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Depositional sequences in deep-shelf environments formed through carbonate-mud import from the shallow platform (Late Oxfordian, German Swabian Alb and eastern Swiss Jura)

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Key words: Deep shelf, carbonate-mud export, limestone-marl alternations, sequence stratigraphy, cyclostratigraphy, Oxfordian, Swabian Alb, Swiss Jura

ABSTRACT

Upper Oxfordian deposits in southern Germany exhibit limestone-marl alternations typical of deep-shelf depositional environments. These deposits contain varying amounts of brachiopods, echinoderms, foraminifera (mainly represented by *Spirillina, Lenticulina, Usbekistania, Bigenerina, Glomospira* and *Reophax*), cephalopods, sponges and associated encrusters, and scarce bivalves, ostracods and gastropods. Fragments of reworked microbialites (tuberoids, *Tubiphytes*, nubecularians, bryozoans, serpulids, and *Terebella*), and glauconite also occur in variable quantities. In one section of the proximal shelf area (eastern Swiss Jura) there is interfingering of facies dominated by platform-derived elements (ooids, oncoids, coral fragments, peloids, bivalves, ostracods, gastropods) and of facies related to a more parautochthonous, distal sedimentation (*Rhaxella* and other sponge-spicules, brachiopods, *Lenticulina, Spirillina*). The complete record of each ammonite zone as well as the recognition of different ammonite horizons suggest that no important sedimentary gap is present.

For the deep-shelf deposits of southern Germany, statistical analysis shows that the higher the total percentage of particles is in a sample, the more frequent are glauconite, bioturbation, nodularization, cephalopods, sponges, and microbial crusts. Wackestone and packstone samples thus generally correspond to lower sedimentation rates than mudstones that reflect a high carbonate-mud sedimentation rate.

The carbonate mud is thought to be exported from the shallow platform because scarce nannofossils and/or insignificant bioerosion in sponge reefs exclude the possibility of relating carbonate-mud variations to changes in autochthonous productivity. Variation in carbonate-mud exportation from the platform towards the deep shelf has thus been implied from the relative abundance of particulate elements (fauna, tuberoids) which are considered as mainly autochthonous or parautochthonous. Consequently, changes in carbonate-mud content in the studied deep-shelf settings may be related to carbonate production on the shallow platform and to the export dynamics from the platform to deeper sedimentary environments. Variation in carbonate sedimentation rate has been used to interpret depositional sequences in terms of sequence stratigraphy and cyclostratigraphy: constrained by a detailed bio- and chronostratigraphical framework, a correlation of these sequences is proposed between the sections in southern Germany and the eastern Swiss Jura.

RESUME

Les dépôts de l'Oxfordien Supérieur du sud de l'Allemagne sont constitués d'alternances calcaires-marnes typiques d'environnements de plate-forme profonde. Ces dépôts contiennent des quantités variables de brachiopodes, échinodermes, foraminifères (principalement *Spirillina, Lenticulina, Usbekistania, Bigenerina, Glomospira* et *Reophax*), céphalopodes, éponges et les organismes encroûtants qui leur sont associés, de même que de rares bivalves, ostracodes et gastéropodes. Fragments remaniés de microbialites (tubéroïdes, *Tubiphytes*, nubéculaires, bryozoaires, serpules et *Terebella*) et la glauconie apparaissent également en quantités variables. Dans un profil de rampe proximale (Jura suisse oriental), des faciès composés d'éléments dérivés de la plate-forme peu profonde (ooïdes, oncoïdes, fragments de coraux, péloïdes, bivalves, ostracodes, gastéropodes) alternent avec des faciès parautochtones de sédimentation de rampe distale ou de plate-forme profonde (*Rhaxella* et autres spicules d'éponges, brachiopodes, *Lenticulina, Spirillina*). Une biostratigraphie basée sur ammonites suggère qu'aucun hiatus important n'interrompt la sédimentation.

Une analyse des dépôts de plate-forme profonde du sud de l'Allemagne montre que plus les pourcentages d'éléments figurés sont élevés, plus l'abondance de la glauconie, de la bioturbation, de la nodulisation des bancs, des céphalopodes, des éponges et des encroûtements microbiens augmente. Ainsi, les wackestones et packstones représentent des taux de sédimentation plus faibles que les mudstones qui reflètent des taux élevés de sédimentation de la boue carbonatée.

La boue carbonatée est vraisemblablement exportée de la plate-forme peu profonde parce que les rares nannofossiles composant les roches et/ou la faible bioérosion dans les récifs à spongiaires excluent la possibilité de relier les fluctuations en boues carbonatées à des changements dans la production autochtone. Les variations dans l'export de boues carbonatées de la plate-forme peu profonde aux environnements de plate-forme profonde sont alors reflétées par l'abondance relative dans les sédiments des éléments figurés (faunes, tubéroïdes) considérés comme principalement autochtones ou parautochtones. Dès lors, les variations dans les proportions de boue carbonatée dans les contextes de plate-forme profonde étudiés pourraient être reliés aux fluctuations de production carbonatée sur la plate-forme peu profonde et à la dynamique d'export de ces boues des environnments peu profonds aux environnements profonds de la plate-forme. Les variations dans les taux de sédimentation carbonatée ont été utilisées pour interpréter les séquences de dépôt en termes de stratigraphie séquentielle et de cyclostratigraphie (cycles de Milankovitch): dans le cadre d'une bio- et chronostratigraphie très détaillées, une corrélation est proposée entre les profils du sud de l'Allemagne et du Jura oriental suisse.

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Fig. 1. Location of the studied sections. Plettenberg corresponds to a quarry which was not studied in detail but allows comparisons with the other sections.

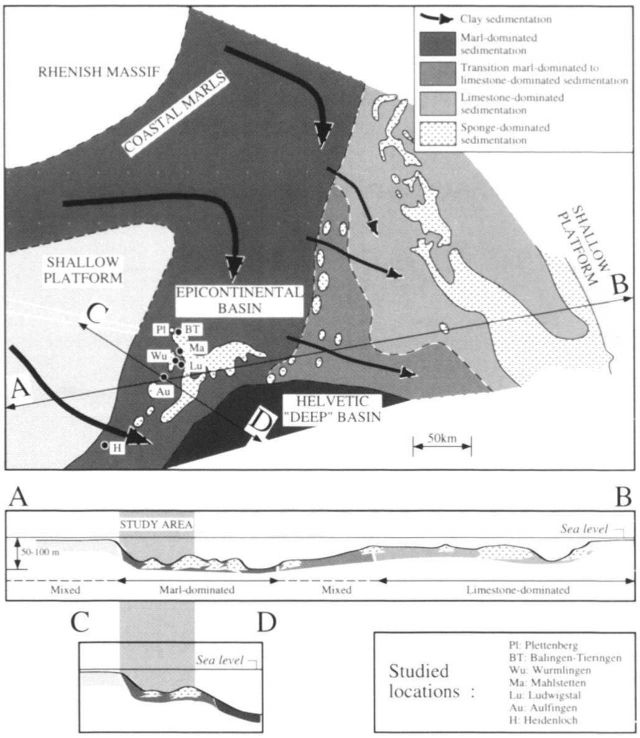

Fig. 2. Palaeogeographic map of southern Germany during the Middle-Late Oxfordian. Modified from MEYER & SCHMIDT-KALER (1989). Facies correspond to the situation during the Malm-alpha (Tranversarium-Bifurcatus-Bimammatum Zones). During the deposition of the Malm-beta (Planula Zone), limestones dominated in all palaeoenvironments presented in this map.

1. Introduction

High-resolution sequence stratigraphy (e.g., Howell & Aitken 1996) is a powerful tool for understanding the spatial and temporal evolution of sedimentary systems. Cyclostratigraphy relates the sedimentary record to climatic and/or eustatic changes driven by orbital cycles (Milankovitch 1941, Berger et al. 1989) and provides a good time assessment (e.g., Schwarzacher 1991, House & Gale 1995). However, before any sequence-stratigraphic and/or cyclostratigraphic interpretation can be attempted, the criteria for the identification of depositional sequences have to be defined. Because of the very detailed bio- and chronostratigraphic framework (at the ammonite-horizon level; Schweigert 1995a, b), the deep-shelf sedimentary rocks of the western Swabian Alb (southern Germany) provide a good field for investigation, while the Argovian Jura (north-eastern Switzerland), in a more proximal setting, gives good indications of platform influences. Previous work in Switzerland, Spain and France (Pittet & Strasser 1997), good lithostratigraphic, biostratigraphic, chronostratigraphic and palaeoenvironmental frameworks (Gygi 1986, 1995, Gygi & Persoz 1986, 1987), and ongoing studies in the Swiss Jura also permit comparisons on a larger scale.

In this paper, we want to show that, through detailed facies analysis and a sequence-stratigraphic and cyclostratigraphic interpretation constrained by ammonite biozonation, we are able to propose correlations of small-scale depositional sequences from shallow platform to deep shelf, and over long distances. Such high-resolution correlations are prerequisites for future studies of the climatic and ecological factors that influenced the sedimentary system.

2. Geological setting

Six Upper Oxfordian sections (Fig. 1) have been analysed sedimentologically. Five of these sections belong to a relatively deep shelf setting in southern Germany (Fig. 2). The palaeoenvironmental reconstruction by Meyer & Schmidt-Kaler (1989) suggests a distance of about 50 km between the shallow platform of the Swiss Jura and the deep-shelf environments studied in this paper. One section from the eastern Swiss Jura has a much more proximal position on a ramp: a distance of 5 to 10 km from the platform edge is suggested in the reconstruction of the depositional environments by Gygi & Persoz (1986).

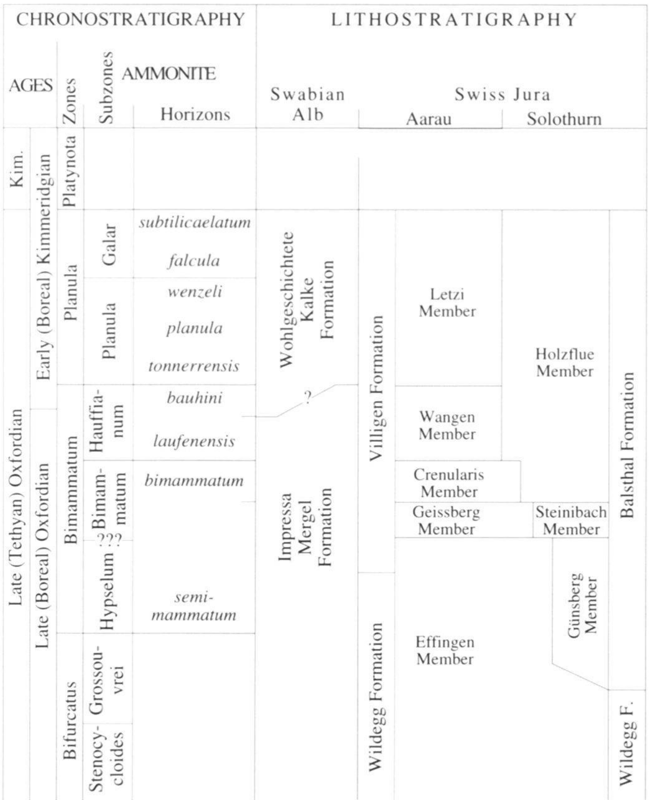

Fig. 3. Stratigraphy of the Late Oxfordian-Early Kimmeridgian in southern Germany and the eastern Swiss Jura. Modified from SCHWEIGERT (1995a) and GYGI & PERSOZ (1986).

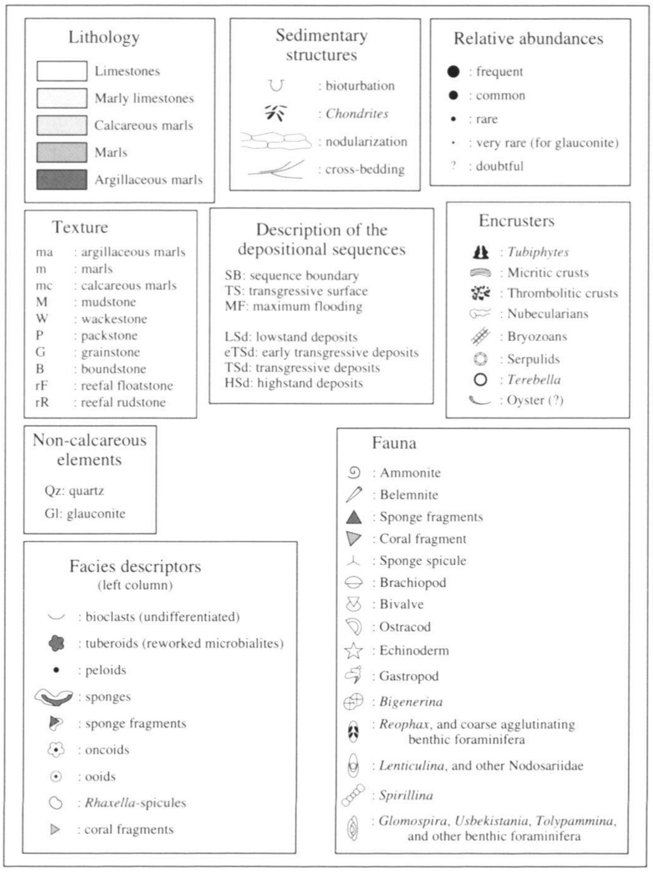

Fig. 4. Legend for the description of the sections.

The studied stratigraphic interval (Fig. 3) goes from the uppermost Bifurcatus Zone to the beginning of the Platynota Zone. More and more evidences are emerging that the base of the Boreal Kimmeridgian is older than the base of the Tethyan Kimmeridgian: the base of the Boreal Kimmeridgian correlates with the uppermost Bimammatum Zone (Matyja & Wierzbowski 1988, 1994, Atrops et al. 1993, Schweigert 1995 a, b).

Lithostratigraphically, the five German sections comprise the upper part of the Impressa-Mergel Formation (Schweigert 1995a), also described as Malm-alpha2 (Quenstedt 1843), Untere Weissjura-Mergel or Oxford-Mergel (Geyer & Gwinner 1984) of the Bifurcatus and Bimammatum Zones. The Wohlgeschichtete Kalke Formation (Geyer & Gwinner 1984) of the Planula Zone and lowermost Platynota Zone corresponds to the Malm-beta of Quenstedt (1843) or to the Oxford-Kalke (Gwinner 1976). The lowermost part of the Platynota Zone has been studied in one profile only (Aulfingen; Fig. 1).

The profile of Heidenloch (Fig.1; also studied by Gygi 1969) in the eastern Swiss Jura spans the uppermost Hypselum Subzone, the Bimammatum and Hauffianum Subzones, the Planula Zone, and possibly the base of the Platynota Zone. Lithostratigraphically, it corresponds to the Geissberg, Crenularis, Wangen and Letzi Members of the Villigen Formation (Gygi & Persoz 1986, Gygi 1995). However, these members are not well expressed in the Heidenloch section: if the Geissberg and Wangen Member facies can be identified, neither the Crenularis nor the Letzi Members show typical facies as described by Gygi & Persoz (1986). The section lies in an intermediate position between platform edge (Balsthal Formation) and epicontinental basin (Villigen Formation).

3. Methodology

The sections have been studied through field observations, polished slabs, and 284 thin sections. Each sample and the corresponding thin section has been described with its skeletal and non-skeletal grain content, its texture, and its intensity of bioturbation and nodularization. The relative abundances of the main components in the samples have been used to perform a statistical study (factor analysis with Statview 4.02 software). This approach provides useful criteria for defining depositional sequences.

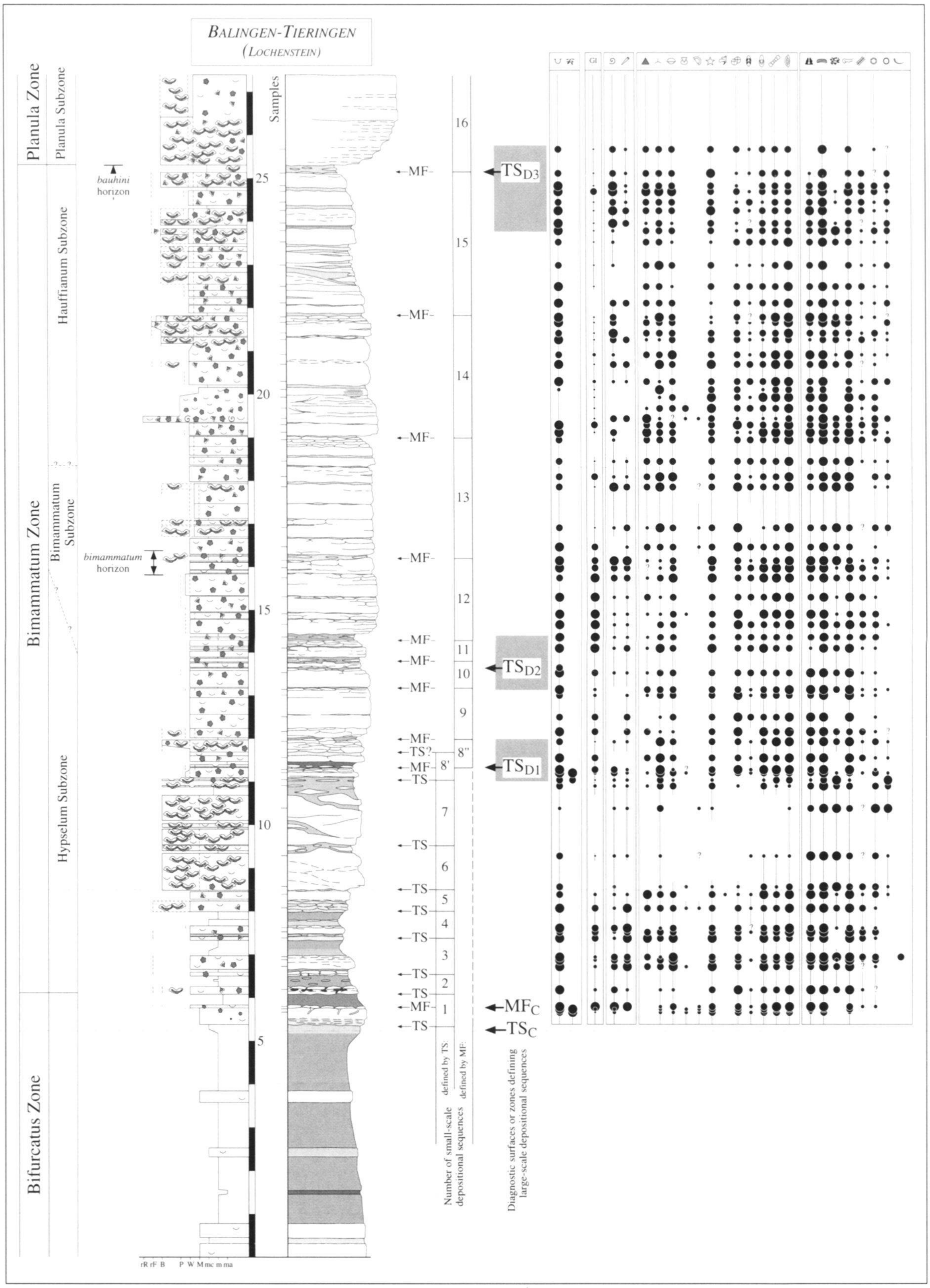

Fig. 5. Description and depositional sequences of the Balingen-Tieringen section. Location shown in Fig. 1; palaeogeographic position in Fig. 2; legend in Fig. 4.

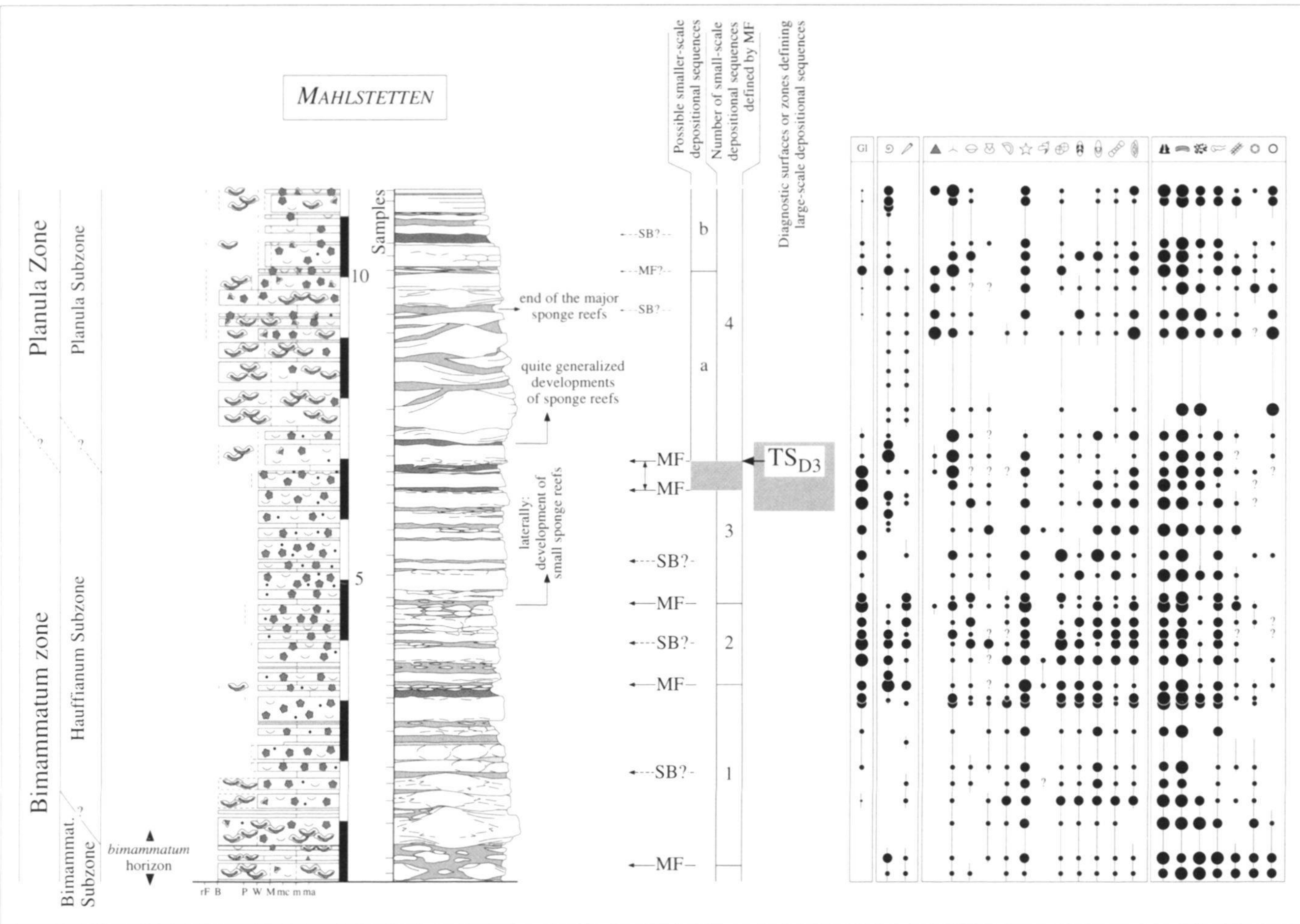

Fig. 6. Description and depositional sequences of the Mahlstetten section. Location shown in Fig. 1; palaeogeographic position in Fig. 2; legend in Fig. 4.

Using the criteria obtained by statistics to identify small-scale and large-scale depositional sequences, the sections have then been interpreted using the concepts of high-resolution sequence stratigraphy and cyclostratigraphy. Based on a well-established ammonite zonation (Schweigert 1995a, b), the correlation of the different sections is attempted, and finally compared with already existing high-resolution sequential analyses (Pittet & Strasser 1997) from sections in Switzerland, France and Spain.

4. Facies description

4.1. Deep-shelf facies (southern Germany)

General lithotypes:

Sedimentation in the Bifurcatus Zone is dominated by marly sedimentation with rare limestone beds. This interval has not been studied in detail, except in its uppermost part (near the transition Bifurcatus-Bimammatum) where a major facies change occurs, with a well-marked increase in the amount of carbonate sedimentation in the Balingen-Tieringen section (Fig. 5; for the legend to all detailed sections see Fig. 4).

The Hypselum Subzone is in its major part formed by limestone-marl alternations with a more or less equivalent amount of carbonate beds and marly intervals. Common glauconite, abundant cephalopods, intense bioturbation and nodularization suggest that sedimentation rates were relatively low. The limestone facies are commonly wackestones with bioclasts, tuberoids (reworked fragments of microbialites or sponges) and some peloids, and boundstones with sponge-microbialite associations (Fig. 5).

The uppermost Hypselum Subzone as well as the Bimammatum and Hauffianum Subzones always display limestone-marl alternations, but these alternations are here dominated by limestones (see Figs 5, 6 and 7). The facies of the limestones are quite similar to those of the lower Hypselum Subzone. They are composed of mudstones-wackestones and wackestones-packstones with bioclasts, tuberoids, and some peloids.

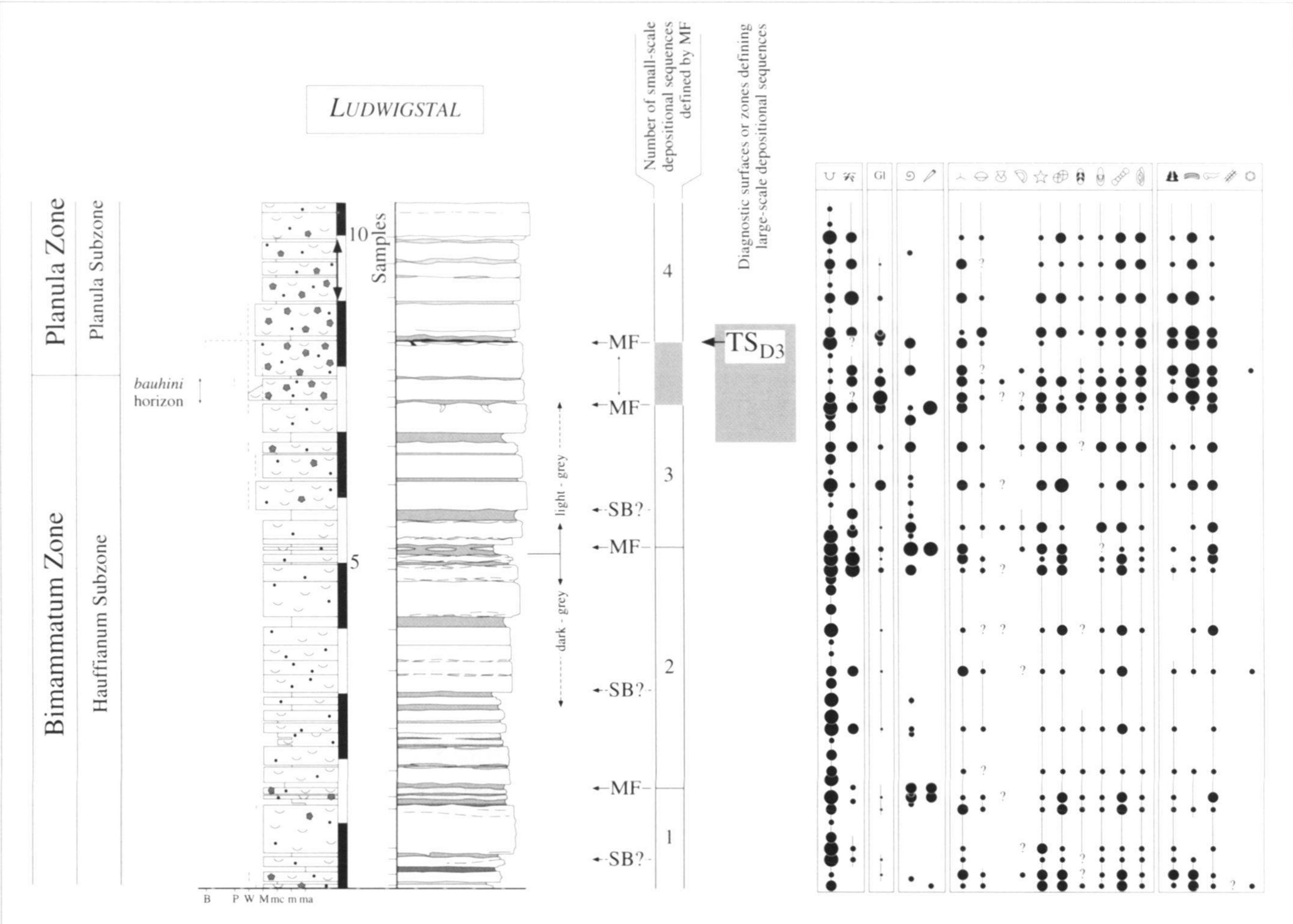

Fig. 7. Description and depositional sequences of the Ludwigstal section. Location shown in Fig. 1; palaeogeographic position in Fig. 2; legend in Fig. 4.

Sponge-reef developments are common. The limestone beds are generally less nodularized than in the lower part of the series, and the glauconite content is lower. Cephalopods are still common.

The Planula Zone and the lowermost Platynota Zone are dominated by carbonates (Figs 8 and 9). The dominant facies are carbonate mudstones commonly containing less than 1% of particles (bioclasts, tuberoids or peloids), in which bioturbation is weak (dominated by Chondrites). Glauconite is very rare and cephalopods are generally absent. The uppermost part of Planula (Galar Subzone) and the lowermost Platynota Zone record renewed marl sedimentation, and the mudstones contain more particles (tuberoids, microfauna) as well as some cephalopods and sessile fauna (brachiopods, crinoids). The intensity of bioturbation increases. The boundary between Planula and Platynota is characterized by a condensation level. The Platynota Zone records an important increase in marl sedimentation (Fig. 9).

General facies composition:

If the particle content in the limestones varies strongly in the studied interval, the general composition of the particle assemblage stays quite similar. The most common elements are tuberoids. These are generally micritic, but can locally be thrombolitic and partly encrusted (mainly by *Tubiphytes*).

Macrofauna is represented by ammonites, belemnites, brachiopods, crinoids and siliceous sponges (mainly Hexactinellids). Microfauna comprises siliceous spicules, echinoderms (echinoids, crinoids, holothurians and *Saccocoma*), and benthic foraminifera. *Lenticulina, Spirillina,* agglutinating foraminifera such as *Usbekistania, Glomospira, Tolypammina, Bigenerina,* and *Reophax* are the main types of foraminifera present in the samples (Schmalzriedt 1991). Planktonic foraminifera have not been recognized. Rare bivalves, gastropods and ostracods have been found. Microencrusters associated with sponges, or reworked as bioclasts or tuberoids, are domi-

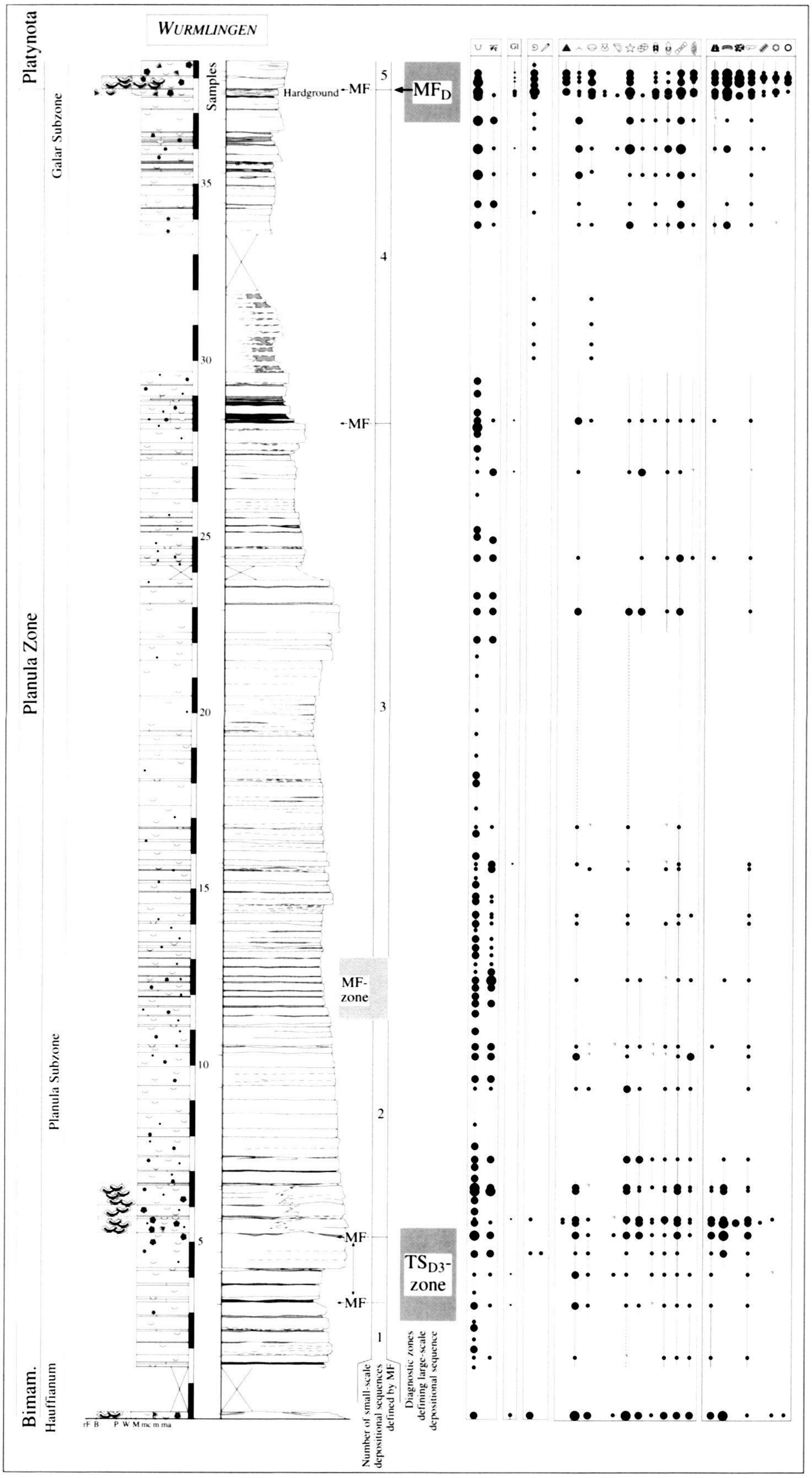

Fig. 8. Description and depositional sequences of the Wurmlingen section. Location shown in Fig. 1; palaeogeographic position in Fig. 2; legend in Fig. 4.

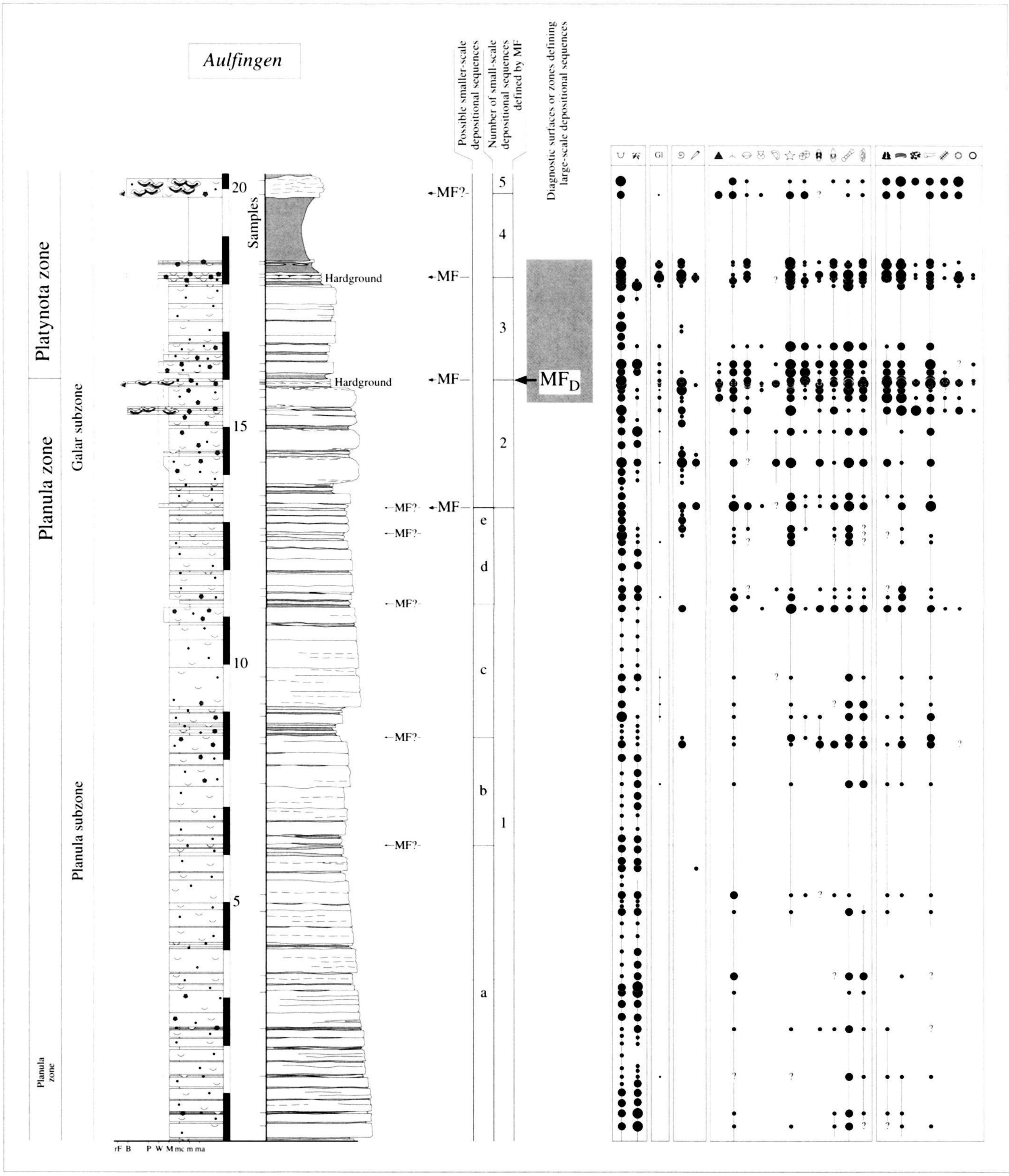

Fig. 9. Description and depositional sequences of the Aulfingen section. Location shown in Fig. 1; palaeogeographic position in Fig. 2; legend in Fig. 4

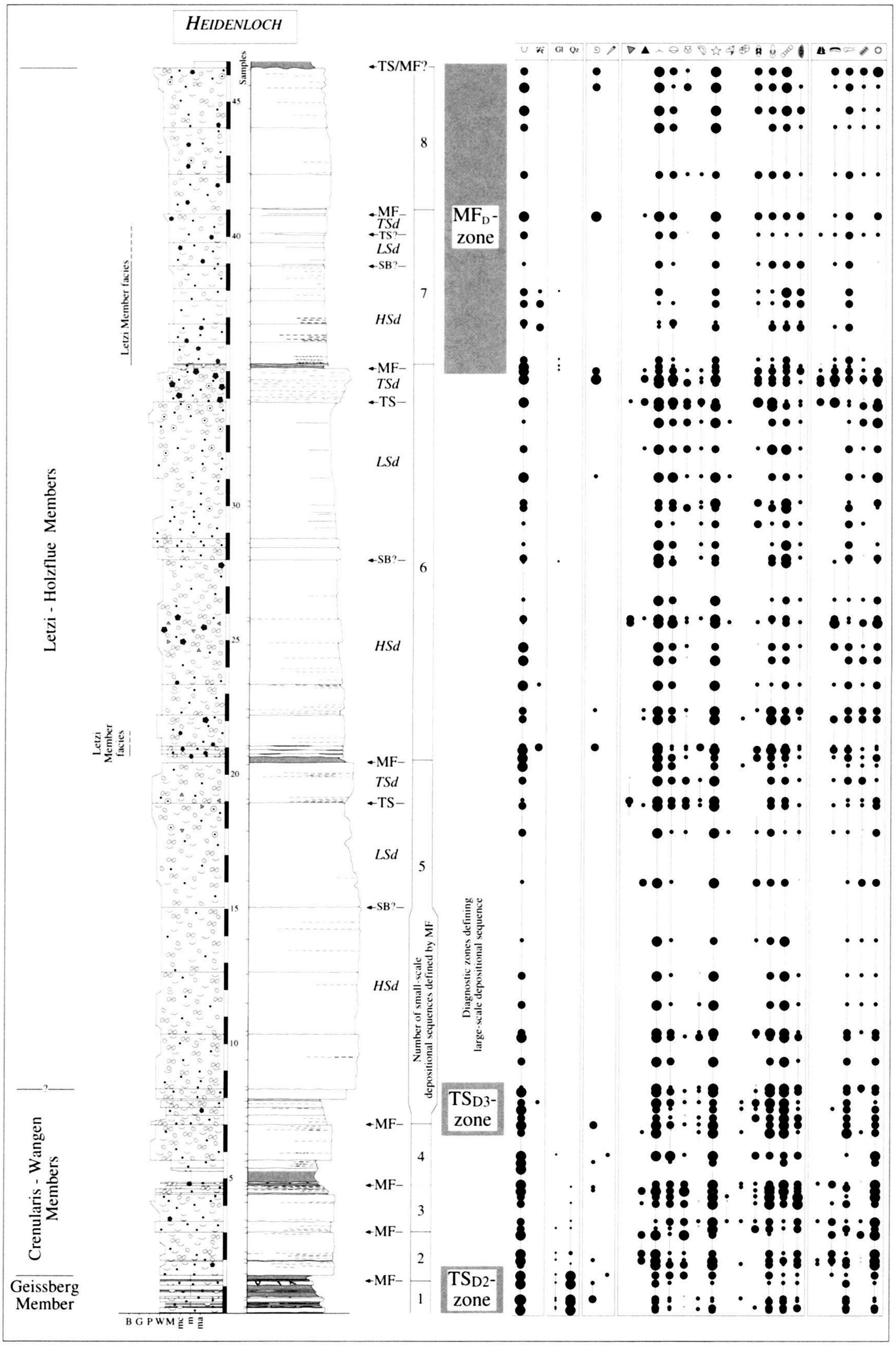

Fig. 10. Description and depositional sequences of the Heidenloch section. Location shown in Fig. 1; palaeogeographic position in Fig. 2; legend in Fig. 4

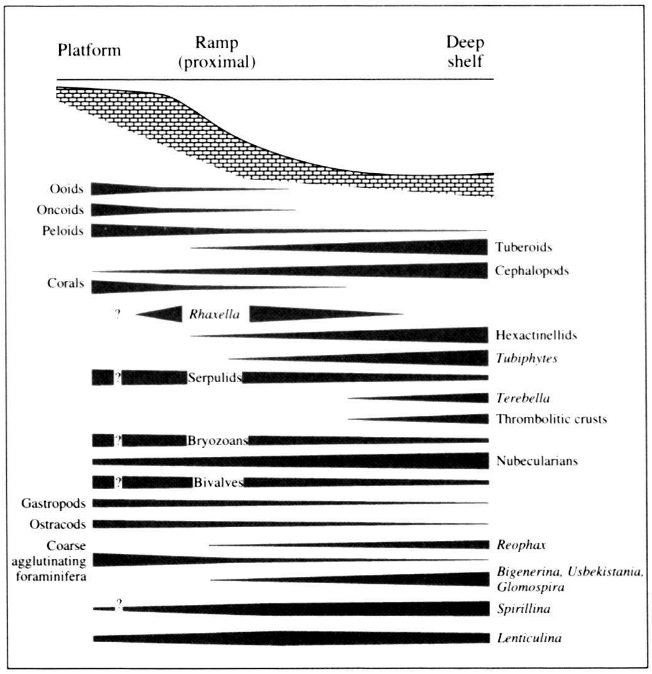

Fig. 11. General distribution of proximal and distal facies components

nated by structureless micritic crusts. Thrombolitic crusts, *Tubiphytes,* and nubecularians are very common. Serpulids, terebellids, and bryozoans are present. *Placopsilina* and oysters are scarce.

4.2. Proximal ramp facies (Heidenloch section)

Lithotypes:

There are no biostratigraphic data available for the Heidenloch outcrop. However, the lithostratigraphic and chronostratigraphic position of the studied profile can be deduced from the general framework given by Gygi (1969, 1995) and Gygi & Persoz (1986).

Variations of facies are more important and more frequent in this proximal setting. Generally, cephalopods are scarce and glauconite is rare. Four major lithotypes can be distinguished. The limestone-marl alternations of the Geissberg Member (Fig. 3) are slightly sandy (quartz) biopelmicritic wackestones, containing some glauconite. The second lithotype is dominated by well-bedded wackestones and packstones. Marl intercalations are rare. The facies are biopelmicrites locally rich in *Rhaxella*-spicules (siliceous demosponge; e.g., Reif 1967, Haslett 1992) and some rare tuberoids. Bivalves and serpulids can be abundant. This facies could correspond to the Wangen Member and/or represent a transitional facies between the Crenularis and Wangen Members. The third lithotype is formed by thick limestone beds, rarely separated by marly intervals. The limestones generally are biopelmicritic wackestones and packstones dominated by *Rhaxella*-spicules. Scarce ooids, oncoids and coral fragments attest to the export of coarse-grained platform material towards the ramp. Interlayered with this facies are thin intervals of mudstones which represent the fourth lithotype. They are composed of biopelmicrites with some tuberoids. This lithotype may be related to the Letzi Member facies and is similar to the deep-shelf facies of the Planula Zone in South Germany.

General facies composition:

The main components of the samples are bioclasts and peloids, rarely tuberoids. The macrofauna is well represented by brachiopods, and bivalves can be abundant in some intervals. Cephalopods, mainly ammonites, are relatively rare. Sponges are present as fragments (mainly Lithistids) and as abundant *Rhaxella*-spicules (some other siliceous spicules also occur, but only in small amounts in the Letzi Member facies). Gastropods and coral fragments generally appear more or less contemporaneously, associated with an increase in bivalves, ostracods, ooids, and oncoids. Echinoderms (mainly echinoids) are ubiquitous.

Foraminifera are well represented. As in more distal environments, *Spirillina* and *Lenticulina* are important components of the facies, but *Usbekistania, Glomospira, Bigenerina, Tolypammina*, and *Reophax* are extremely rare. Miliolids, coarse agglutinating forminifera (Lituolidae) and biseriate foraminifera *(Textularia?)* also contribute to the foraminifera assemblage.

The two main encrusting organisms are bryozoans and serpulids. Nubecularians are also present. *Tubiphytes* is common in one single interval only (Heidenloch section, 34–35 metres, Fig. 10), otherwise it is quite rare. Micritic crusts (on tuberoids and oncoids) also are a common component of the facies. *Placopsilina* is rare, but occurs more frequently than in distal setting. *Koskinobulina socialis* occurs very rarely. It has not been seen in distal settings. Thrombolitic crusts and terebellids have not been found in the samples.

In the first two lithotypes described above, the bioturbation can be quite intense. In the third and fourth types, only some levels are strongly bioturbated. *Chondrites* only occurs in more muddy facies (such as the Letzi Member facies).

4.3 Comparison of proximal vs. distal facies

Figure 11 gives the general trends of distribution of characteristic elements in proximal areas (ramp) to deep-shelf facies mainly based on the data described in this work. Complementary data come from Pittet (1996) on Middle to Upper Oxfordian platform sediments of the Swiss Jura. Some of these trends have also been demonstrated by Leinfelder et al. (1993a, b), Werner et al. (1994), Nose (1995) and Schmid (1996) in the Upper Jurassic of Spain, Portugal and Germany. These trends are possibly controlled not only by a proximal-to-

Tab. 1. Statistical parameters for factor analysis and results.

Factor Analysis Summary

Number of Variables	24
Est. Number of Factors	12
Number of Factors	8
Number of Cases	198
Number Missing	5
Degrees of Freedom	299
Bartlett's Chi Square	2818.822
P-Value	<.0001

Factor Extraction Method: Principal Components
Extraction Rule: Method Default (Non-constrained number of factors)
Transformation Method: Orthotran/Varimax

Proportionate Variance Contributions

	Orthogonal	Direct Oblique	Direct Oblique - Joint	Oblique - Total
Factor 1	.535	.333	.383	.716
Factor 2	.140	.087	-5.629E-4	.086
Factor 3	.070	.044	-1.463E-3	.042
Factor 4	.064	.040	4.609E-3	.044
Factor 5	.056	.035	6.916E-5	.035
Factor 6	.049	.030	3.589E-3	.034
Factor 7	.047	.029	-8.967E-3	.020
Factor 8	.040	.025	-2.578E-3	.022

Orthogonal Solution

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8
Element abundance	.827	-.119	.024	-.261	.029	-.125	-.146	.015
Bioturbation	.478	-.178	-.507	.373	-.031	.035	.325	.268
Nodulization	.624	-.013	-.505	.116	.101	.154	.131	-.039
Chondrites	-.656	-.161	9.153E-3	.141	.079	-.043	.170	.187
Glauconite	.655	-.353	-.225	-.275	.013	-8.846E-3	-.157	.274
Ammonites	.541	.152	-.081	.466	.321	.257	-.346	.127
Belemnites	.520	-.030	-.365	.095	-.334	.080	-.455	-.060
In-situ sponges	.253	.695	-.049	.033	.081	.363	.319	-.215
Sponge fragments	.646	.277	.226	.371	-.073	-.308	-.057	.017
Sponge spicules	.406	.094	.476	.159	-.474	.358	.020	.320
Brachiopods	.808	-.100	.052	.161	.050	-.172	-6.612E-3	-.159
Echinoderms	.651	-.305	.093	.013	.233	.227	-.129	-.216
*Reophax**	.487	-.278	.265	-.185	.508	.141	.077	.179
Lenticulina	.769	-.335	.063	-.049	-.050	.073	-.046	-.202
Bigenerina	.498	-.454	.052	.023	-.399	.190	.241	-.283
Spirillina	.375	-.543	.244	.413	.168	-.145	.189	-.158
*Glomospira***	.755	-.127	.187	.020	-.109	-.177	.071	.164
Micritic crusts	.859	.151	.069	-.208	.070	.059	.125	.014
Thrombolitic crusts	.554	.572	-.062	-.112	-.027	-.023	.113	.104
Tubiphytes	.814	.117	-.032	-.340	.031	.077	.135	.065
Nubecularians	.799	-.085	.147	-.053	-.067	.044	-.014	.137
Serpulids	.672	.290	-.092	-.114	-.042	-.177	-.031	-.217
Terebella	.417	.671	.227	.159	.116	-.058	-.129	-.044
Bryozoans	.683	.156	-.134	3.058E-3	-.044	-.414	.173	.071

*Reophax**: *Reophax*, and coarse agglutinating foraminifera
*Glomospira***: *Glomospira*, *Usbekistania*, *Tolypammina*, and other benthic foraminifera

Sampling Adequacy

Element abundance	.937
Bioturbation	.871
Nodulization	.933
Chondrites	.977
Glauconite	.916
Ammonites	.899
Belemnites	.931
In-situ sponges	.775
Sponge fragments	.891
Sponge spicules	.869
Brachiopods	.941
Echinoderms	.931
*Reophax**	.930
Lenticulina	.959
Bigenerina	.907
Spirillina	.810
*Glomospira***	.933
Micritic crusts	.946
Thrombolitic crusts	.926
Tubiphytes	.941
Nubecularians	.976
Serpulids	.957
Terebella	.878
Bryozoans	.952

Total matrix sampling adequacy: .929

distal factor or by a bathymetric factor, but are also dependent on environmental changes such as oxygenation, nutrient availability, salinity, or light (Schmid 1996). Similar distribution patterns have been seen in shallow coral bioconstructions (Dupraz 1997).

The studied Upper Oxfordian locations in the western Swabian Alb always exhibit relatively distal facies. Therefore, facies composition is not a useful criterion for interpreting proximal-to-distal changes that could reflect progradational-retrogradational fluctuations and/or relative variations of sea level. In proximal areas such as in Heidenloch (Figs 1 and 10), however, changes marking an evolution from proximal to distal facies can be helpful to trace such variations.

4.4 Factor analysis applied to deep-shelf samples

The general variations in facies and particle composition are relatively small in the deep-shelf setting, but the percentage of particles varies in a much greater proportion. A statistical approach (Factor analysis) has therefore been applied to the 203 samples of the South German sections. The proximal ramp profile has not been integrated in the statistical analysis because of its quite different facies composition.

The following components or features have been used as variables:

- sedimentary features and trace fossils: bioturbation, nodularization, *Chondrites;*
- minerals: glauconite;

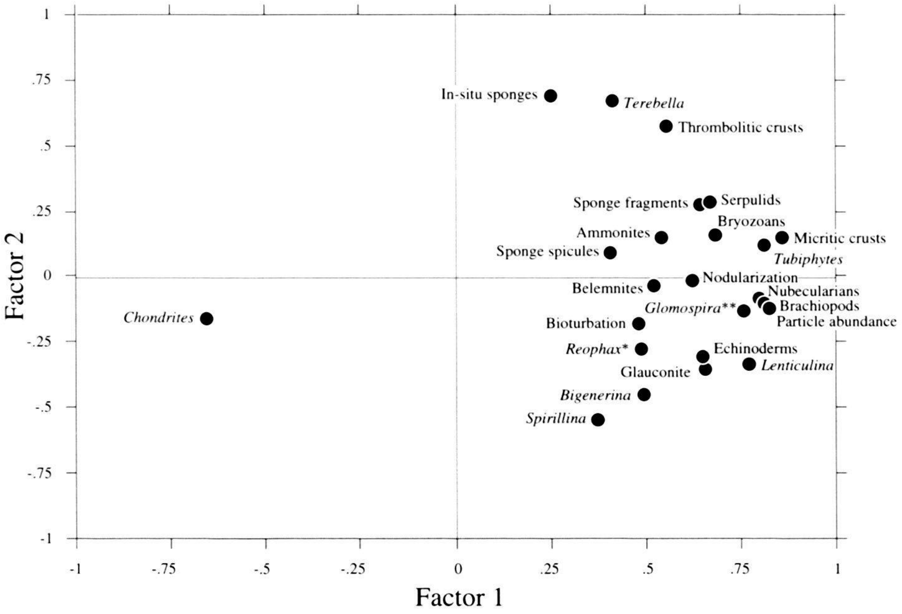

Fig. 12. Factor plot between the two main factors influencing the descriptors of distal ramp facies. Factor 1 corresponds to carbonate-mud sedimentation rate, whereas Factor 2 corresponds to sponge reef developments. See text for comments, and Table 1 for statistical values. *Reophax** corresponds to *Reophax* plus coarse-grained agglutinating foraminifera; Glomospira** corresponds to *Glomospira, Usbekistania, Tolypammina*, and other benthic foraminifera (excluding *Lenticulina, Bigenerina, Spirillina, Reophax* and coarse-grained agglutinating foraminifera).

- lithoclasts: sponge fragments;
- macrofauna: ammonites, belemnites, sponges, brachiopods, echinoderms;
- microfauna: spicules, *Lenticulina, Spirillina, Bigenerina, Glomospira + Usbekistania + Tolypammina* + small agglutinating foraminifera, *Reophax* + other bigger agglutinating foraminifera;
- encrusters: micritic crusts (that are mainly found in tuberoids), thrombolitic crusts, *Tubiphytes*, nubecularians, bryozoans, serpulids, terebellids;
- total abundance of fauna + tuberoids.

Ostracods and bivalves have not been used in this factor analysis because their occurrences are quite low.

A relative abundance index (from 0 to 3) has been attributed to each variable in a sample:

- for macroscopic variables such as bioturbation or nodularization, as well as for ammonites, belemnites, and sponges, this index has been attributed in the field and on macroscopic samples;
- for microscopic particles, a type of particle has an index of 3 when it is always present in the field of view under the microscope (i.e., it is at its most common). An index of 2 has been attributed when this particle appears commonly in the thin section, and an index of 1 when it appears rarely (2 to 5 occurrences in the thin section, depending on the size of the particle). An index of 0 expresses absence.
  This index is adapted to the size of the particles: for bigger particles, it has been estimated under 40x magnification, and for the smaller particles under 100x magnification;
- for very rare glauconite, an index of 0.5 has been attributed;
- the estimation of the total abundance of particulate elements is based on the Dunham classification: mudstone=1; wackestone=2; packstone=3. Transitional values have also been used: for a sample varying between mudstone and wackstone an index of 1.5 has been attributed.

The number of factors has not been constrained, and a principle component method has been applied (Table 1). Eight factors have been obtained with this statistical method. The dominant factor contributes 53.5% to the variance of the assemblage in the orthogonal solution (the factors are seen as independent from each other), and 71.6% in the oblique solution (factors are regarded as interdependent). A second factor has a relatively high variance contribution in the orthogonal solution (14%), but this contribution decreases to 8.6% in the oblique solution (Table 1). The other factors have a very low contribution to the variances in the assemblage (< 4.5%) and will not be interpreted in this study.

The variables are influenced by the dominant factor in the same sense (Factor 1 in Fig. 12 and Table 1); only *Chondrites* lies in an opposite sense. Total abundance of particulate elements, brachiopods, as well as the main components of the tuberoid facies (micritic crusts, *Tubiphytes* and nubecularians) are strongly related to Factor 1. This factor indicates that the more abundant particulate elements (fauna + tuberoids) are in a sample, the more common are glauconite, nodularization, cephalopods, spicules, sponge fragments, brachiopods, echinoderms, foraminifera, and encrusters. To a lesser degree, in-situ sponges and terebellids are also influenced by this factor. The positive correlation between element-rich wackestone-to-packstone facies and features expressing condensation (nodularization, bioturbation, glauconite) suggests that wackestone-to-packstone samples correspond to a generally lower accumulation rate than mudstones containing only few elements. Consequently, mudstones correspond to high carbonate-mud sedimentation rate. The dominant factor thus appears to reflect changes in the input of carbonate mud which dilutes to various degrees the mainly autochthonous and parautochthonous particles.

Chondrites is the dominant trace-fossil in mudstones, whereas other trace-fossils (e.g., *Thalassinoides, Planolites*) are scarce or absent. *Chondrites* occurs only exceptionally in wackestones. Two possible explanations can be proposed. When carbonate mud is rapidly deposited, the sediment becomes dysaerobic and, therefore, favours organisms tolerant of low-oxygen conditions such as *Chondrites* (e.g., Savrda & Bottjer 1987, Bromley 1990). The dominant presence of small *Chondrites* during the Planula Zone deposition, and their relatively shallow penetration into the sediment (5 to 10 centimetres below the bedding surfaces) confirm such dysaerobic conditions (Bromley 1990). A very soft nature of the sediment (soupground, Bromley 1990) represented by pure carbonate mud could be another explanation for the domination of *Chondrites:* burrows such as *Thalassinoides* could not be supported in the soupy substrate.

The second factor can be related to sponge-reef systems (Factor 2, Fig. 12, Table 1). In-situ sponges, thrombolitic crusts and terebellids, well described by this factor, correspond to the three major constituents of sponge reefs. They are rare in tuberoid facies. Serpulids also seem to be partially related to this factor.

Comparing the variance contributions between the orthogonal and oblique solutions, the sedimentation-rate factor (Factor 1) enhances its contribution, the sponge-reef factor (Factor 2) diminishes its contribution. Therefore, sedimentation rate seems to be one important controlling factor of sponge-reef installation and development (Krautter 1995). In-situ sponges, thrombolitic crusts and terebellids, as indicators of reef systems, are less constrained by sedimentation rate than the other variables considered: this could mean that reef growth is generally faster than carbonate-mud sedimentation rate. Field observations and sample descriptions argue for this interpretation: cephalopods are less common in sponge reefs than in tuberoid facies, and glauconite content is normally low in the sponge-reef samples.

This analysis shows that variations in elements (considered as mainly autochthonous and parautochthonous; Fig. 12) are constrained by carbonate-mud input in the deep-shelf setting. High sedimentation rate of carbonate mud in the Planula Zone (mudstones) could therefore explain the very rare occurrences of macro- and microfauna, tuberoids, glauconite, bioturbation, and nodularization. Abundant sponge-reef development in the Bimammatum Zone and richness in microbialites, on the other hand, give evidence of relatively low sedimentation rates (Leinfelder et al. 1993b, Schmid 1996).

The top of the limestone beds is frequently marked by condensation features that precede marl deposition. Establishment of sponges in clay-rich environments is common and argues for a low sedimentation rate of clays. Relatively marl-rich intervals (e.g., Hypselum Subzone; Fig. 5) exhibit higher contents in glauconite, and are intensively bioturbated. Consequently, it is suggested that the formation of limestone-marl alternations is rather controlled by variations in carbonate-mud sedimentation rate than by fluctuating clay sedimentation rate.

Reworked pyritized tuberoids (also seen in Oxfordian deep-shelf settings in the southern Jura; Gaillard 1983), encrustation of these tuberoids (commonly by *Tubiphytes*), and broken thick-walled *Lenticulina* argue for transport and reworking processes, and for periods of low sedimentation rate (mainly of carbonate mud). Intervals rich in tuberoids may correspond to low sedimentation rates, because time is needed for forming the microbialites associated with sponges, for breaking them into tuberoid lithoclasts, and for reworking them several times.

5. Origin of the carbonate mud

The calcareous nannofossil assemblages in the studied sections are being investigated by Dr. Emanuela Mattioli (Perugia, Italy). Preliminary results show that the nannofossil abundance is generally low, and that marl intervals are relatively richer in nannofossils than the limestone beds. Furthermore, condensed limestone intervals are enriched in calcareous nannofossils. Therefore, calcareous nannofossils cannot be invoked as being responsible for carbonate-mud production, and they probably contribute only a small proportion to the total carbonate. The same is proposed by Gygi & Persoz (1986) for the mudstone formation of the Letzi Member (Planula Zone; Fig. 2) where scarce nannofossil content is believed to be a primary feature.

Abundant carbonate production related to sponge-reef systems is not likely. Reefs are composed of siliceous sponges associated with microbialites. Bioerosion, responsible for important carbonate-mud production in coral reefs (e.g., Peyrot-Clausade et al. 1995, Dullo et al. 1996), is scarce in the observed sponge reefs. Furthermore, it would be paradoxical that carbonate mud produced in sponge-reef systems correlates negatively with sponge-reef bioconstructors (see discussion above) and related particles (tuberoids), or with fauna that seems to be largely autochthonous or parautochthonous. This last argument underlines that carbonate production cannot be directly related to bioconstuctions in the studied deep-shelf environments.

Consequently, the carbonate mud is thought to be imported from the platform. Fluctuations in carbonate mud seen in the studied sections are most probably related to carbonate production on the platform, and to the dynamics of exportation from the platform to the deep shelf. Varying input of carbonate mud into the deep-shelf system will thus influence the relative abundance of fauna and tuberoids. During the Planula Zone which corresponds to the highest record of carbonate mud in deep-shelf environments, the Swiss Jura platform accumulated thick oolitic grainstones and packstones (Verena Oolite and Holzflue Members, Gygi & Persoz 1986). Furthermore, a general transgressive trend (Gygi 1986, Pittet 1996) led to expansion of the Verena Oolite of about 15 to 20 kilometres towards the northern proximal areas (Gygi & Persoz 1986, Gygi 1986), thus extending the carbonate production area. Aggradation on the distal platform and on the platform margin is suggested by the palaeogeographical stability of oolitic and reefal facies belts (see Plate 1 of Gygi & Persoz 1986).

On the proximal ramp (Heidenloch, Figs 1 and 10), facies exhibit an interfingering of particles exported from the platform (e.g., ooids, corals, oncoids, and probably also peloids) and autochthonous to parautochthonous particles (e.g., *Rhaxella*, tuberoids, brachiopods). A size segregation of exported carbonate sediments from proximal to distal areas appears. The proximal area records coarse- and fine-grained sediment (with the formation of packstone and packstone-to-grainstone facies), while distal areas record mainly carbonate mud mixed with autochthonous to parautochthonous material. Davaud & Lombard (1973), Gaillard (1983), and Brachert (1992) have described exportation of carbonate mud in similar (Oxfordian) platform-to-ramp (or deep-shelf) settings.

Sedimentary structures pointing to gravity transport are very rare; only one thick turbidite (about 80 centimetres) is found in the Balingen-Tieringen section (Fig. 5). Its composition is quite similar to that of under- and overlying sediments, but ammonites, belemnites, sponges, tuberoids and other fauna are reworked. A slight enrichment in bivalves and ostracods is the only feature possibly indicating a proximal origin of part of the coarse material, whereas the mud content is low.

Some tempestitic features have been recognized in the Effingen and Geissberg Members (Gygi & Persoz 1986, Pittet 1996). In the upper Geissberg Member in Heidenloch (Fig. 10) possible tempestites (commonly bioturbated) have been recognized. Other sedimentary features in the Geissberg Member have been interpreted as gravity flows (Gygi 1969, Gygi & Persoz 1986). In the Letzi Member facies of the Heidenloch profile, only rare, very small and fine-grained tempestites have been recognized. However, bioturbation is generally intense and may have destroyed primary sedimentary structures.

If such sedimentary features are difficult to find in relatively proximal areas such as Heidenloch, then storm deposits in more distal areas may be recorded only as mud. Such muddy tempestites (or mud flows, or turbidites) could also explain the great number of beds in the Wohlgeschichtete Kalke Formation. Ricken (1986) has interpreted these beds as resulting from compaction processes. Systematically investigated beds in the Aulfingen profile (Fig. 9), however, demonstrate that they are the result of primary sedimentary processes: the maximum abundance of *Chondrites* traces generally occurs 5 to 10 centimetres below the surface of the bed. A sedimentary origin of similar beds in the Franconian Alb is also inferred by Brachert (1992).

In the outer-shelf environments of the Bahamas, Holocene deposits of carbonate mud are thought to be predominantly formed through exportation from the shallow platform (e.g., Boardman & Neumann 1984, Boardman et al. 1986, Milliman et al. 1993). The carbonates which form during high sea-level while the platform is flooded (Droxler & Schlager 1985, Grammer & Ginsburg 1992) can contribute to more than 70% of the outer-shelf deposits and probably correspond to more than half of the production on the shallow platform (Milliman et al. 1993). Transport occurs through turbidity currents (e.g., Droxler & Schlager 1985) initiated by storms, or through density cascading (Wilson & Roberts 1995). Ebb tides and storm currents cause rapid deposition of coarser-grained sediments close to the platform and formation of a nepholoid layer rich in carbonate mud that will cover large areas (Wilson & Roberts 1995). The Bahamian outer-shelf sediments are thought to have originated mainly through inorganic precipitation (Milliman et al. 1993) in platform environments (whitings, Shinn et al. 1989) or, possibly, at the water-sediment interface (Milliman et al. 1993). Robbins et al. (1997) have shown that modern carbonate mud production by whitings can largely exceed the volume deposited on the platform itself, and account for more than 40% of the total (platform and periplatform) lime-mud accumulation. Calcifying green algae can also be important contributors to the carbonate production (e.g., Neumann & Land 1975, Boardman & Neumann 1984).

Density cascading of carbonates from the platform to the deep shelf (Wilson & Roberts 1995) may potentially explain the sedimentary record in Upper Oxfordian sediments. However, demonstration of this hypothesis is not possible in absence of specific sedimentary features related to such a process. Increasing carbonate export during the Planula Zone, recognized as a transgressive interval (Gygi 1986, Pittet & Strasser 1997), is explained by the increasing surface of the shallow-water environments where carbonates can be produced. Relative scarcity of recognized green algae in Oxfordian shallow platform environments of the Swiss Jura (Pittet 1996) and abundance of oolitic deposits (Gygi & Persoz 1986) indicate that inorganically and/or microbially produced carbonates seem to predominate.

6. Formation of depositional sequences

Organic and inorganic carbonate productivity on the shallow platform is strongly controlled by water depth, but factors other than sea level are also important. Siliciclastic and nutrient input, related to climatic and/or tectonic conditions, can lead to eutrophication and decrease of carbonate productivity (e.g., Hallock & Schlager 1986). Tectonic factors such as subsidence, formation of structural highs and lows, or development of depocenters (Allenbach 1997) play an important role in the creation of accommodation on the platform. High production of carbonate will lead to greater exportation towards the deep shelf, and low production of carbonate on the platform can lead to sediment starvation on the deep shelf.

Sea-level variations play an important role in the exportation of carbonate mud from the platform to the deep shelf

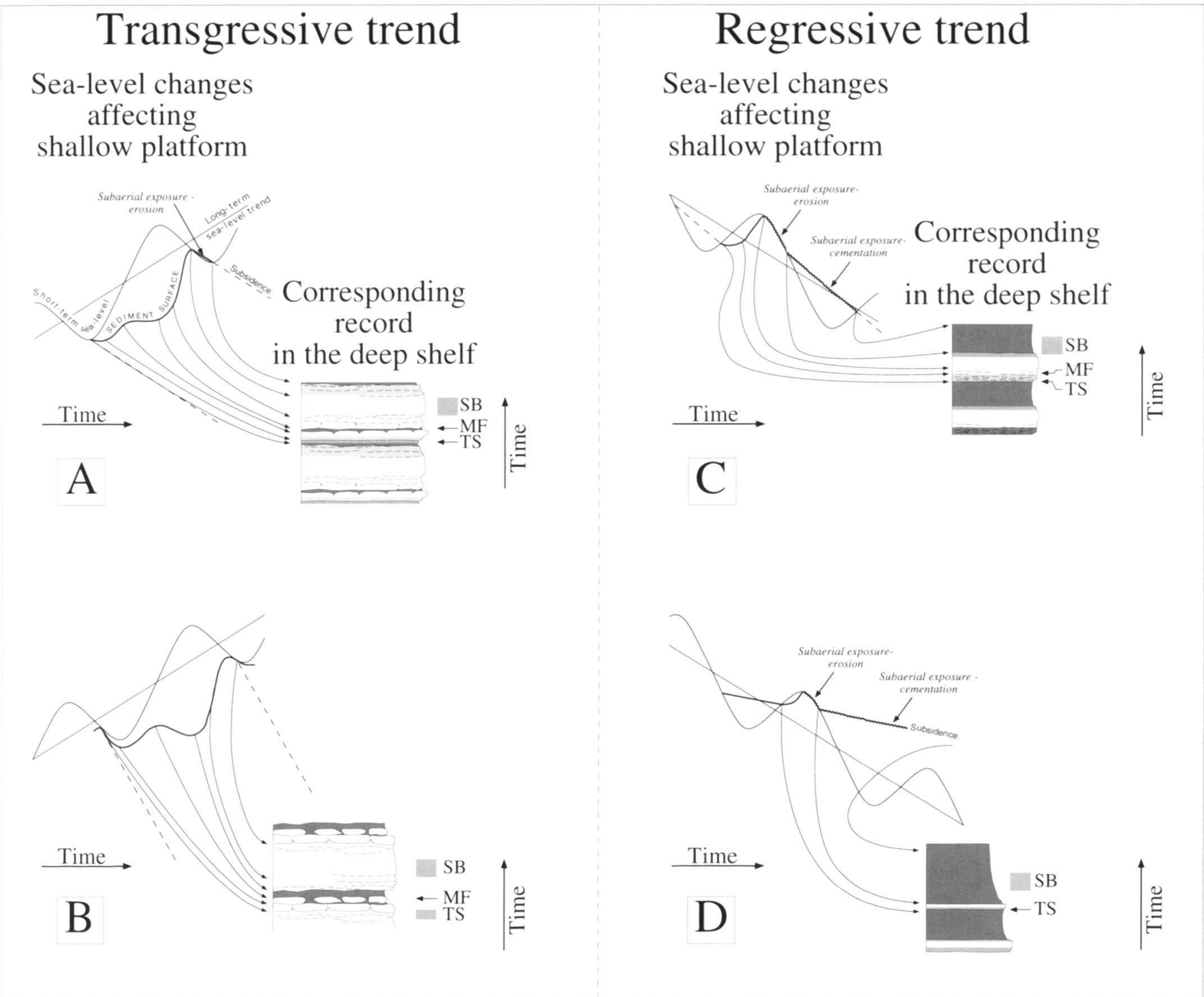

Fig. 13. Model for the exportation of carbonates from the shallow platform to the deep shelf driven by long- and short-term sea-level variations, and their associated sedimentary record in the deep shelf. A. Transgressive long-term sea-level trend (general case); B. Transgressive long-term sea-level trend, a case with very short subaerial exposure period on the shallow platform (no cementation), or without subaerial exposure; C. Regressive long-term sea-level trend (general case); D. Regressive long-term sea-level trend, with the long-term sea level falling below the platform edge. (SB: sequence boundary; TS: transgressive surface; MF: maximum flooding).

(Droxler & Schlager 1985, Schlager et al. 1994). Retrogradational vs. progradational conditions may further diminish or enhance export to the deep shelf, respectively. Rapid flooding can lead to drowning of the platform (Schlager 1989) and to rapid changes in environmental conditions that will stop or diminish production of carbonates.

Pathways of discharge of clays towards the deep shelf or epicontinental basin may be different from those of carbonate mud: for example, drainage of siliciclastics along subsident zones on the platform has been observed in the Upper Oxfordian of the Swiss Jura (Pittet 1994, 1996), contributing to lower carbonate production in these areas.

For the formation of the observed depositional sequences the following scenario can be proposed:

At the beginning of a sea-level rise, accommodation is created on the shallow platform, but carbonate production is still low (start-up phase of Kendall & Schlager 1981). Therefore, carbonate export from the platform is limited, and the deep shelf records only little carbonate (Fig. 13). Once carbonate production picks up on the platform, increasing accommodation during transgression now allows carbonate accumulation on platform and deep shelf. Rapid sea-level rise may then outpace carbonate production: the sediment surface drops below the depth optimal for carbonate production, and the carbonate-producing environments are shifted towards more proximal areas. Therefore, in deep-shelf environments, only marl deposition is recorded, and condensation features occur (Fig. 13 A, B). Condensation and related marl deposition can be enhanced by increased distality due to a strongly transgressive trend.

During early sea-level highstand (Fig. 13 A, B) and/or slow sea-level rise (Fig. 13 C, D), carbonate production again becomes intense on the platform, infilling rapidly the space created beforehand, and allowing for a gentle progradation of the sedimentary environments and for export of carbonates towards the deep shelf (highstand shedding of Schlager et al. 1994). During late highstand, production of carbonates slows down because water depth now is too shallow for the carbonate-producing organisms, or water volumes are too small to allow formation of ooids and carbonate mud. When sea level begins to fall, progradation is forced and exportation of carbonates to the deep shelf increases. If emersion takes place on the platform and sea level continues to fall, erosion and export of carbonates will be important as long as carbonates are not yet cemented. If carbonates are cemented on the platform, mainly terrigenous clays are transported towards the deep shelf where marly intervals form (Fig. 13 A, C, D). If there is no emersion on the platform because a short-term sea-level fall is attenuated by a long-term sea-level rise or strong subsidence, carbonate production and progradation continue, and thick carbonate deposits can potentially accumulate in the deep-shelf setting (Fig. 13 B).

In the deep-shelf depositional environments, the recognition of high vs. low carbonate sedimentation rates, condensed vs. non-condensed intervals, limestone-dominated vs. marl-dominated sedimentation, and/or intervals rich in autochthonous to parautochthonous elements vs. intervals poor in autochthonous to parautochthonous elements can thus be used as indicators of relative sea-level rises and falls.

On the long-term sea-level evolution (a few million years), generally increasing carbonate sedimentation is related to increasing accommodation and carbonate productivity on the platform, accompanied by increasing export to the deep shelf. Intense condensation and marl layers in such limestone-dominated intervals are due to flooding of the platform (transgressive surfaces or zones, or maximum-flooding surfaces or zones; Montañez & Osleger 1993, Pasquier & Strasser 1997; e.g., Figs 5 to 9: TS_{D1}, TS_{D2}, TS_{D3}, and MF_D). Marl-dominated intervals are interpreted as lowstand deposits when carbonate production on the platform is reduced (e.g., Fig. 5, from 0 to 5 metres). Relatively constant ratios in carbonate and marl are interpreted as highstand deposits (e.g., Fig. 5, from 6 to 10 metres).

During long-term transgressive periods, marine flooding on the short-term (a few 10 to 100 ka) will be enhanced by adding short-term sea-level rises to the general transgressive trend (Fig. 13 A, B). The short-term maximum-flooding surfaces will therefore be the best expressed surfaces during long-term sea-level rises and, in this case, small-scale depositional sequences will be defined by their maximum-flooding surfaces expressed by condensed intervals (e.g., Fig. 5, from 11.5 to 25.3 metres, and Figs 6 and 7). The sequence boundaries of the short-term sequences correspond to the maximum of carbonate export from the platform to the deep shelf and lie in carbonate-dominated, non-condensed sediments (e.g., Figs 6 and 7).

During long-term regressive periods, carbonate will mainly be deposited during short-term rising sea level and will correspond to transgressive and (early) highstand deposits of short-term cycles (Fig. 13 C, D). The first record of limestones after a relatively important marl deposition thus lies above the short-term transgressive surface which defines a small-scale depositional sequence (e.g., Fig. 5, from 5 to 11 metres). Maximum-flooding surfaces can be placed into the most condensed carbonate beds of these sequences. Enrichment in marls corresponds to low carbonate productivity on the platform, or to emersions. For this reason, the short-term sequence boundaries are placed into the generally well-developed marly intervals (Fig. 13 C, D).

In the proximal area, interfingering of deposits enriched in platform elements (generally packstones) with deposits including more distal and/or parautochthonous components (generally mudstones and wackestones) add supplementary arguments for the sequence interpretation.

In a deep-shelf context which was indirectly controlled by relative sea-level variations affecting shallow-platform evolution, depositional sequences are formed by sedimentary deposits that can be related to different phases of sea-level variations. Accordingly, deposits interpreted as having formed under increasing relative sea level, highstand, or lowstand of relative sea level are named respectively transgressive deposits (TSd), highstand deposits (HSd), or lowstand deposits (LSd). Early transgressive deposits (eTSd) can locally be identified. These successive deposits are separated by diagnostic surfaces or zones which are interpreted using the terminology of sequence stratigraphy (e.g., Vail et al. 1991): transgressive surface or zone (TS), maximum-flooding surface or zone (MFS or MF), sequence boundary or sequence-boudary zone (SB). This terminology is used for large-scale as well as for small-scale depositional sequences (Posamentier et al. 1992, Pasquier & Strasser 1997, Pittet & Strasser 1997). However, because of the indirect record of relative sea-level variations affecting the shallow platform, it is not always possible to identify each surface or zone, and each type of deposit recorded in the deep shelf. Furthermore, a long-term relative sea-level variation is not a smooth process, and a transgression can be punctuated by different transgressive pulses resulting in the development of successive transgressive surfaces or zones (TS) during a long-term transgressive trend (Mitchum & Van Wagoner 1991).

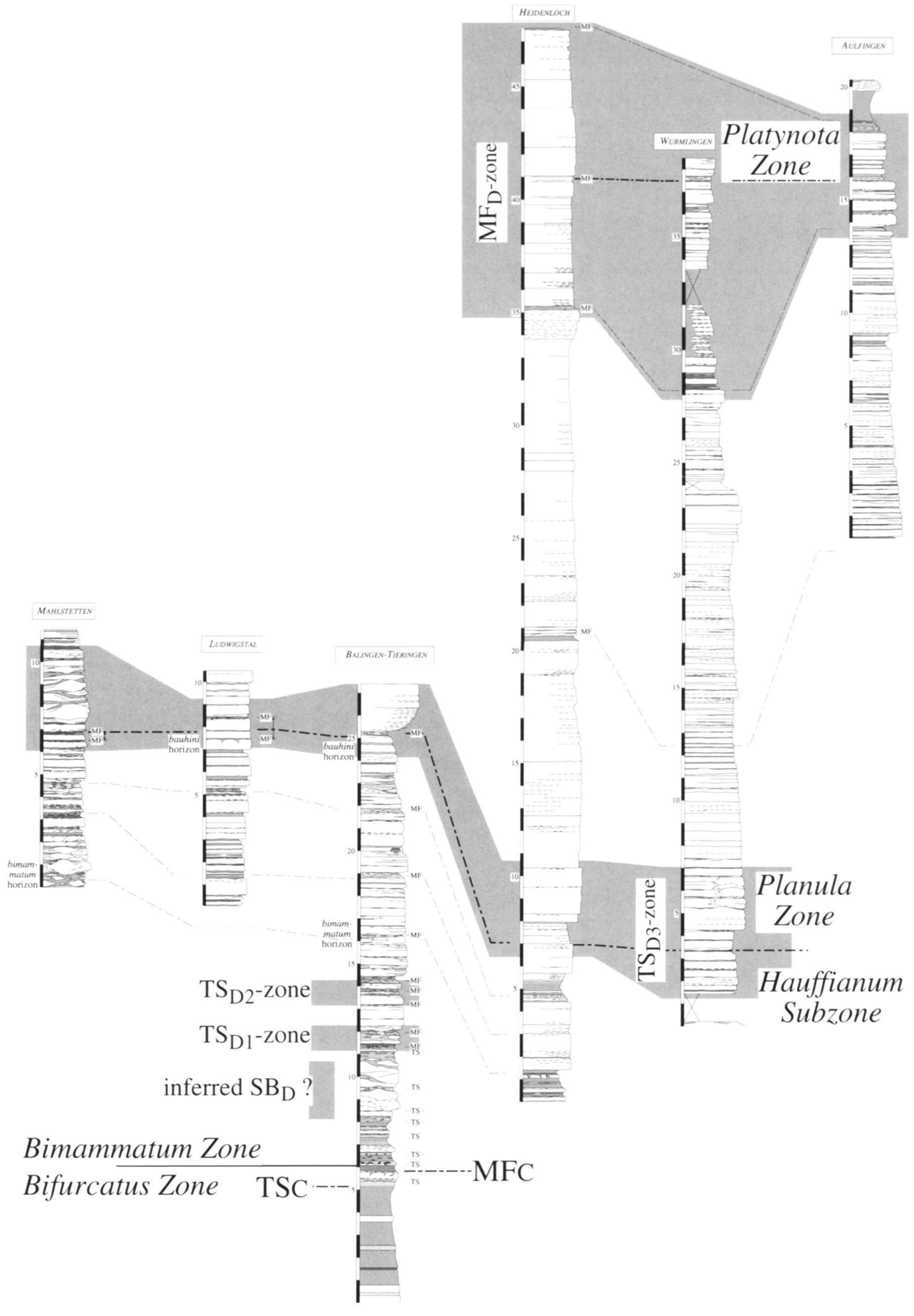

Fig. 14. Correlation between the studied sections in southern Germany and the eastern Swiss Jura.

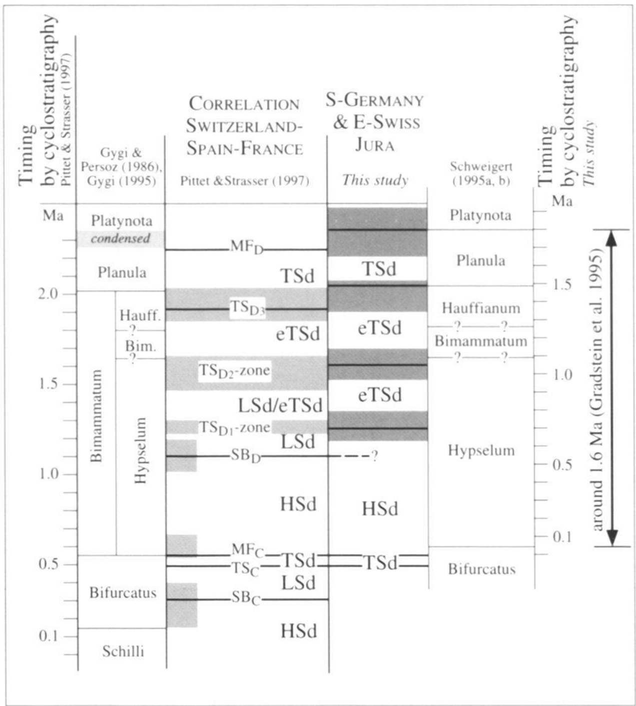

Fig. 15. Correlation between the studied sections in southern Germany and the eastern Swiss Jura compared with previously studied sections in Switzerland (eastern and central Swiss Jura), Spain (Soria and Cazorla regions), and France (Normandy). Sequence-stratigraphic interpretations (large-scale depositional sequences) are integrated into the biostratigraphic framework. The cyclostratigraphic interpretation (small-scale depositional sequences induced by the 100-ka eccentricity cycle) is compared with the dating of GRADSTEIN et al. (1995). Sequence-stratigraphic labeling from PITTET (1996) and PITTET & STRASSER (1997).

7. Correlation

By using the criteria for the identification of depositional sequences described above and in a generally well-constrained chronostratigraphic framework, it is possible to correlate the long-term evolution of relative sea-level in the deep-shelf setting of the German Swabian Alb and the eastern Swiss Jura (Fig. 14). This correlation can then be compared with the correlation obtained by sequence stratigraphy and cyclostratigraphy in platform environments (central Swiss Jura and Soria region of north-eastern Spain), in Prebetic mid-shelf environments (Cazorla region, southern Spain), and in the epicontinental basin of the eastern Swiss Jura (Fig. 15).

The record of each ammonite zone and subzone as well as the recognition of different ammonite horizons suggest that no important sedimentary gap occurred during the sedimentation. This, of course, is a prerequisite for a correlation of small-scale depositional sequences. Bed-by-bed correlation is not possible from one section to the other. However, the sedimentary record suggests changes in short- and long-term processes which influenced the amount of carbonate produced on the shallow platform and exported towards deeper areas. These changes in carbonate-mud export affecting the whole study area define the depositional sequences used in correlation, even though individual beds may result from different factors which interfere with the effect of sea-level changes (e.g., shallow platform and deep-shelf morphologies, position of pathways of discharge from the shallow platform to the deep shelf).

Long-term evolution

Many of the identified transgressive-surface zones and maximum-flooding zones are dated by ammonites. In the Swabian Alb, the transgressive surface TSc and the maximum-flooding MFc have only been observed in the Balingen-Tieringen profile (Fig. 5), the only section displaying the Bifurcatus-Bimammatum transition and the Hypselum Subzone. For this reason, these two levels are not well-constrained in southern Germany. However, time-equivalent surfaces have already been recognized in Normandy (Rioult et al. 1991, Pittet & Strasser 1997): TSc in the upper Koldeweyense Subzone corresponds to the upper Bifurcatus zone, and MFc at the Koldeweyense-Serratum boundary to the Bifurcatus-Bimammatum boundary (Cariou et al. 1991). In sections of southern Spain (Cazorla region), TSc is dated from the upper Bifurcatus Zone, and MFc is located at the Bifurcatus-Bimammatum boundary (Pittet & Strasser 1997). In platform environments of north-eastern Spain (Soria region), dating of these equivalent levels is implied by data of Aurell (1991) and Aurell & Meléndez (1993), and in the Swiss Jura by the work of Gygi & Persoz (1986) and Gygi (1995).

The SBD episode identified by Pittet & Strasser (1997) has not been recognized in southern Germany. Only one of the studied sections (Balingen-Tieringen, Fig. 5) covers the interval containing this sequence boundary. There it may correspond to sponge-reef developments (Fig. 14) which are laterally replaced by marls. The TSD1-zone has been identified only in the Balingen-Tieringen profile (Fig. 5) but has also been recognized in platform environments of the Swiss Jura and the Soria region (Pittet & Strasser 1997).

The TSD2-zone, just below the *bimammatum* horizon (Figs 3, 5, 6, 14 and 15) has been recognized in all previously studied areas (Pittet & Strasser 1997) comprising this time interval (Cazorla and Soria regions in Spain, Swiss Jura). It is considered as a main transgressive pulse by Gygi (1986) in the Late Oxfordian which leads to opening of the environments on the shallow platform. Associated are condensation features and/or sponge developments in the epicontinental basin (Crenularis Member; Gygi & Persoz 1986, Gygi 1986), and an increasing carbonate record in the mid-shelf setting of the Cazorla region (possibly corresponding to increasing carbonate productivity on adjacent shallow platforms; Pittet 1996). The TSD2-zone also corresponds to an invasion of subboreal/boreal ammonites such as *Amoeboceras* and *Ringsteadia* as well as to the first occurrence of *Geyssantia* (taxon typical of eastern Spain). It thus marks a possible opening of North-South and East-West marine connections (Schweigert 1995a).

The TSD3 episode (Figs 3, 5, 6, 7, 8, 10, 14 and 15) occurs at the transition between the Bimammatum and Planula Zones (*bauhini* horizon). This transgressive pulse is the best-marked and probably strongest in the Late Oxfordian. It has been recognized in southern Spain (Cazorla region) where drowning of the platform occurs, and in the Soria region where it corresponds to formation of thick siliciclastic tidal deposits (Pittet & Strasser 1997). In the Swiss Jura, it corresponds to the accumulation of thick ooid shoals (Verena Member with up to 45 metres of ooid deposits; Gygi & Persoz 1986) which correlate with the Planula Zone (Gygi 1995). The abundant subboreal/boreal ammonite fauna in the *bauhini* horizon (Schweigert 1995b) also suggests an increase in marine connections related to this transgression.

The MFD-zone corresponds to the Planula-Platynota transition (Figs 3, 8, 9, 10, 14 and 15). This maximum-flooding interval has also been recognized and dated in the Cazorla region (Pittet & Strasser 1997). In the Soria region, this zone corresponds to initiation of coral reefs above the siliciclastic tidal deposits. In the Swiss Jura it may correspond to the top of the Verena Oolite which correlates with intense condensation features in the epicontinental basin (Gygi 1986, 1995, Gygi & Persoz 1986). This maximum flooding has also been noted by Marquez et al. (1991) and Baumgärtner & Reyle (1995) in Spain.

Small-scale depositional sequences and cyclostratigraphic interpretation

The interpretation of the small-scale depositional sequences (where possible) has been integrated into the chronostratigraphic framework and into the long-term sequential interpretation (Figs. 14 and 15). Figure 14 shows that the small-scale depositional sequences can be correlated between the sections in southern Germany, and also with the Swiss Jura section of Heidenloch. From the *bimammatum* horizon to the transition between the Bimammatum and Planula Zones (TSD3), the four sections covering this interval exhibit 3 small-scale sequences that can be correlated. The Planula Zone corresponds to 3 small-scale sequences, and one small-scale sequence occurs at the base of the Platynota Zone.

The interval between the Bifurcatus-Bimammatum transition and the *bimammatum* horizon is found only in the Balingen-Tieringen section. Eleven small-scale depositional sequences have been identified within (Fig. 5).

According to the interpretation of the shallow-water sections in the Swiss Jura and the correlations with the already mentioned Spanish sections, the interval corresponding to the Bimammatum Zone contains 15 small-scale depositional sequences, the one corresponding to the Planula Zone comprises 3 (Pittet & Strasser 1997). These numbers thus compare well with the ones obtained for the same intervals in the present study (Fig. 15).

Dating by Gradstein et al. (1995) implies that the Bimammatum and Planula Zones span about 1.6 Ma. A total number of 18 small-scale depositional sequences have been identified in these zones, suggesting that one small-scale sequence has a mean duration of around 89 ka. This time constraint and the fact that these sequences can be correlated over long distances and from one depositional environment to another indicate that the formation of the sequences was controlled by allocyclic processes probably linked to the 100-ka cycle of orbital eccentricity (Berger et al. 1989). Whereas the platform facies reacted mostly to climatic and sea-level changes (Pittet et al. 1995, Pittet 1996), the deposition on the deep shelf studied here was controlled by carbonate-mud import in tune with the cyclic processes on the platform.

8. Discussion and conclusions

This study suggests that carbonate-mud export from the platform to the deep shelf during the Late Oxfordian in the Swabian Alb and the eastern Swiss Jura is an important sedimentary process that has to be considered as a major controlling factor on deep-shelf sedimentation. A control of this export by short- and long-term sea-level variations which drive changes of carbonate productivity on the platform and/or changes of proximality-distality are thought to be responsible for the formation of small- and large-scale sequences on the deep shelf. These sequences can be identified by rhythmic changes from non-condensed to condensed facies. If the physical mechanisms driving carbonate-mud export are largely unknown, the uppermost Oxfordian (Planula Zone) displays sedimentary structures that suggest event deposits (muddy tempestites or turbidites, or density-cascading deposits).

Within a detailed stratigraphic framework based on ammonite zonation, these small- and large-scale sequences can be correlated at the scale of the study area, and can be integrated with previous correlations in Switzerland, Spain and France. Correlations are thus possible over long distances and evidence an allocyclic control on the formation of the sedimentary sequences. Climatic and/or eustatic changes possibly at the scale of the Tethys are responsible for their formation. Large-scale sequences can be related to long-term sea-level changes, whereas small-scale sequences are thought to be controlled by Milankovitch cycles. Moreover, with the numerical dating of Gradstein et al. (1995) it is possible to argue for a major control by the first eccentricity cycle (100 ka) on the formation of the better developed small-scale sequences in shallow-marine environments (north-western Switzerland, north-eastern Spain, northern France) as well as in more distal environments such as the ramp (eastern Switzerland), the epicontinental basin, or the deep shelf (southern Germany, southern Spain).

If the growth of sponge bioherms occurs in many different situations, it is notable that the main episode of sponge-reef initiation and true sponge reefs commonly occur during long-term transgressive pulses. An example is the *bimammatum* horizon (TSD2-zone) in Mahlstetten (Fig. 6), in Plettenberg quarry near Schömberg (Fig. 1; dated by G. Schweigert, pers. comm. and personal observations), and its equivalent in the epicontinental basin of the eastern Jura (Crenularis Member; see Gygi 1969, 1986, Gygi & Persoz 1986). At the transition between Bimammatum and Planula (TSD3-zone) in Balingen-Tieringen (Fig. 5), in Mahlstetten (Fig. 6), in Wurmlingen (Fig. 8), and in Plettenberg quarry, sponge reefs form a nearly continuous level. It correlates with the Knollen Beds of the eastern Swiss Jura (Gygi & Persoz 1986) and corresponds to a main transgressive pulse in the Late Oxfordian. This relationship between long-term sea-level rise and reef development is a common feature in the Upper Jurassic (e.g., Leinfelder 1993, 1994, Keupp et al. 1993).

Growth of sponge reefs during late highstand or lowstand conditions in the Balingen-Tieringen locality (Fig. 5) is probably related to generally low sedimentation rates during the Hypselum Subzone. The Ludwigstal locality (Fig. 7) shows features uncommon for the Bimammatum-Hauffianum sedimentation history: lack of sponges, mudstone facies, rare tuberoids, and bioturbation commonly dominated or represented only by *Chondrites* cannot be related to higher sedimentation rates (see correlation in Fig. 14) but probably to specific environmental conditions. Oxygen-depletion (e.g., Oschmann 1990, Leinfelder 1993, 1994, Schmid 1996) or low light conditions due to possibly greater water depth (Schmid 1996) seem to be more reasonable factors influencing the Ludwigstal locality.

It is clear from the present study that, in order to interpret the observed sedimentary record on the deep shelf, processes affecting carbonate productivity on the platform and carbonate export from the platform to deeper depositional environments have to be considered. The fact that large- and small-scale depositional sequences can be correlated over long distances suggests that these processes were related to basin-wide eustatic and climatic changes. Sea-floor morphology was responsible for local distribution of facies and thicknesses of the depositional sequences.

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