEIGERT & FRANZ 2004) which would explain the large thickness difference due to a larger subsidence in the Swabian realm. In this formation, lithographic limestones (see below) occur in greater abundance (Fig. 4).

2.6 Lower Tithonian

In southwestern Germany, the **Hangende Bankkalke Formation** (up to 200 m; formerly 'Weißjura zeta 3') starts above a discontinuity (not shown in Fig. 2 due to small scale), marking the beginning of the Tithonian (ROLL 1931, SCHWEIGERT 1996). The well-bedded limestone complex with subordinate marls resembles the Wohlgeschichtete Kalke Fm (see above) in outcrop. Apart from bivalves and brachiopods, fossils are fairly rare in most parts. Ammonite faunas of the lower Hybonotum Zone have been detected proving early Tithonian age (SCHWEIGERT 1996). Due to post-Jurassic erosion, the primary top surface of the Hangende Bankkalke Fm is not preserved.

At the same time in Bavaria, the upper part of the Rögling Fm (see above), the Solnhofen and the Mörnsheim formations were deposited, all containing **lithographic limestones** (localities see Fig. 4). In general, the elevations between the Plattenkalk basins were formed by older silicous sponge-microbial reef mounds, their tops now often being overgrown by corals (cf. FLÜGEL et al. 1993). The characteristic laminated fabric of the lithographic limestones is due to the absence of bioturbation, probably caused by hypersaline stagnant bottom water. Many of the thicker limestone beds ('Flinze') are interpreted as turbidites, occurring in the deeper plattenkalk basins such as Solnhofen. The currents which brought micritic lime mud and caused the mixing of surface and poisonous bottom water where probably caused by monsoonal winds (VIOHL 1998). Accordingly, the organisms which come from different habitats were all swept in from shallow-water and island areas surrounding the Plattenkalk basins or sunk from the water column, respectively. For further discussion of depositional models, see KEUPP 1977a, b, BARTHEL 1978, BARTHEL et al. 1978, and VIOHL 1998.

The **Solnhofen Formation** (40-90 m; formerly 'Weißjura zeta 2') belongs to the middle Hybonotum Zone (GROISS et

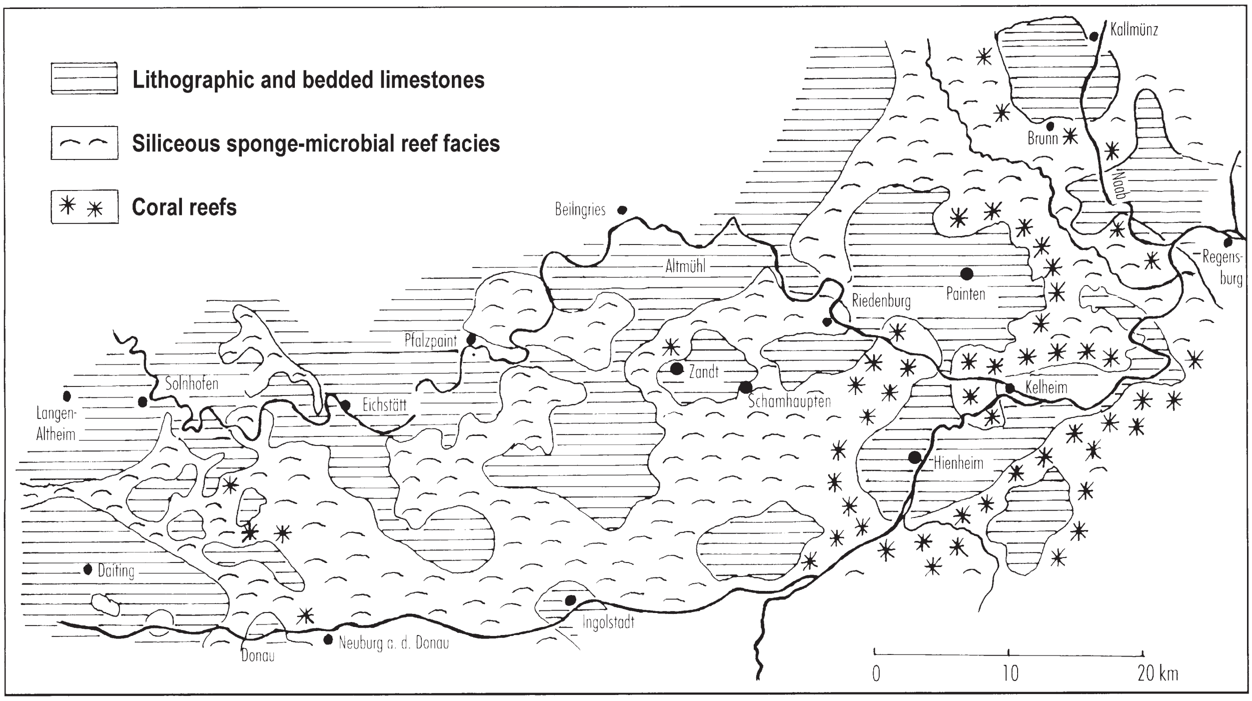

Figure 4: Distribution of Lithographic Limestones (Plattenkalk basins) in the Southern Franconian Alb. The age ranges from Upper Kimmeridgian (Rögling Fm: Painten, Brunn, Schamhaupten) to Lower Tithonian (Solnhofen Fm: Solnhofen, Eichstätt, Zandt, Pfalzpaint, Langenaltheim; Mörnsheim Fm: Mörnsheim, Hienheim, Daiting). Modified from Röper & Rothgaenger (1998), after Meyer & Schmidt-Kaler (1989).

al. 2000); it is the type locality of the Solnhofen Lithographic Limestones (Solnhofener Plattenkalke). It contains the Fossillagerstätten of Solnhofen and Eichstätt, world-famous for the ancestral bird *Archaeopteryx* and numerous other well-preserved fossils (Barthel 1978, Viohl 1998, Wellnhofer 1999). Mainly in the Solnhofen Fm, large slumped intervals ('Krumme Lagen') are intercalated in the succession.

Partly marked by a hardground (Wings 2000), the Solnhofen Fm is followed by the **Mörnsheim Formation** (30-60 m; formerly 'Weißjura zeta 3'). It consists of bedded limestones and plattenkalke rich in cephalopods from the late Hybonotum Zone (Meyer & Schmidt-Kaler 1989, Groiss et al. 2000).

On the large platform of southern Bavaria, a siliceous sponge facies was still widespread, but corals increasingly flourished along its northern and eastern, probably elevated margin (Meyer & Schmidt-Kaler 1989, 1990a, Meyer 1994). This, together with now widely extending reefal debris beds, indicates a distinct shallowing trend. However, sea-level was still high enough to allow for a mainly Tethyan radiolarian ingression through the southern Bavarian platform (Zügel 1997), corroborating observations on nannoplankton distributions by Keupp (1977a). The younger Upper Jurassic formations, starting with the **Usseltal Formation** (up to 40 m; formerly 'Weißjura zeta 4'), have been largely reduced owing to postjurassic erosion, which prevents comprehensive palaeogeographic reconstructions. In Swabia, no sediments from this time have been preserved. The Usseltal Fm (Mucronatum Zone; Scherzinger & Schweigert 2003) starts with bedded limestones, shifting to marls in the upper part (Meyer & Schmidt-Kaler 1989). The **Rennertshofen Formation** (ca. 50 m; formerly 'Weißjura zeta 5') represents a succession of bedded limestones with varying bed thickness (Meyer & Schmidt-Kaler 1989) of the Mucronatum and Vimineus zones (Scherzinger & Schweigert 2003). Finally, the bedded limestones and marls of the **Neuburg Formation** (ca. 50 m; formerly 'Weißjura zeta 6') still contain ammonites of the Ciliata to Palmatus zones in the lower part, but the environment becomes more and more shallow towards the top, exhibiting occasional indicators for partially brackish conditions such as special bivalves and gastropods (Barthel 1969). The uppermost part could already represent lowermost Upper Tithonian (Meyer & Schmidt-Kaler 1989). In the subsurface of the Molasse basin, beds younger than the Neuburg Fm show a partly evaporitic Purbeck facies, clearly indicating very shallow conditions and an arid climate (Meyer & Schmidt-Kaler 1989, Meyer 1994, Flügel 2004: 766). The southward transition to the pelagic facies of the Tethys is deeply buried beneath the alpine nappes.

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