

## DELINEATING SEQUENCE STRATIGRAPHIC PATTERNS IN DEEPER RAMP CARBONATES: QUANTITATIVE PALYNOFACIES DATA FROM THE UPPER JURASSIC (KIMMERIDGIAN) OF SOUTHWEST GERMANY

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**ABSTRACT:** The delineation of sequence stratigraphic patterns in deeper ramp carbonates is notoriously difficult using sedimentological criteria. Hence, in an effort to better understand the processes controlling the formation of deeper-water carbonate ramps, fully quantitative palynofacies analyses were carried out on two cores from the Upper Jurassic (Kimmeridgian) of the Swabian Marl Basin, SW Germany. To eliminate the effect of variable carbonate content, absolute palynoclast abundances (i.e., particles per gram of sediment) were calculated with respect to the non-carbonate fraction of the original sediment. The palynofacies data were supplemented by bulk sediment oxygen isotope data and sedimentological information.

Terrestrial and marine palynoclast groups show in-phase, cyclical absolute abundance patterns in both cores investigated. Highest carbonate-adjusted absolute abundances of terrigenous palynoclasts are interpreted to indicate sea-level lowstands and vice versa. The in-phase distribution of marine and terrestrial palynoclast groups points towards a coupling between the terrestrial and marine realms. Increased absolute abundances of terrigenous palynoclasts are interpreted to represent intervals of enhanced land-derived nutrient input into the marine system. Such higher nutrient availability would have caused higher phytoplankton productivity as evidenced in increased absolute abundances of marine palynomorphs. Hence, marine productivity in the epeiric setting of the Swabian Marl Basin was strongly controlled by the nutrient flux from the surrounding landmasses.

In the palynofacies and bulk sediment  $\delta^{18}\text{O}$  records, two hierarchies of sequences are recognized. Well-pronounced medium-scale sequences (with thicknesses of 5–20 m) are built by the stacking of smaller-scale sequences (with thicknesses of 3–7 m). Heavier  $\delta^{18}\text{O}$  values coincide with high absolute abundances of terrigenous palynoclasts. Based on this observation, a model for environmental fluctuations is proposed. Time intervals with high sea level were characterized by relatively high water temperatures, whereas time intervals with low sea level coincided with relatively low water temperatures. Estimates of ammonite zone ages available from the literature were used to constrain the duration of medium-scale sequences. When taking into account the range of dating uncertainties, the obtained value of ca. 370 kyr appears reasonably close to the duration of the 400 kyr eccentricity cycle. We speculate that the formation of medium-scale sequences as evidenced in our palynoclast and  $\delta^{18}\text{O}$  records may be related to eccentricity-driven insolation changes that caused sea-level changes, with higher insolation leading to a sea-level rise. This would imply that the regional record of sea-level and temperature fluctuations within the epeiric Swabian Marl Basin reflects climatic changes that occurred on a more global scale. The integration with sedimentological data shows that marl-dominated intervals were deposited during early sea-level rise and under cooler conditions, whereas limestone-dominated intervals formed during intervals of high sea level and under warmer conditions.

### INTRODUCTION

Carbonate ramps of various geologic ages form important reservoirs for hydrocarbons (e.g., Wilson 1985; Burchette and Wright 1992; Meyer and Price 1993; Sharland et al. 2001). The architecture of the shallower portions of carbonate ramp systems are relatively well understood due to the applicability of sequence stratigraphic markers following the classical

Exxon approach (e.g., Reid and Dorobek 1993; Pomar 2001). In contrast, the recognition of parasequences, sequences, and sequence boundaries in deeper-water carbonate ramps is hindered by the lack of diagnostic sedimentological criteria such as discontinuity surfaces or hardgrounds (e.g., Pawellek and Aigner 2003a, 2003b). Hence, the integration of data from disciplines complementary with sedimentological approaches provides a promising avenue for the reconstruction of environmental conditions leading to the formation of deeper-ramp carbonates.

Since its development in the early 1960s, the analysis of sedimentary organic matter (SOM) in sedimentary rocks, commonly referred to as palynofacies analysis (Combaz 1964), has evolved into a valuable tool for paleoenvironmental reconstructions (e.g., Tyson 1993, 1995). An

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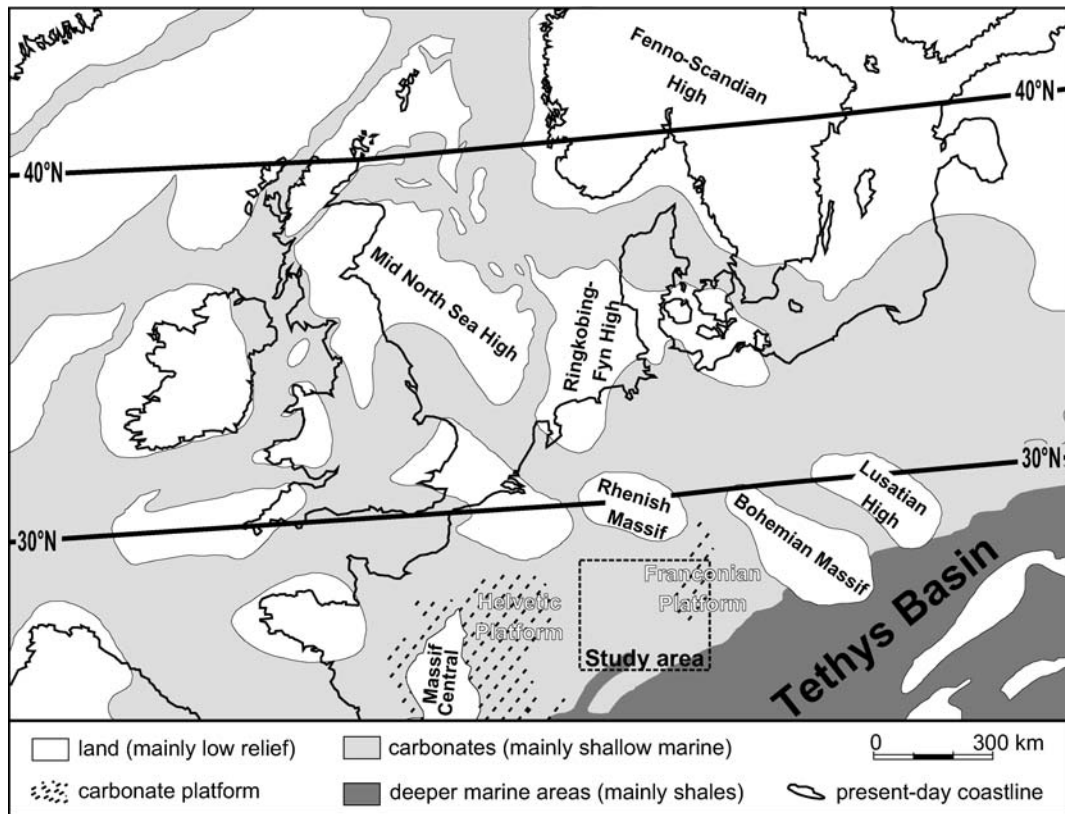


FIG. 1.—Paleogeographical map of Europe for the Kimmeridgian (early Late Jurassic) with location of study area. Modified after Meyer and Schmidt-Kaler (1989), Ziegler (1988), and Dercourt et al. (1993).

advantage of this approach is that it allows the integration of data from marine and terrestrial settings, thus rendering a one-to-one land–sea correlation. Moreover, palynofacies analysis can provide reconstructions of stratigraphic sequences even from lithologically uniform successions where these sequences cannot be identified by purely sedimentological data (e.g., Waterhouse 1995).

Traditionally, the application of palynofacies analysis has focused on siliciclastic sedimentary sequences, because these often represent depositional environments with enhanced SOM preservation potential (e.g., Bustin 1988; van der Zwan 1990; Oboh 1992). Only relatively recently were sediments from carbonate-dominated systems studied by palynofacies analysis following the recognition that even SOM from these relatively well-oxygenated settings yields valuable information to complement standard sedimentological data on the depositional environment, the sequence stratigraphic framework, and the correlation between sections (e.g., Pittet and Gorin 1997; Pittet and Strasser 1998; Westphal et al. 1999; Bombardiere and Gorin 2000; Pittet et al. 2000; Al-Ameri et al. 2001).

To date, most palynofacies studies utilize percentage data of different palynofacies constituents as a basis for paleoenvironmental and sequence stratigraphic reconstructions. This approach, however, can cause misleading interpretations because it is based on closed-system data. Such misinterpretations can be avoided by spiking palynofacies samples with exotic marker spores (Stockmarr 1971), which allows the calculation of absolute palynoclast abundances (i.e., particles per gram of sediment; e.g., Waterhouse 1995; Tyson and Follows 2000; Herrle et al. 2003a; Herrle et al. 2003b; Westphal et al. 2004; Bornemann et al. 2005).

Following the concept of genetic stratigraphy (Homewood 1996; Cross and Lessenger 1998), this contribution aims to decipher the origin, transport, and depositional history of SOM in a deeper carbonate ramp in order to better understand the character and origin of genetic

sequences in such a depositional setting. The palynofacies data were generated following a fully quantitative approach. For our study, we selected the Upper Jurassic (Kimmeridgian) of SW Germany, which is a classical example of a deeper marine, epeiric carbonate-dominated system (e.g., Leinfelder 2001). Its biostratigraphical (e.g., Quenstedt 1858; Geyer 1980; Brenner 1988; Gygi et al. 1998; Schweigert 1995, 2000) lithostratigraphical (e.g., Quenstedt 1858; Gwinner 1976; Brachert 1992; Villinger and Fleck 1995; Schick 2004), and sedimentological (e.g., Gygi and Persoz 1987; Leinfelder 1994; Pawellek and Aigner 2003a, 2003b; Ruf 2005) framework is well established, thus providing a solid basis for our investigations. In a previous contribution, we focused on the development of the sedimentary facies and sequences of selected locations through the early and middle Upper Jurassic of SW Germany with a particular emphasis on reefal cycles (Ruf et al. 2005a). In a more regional approach, the hierarchy of sequences and their correlation with other European basins has been studied by Ruf et al. (2005b), relying on sedimentological data from more than 90 sections across the Upper Jurassic of SW Germany and northern Switzerland that were partially corroborated by stable-isotope and palynofacies information. In the present study, we focus on the palynofacies expression of sequence stratigraphic patterns in the Kimmeridgian of SW Germany. Based on the cyclostratigraphic interpretation of high-resolution palynofacies data and their integration with oxygen isotope data and sedimentological information, we propose a model for the coupling of terrestrial and marine environmental conditions during the Kimmeridgian.

Carbonate systems are known to exhibit a broad variety of sedimentary cycles with different cycle lengths (e.g., Schlager 1992; Kerans and Tinker 1997). Because our study was designed to decipher the origin of mesoscale cycles (i.e., with thicknesses between five and twenty meters), the high-frequency (decimeter-scale) rhythms of limestone–marl alternations in the

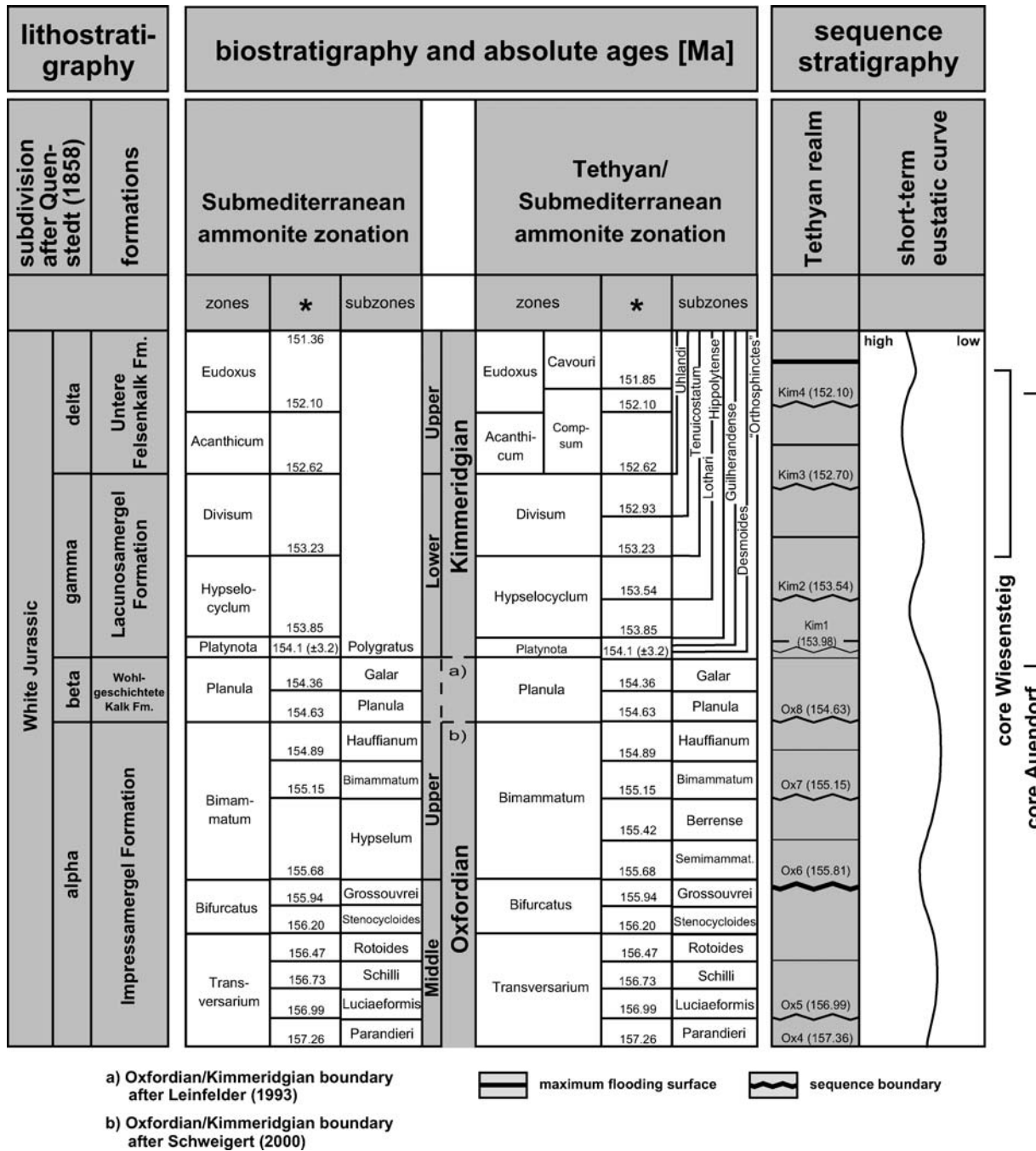


FIG. 2.—Oxfordian to Kimmeridgian lithostratigraphy and biostratigraphy of southwest Germany. Intervals covered by the cores studied are indicated on the right. Lithostratigraphical formations after Deutsche Stratigraphische Kommission (2002), submediterranean ammonite zonation after Schweigert (2000), Tethyan/submediterranean ammonite zonation, absolute age estimates, maximum flooding surfaces, and sequence boundaries after Hardenbol et al. (1998), and eustatic sea-level curve after Haq et al. (1987).

Upper Jurassic of SW Germany (e.g., Seibold 1952; Ricken 1985) are not discussed here.

STUDY AREA

*Paleogeographical and Paleoenvironmental Framework*

The Upper Jurassic carbonates of SW Germany were deposited in the deeper part of a gently inclined carbonate ramp marginal to the Tethys Ocean in the south (Fig. 1). To the southwest and northeast, this so-

called Swabian Marl Basin (Meyer and Schmidt-Kaler 1989, 1990) was bounded by two shallower-water platforms: the Helvetic and Franconian platforms. Clastic input was derived mainly from the Rhenish Massif in the north (Gygi 1986; Ziegler 1988; Meyer and Schmidt-Kaler 1989).

With the onset of the Late Jurassic (i.e., during the Middle Oxfordian; Fig. 2), marls of the Impressamergel Formation (Fm.) were deposited over much of SW Germany. In the Swabian Marl Basin, the marls reach a thickness of ca. 100 m (Ziegler 1977; Geyer and Gwinner 1984). During

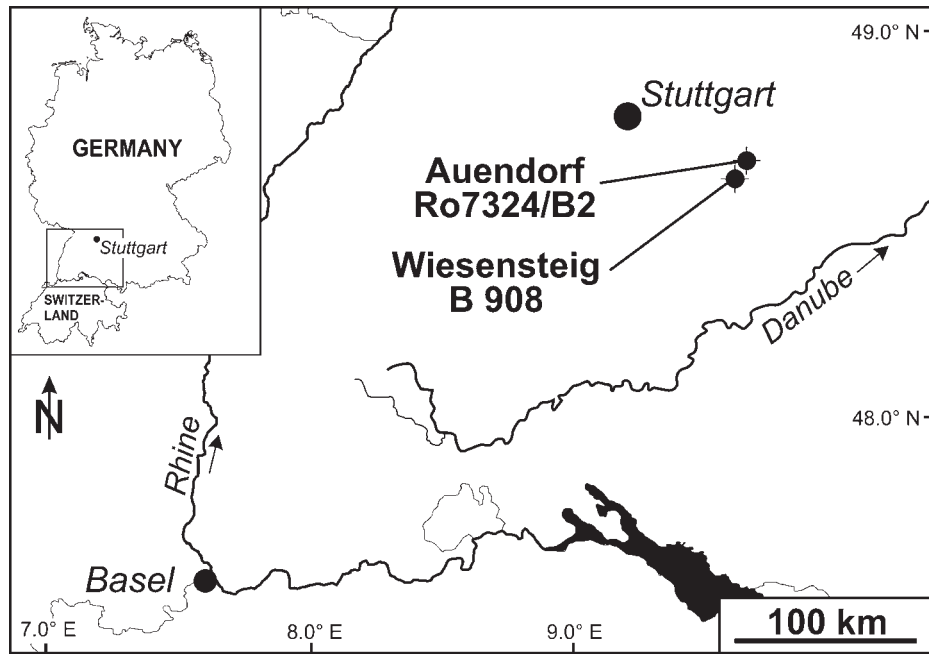


FIG. 3.—Map of study area in Southwest Germany with locations of cores indicated.

the Late Oxfordian, small sponge–algal bioherms started to form in marginal areas of the Helvetic Platform in the western part of the basin (Fig. 1; Meyer and Schmidt-Kaler 1989, 1990). In the earliest Kimmeridgian (*sensu* Schweigert 2000; Fig. 2), the bioherm-dominated facies extended eastwards into the Swabian Marl Basin, grading into well-bedded limestones (“Wohlgeschichtete Kalk Fm.”; thickness 15–90 m) that were deposited in those parts of the basin that remained devoid of bioherms (Geyer and Gwinner 1984; Pawellek 2001). Subsequently, marl sedimentation dominated again throughout most of the basin, resulting in the deposition of the 30–60 m thick Lacunosamergel Fm. (Fig. 2). During the Late Kimmeridgian, the biohermal facies advanced from the west and limestones of the Untere Felsenkalk Fm. formed throughout the Swabian Marl Basin (Ziegler 1977; Geyer and Gwinner 1984; Pawellek 2001). Generally, the sediment thickness in the Late Jurassic Swabian Marl Basin was controlled by preexisting paleo-relief, i.e., underlying troughs and swells of late Paleozoic age (Ruf et al. 2005a).

In the Kimmeridgian, the study area was situated at a paleolatitude of ca. 27° N (Fig. 1; Dercourt et al. 1993) and thus under the influence of the downwelling limb of the Northern Hemisphere Hadley cell. Accordingly, climate conditions in Central Europe were semiarid to arid (Frakes et al. 1992; Mouchet 1998; Abbink et al. 2001), with summer temperatures between 20 and 32°C and winter temperatures between 8 and 20°C (Crowley et al. 1987; Crowley et al. 1989; Rees et al. 2000).

#### Biostratigraphy and Lithostratigraphy

The time interval investigated in this paper comprises the Early to Late Kimmeridgian, biostratigraphically corresponding to the planula to eudoxus ammonite zones. Lithostratigraphically, it represents the upper part of the Wohlgeschichtete Kalk Fm. (characterized by relatively uniform carbonates with thin intercalated marlstone layers), the Lacunosamergel Fm. (consisting predominantly of marls with few intercalated limestone beds), and the Untere Felsenkalk Fm. (consisting of sponge–microbial bioherms or mounds with few, thin intercalated marlstone layers) (Fig. 2). For in-depth information on the biostratigraphy and lithostratigraphy of the Upper Jurassic of SW Germany we refer the reader to the studies of Quenstedt (1858), Ziegler (1977), Geyer

(1980), Gygi (1986, 2000a, 2000b), Gygi et al. (1998), and Schick (2004). Owing to the firmly established correlation between ammonite biostratigraphy and lithostratigraphy in the Upper Jurassic of SW Germany (Fig. 2; Deutsche Stratigraphische Kommission 2002; Schweigert, personal communication 2004) and the age estimates for ammonite zone boundaries as given by Hardenbol et al. (1998), the lithostratigraphic nomenclature can be used to obtain an age estimate for the examined succession. Hence, the time interval studied comprises ca. 2.3 Myr (Fig. 2).

#### Material and Methods

Samples from the cores Auendorf Ro 7324/B2 (coordinates: 48° 36′ 39″ N / 9° 41′ 24″ E) and Wiesensteig B 908 (coordinates: 48° 32′ 25″ N / 9° 36′ 55″ E) were investigated for their palynofacies, oxygen isotope, and sedimentological signals. Both cores are from the central part of the Swabian Marl Basin and are located 9 km apart from each other (Figs. 1, 3).

Lithostratigraphically, core Auendorf Ro 7324/B2 comprises the upper part of the Wohlgeschichtete Kalk Fm., the Lacunosamergel Fm., and the lower part of the Untere Felsenkalk Fm.. Biostratigraphically, this corresponds to the planula (pars) to eudoxus (pars) ammonite zones (Fig. 2). Core Wiesensteig B 908 comprises the upper part of the Lacunosamergel Fm. and the lower part of the Untere Felsenkalk Fm., corresponding to the divisum (pars) to eudoxus (pars) ammonite zones (Fig. 2).

#### Palynofacies

Sixty-seven samples from core Auendorf Ro 7324/B2 and 35 samples from core Wiesensteig B 908 were investigated for their palynoclast contents. Sampled lithologies comprise marls, well-bedded limestones, bioclastic limestones, and biohermal limestones. Average sample resolution is three samples per meter. Critical sections of the cores were sampled in higher resolution, with five to eight samples per meter. Samples were processed using standard palynological techniques (e.g., Wood et al. 1996; Pross 2001). After cleaning, crushing, and drying, known weights of



To obtain comparability between palynofacies samples from limestones and marlstones, a “carbonate adjustment” was performed for all palynofacies samples. First, absolute palynoclast abundances per gram of bulk sediment were calculated using the *Lycopodium* marker spore method of Stockmarr (1971). Subsequently, “carbonate-adjusted” palynoclast abundances were calculated following the equation:

$$A = N \cdot \frac{100}{C}, \quad (1)$$

where  $A$  = carbonate-adjusted number of palynoclasts per gram of sediment,  $N$  = number of palynoclasts per gram of original sediment (including carbonate), and  $C$  = non-carbonate content of the sample in percent. Based on this procedure, the absolute abundances of palynoclast groups discussed in this paper always refer to carbonate-adjusted values.

#### Carbonate Content and Oxygen Isotopes

Carbonate content and oxygen isotope values were measured for all samples studied for their palynofacies signals. Homogeneous micrite areas were selected from freshly cut rock fragments, crushed, and thoroughly homogenized in an agate mill. Oxygen isotope measurements were obtained using a GasBench II connected to a Finnigan MAT 252 mass spectrometer at the Institute of Geosciences, University of Tübingen. Samples are calibrated for  $\delta^{18}\text{O}$  values at NBS-19 ( $\delta^{18}\text{O} = -2.20\text{‰}$  relative to VPDB). External reproducibility for  $\delta^{18}\text{O}$  is  $\pm 0.13\text{‰}$ . Carbonate contents were determined as a by-product of the isotope measurements based on the co-variation of carbonate content and the  $\text{CO}_2$  peak area of mass 44 (e.g., Spoetl and Vennemann 2003). Their external reproducibility is  $\pm 5\%$ .

#### Sedimentology

After cutting, the cores were logged continuously and semiquantitatively. Microscopic analysis was carried out on 290 polished slabs and acetate peels. The lithologies were characterized according to the textural classification of Dunham (1962). The abundances of carbonate components were estimated using comparison charts after Baccelle and Bosellini (1965). Dunham texture, rock composition, and sedimentary structures were then recorded in a standardized core-logging sheet.

### RESULTS

#### Core Auendorf Ro 7324/B2

**Palynofacies.**—All 67 palynofacies samples processed from core Auendorf Ro 7324/B2 yielded palynofacies assemblages in good preservation. Absolute abundances of terrigenous and marine palynoclast groups exhibit an in-phase cyclical increase and decrease, with medium-scale cycles (cycle lengths between 10 and 18 m) superimposed on smaller-scale cycles (cycle lengths between 5 and 10 m) (Fig. 6). This cyclic pattern is expressed most strongly in the middle and upper part of the Lacunosamergel Fm. and the Untere Felsenkalk Fm., where sample resolution is highest.

The absolute abundance of total palynoclasts reaches up to  $6.71 \times 10^5$  particles per gram of sediment (sample Au-61). The maximum absolute abundances of total terrigenous debris and terrigenous palynomorphs are  $3.79 \times 10^5$  and  $1.4 \times 10^5$  particles per gram of sediment, respectively, and occur in the same sample. Marine palynomorphs are not present in all samples investigated, but regularly occur in horizons characterized by high absolute abundances of total terrigenous debris. They are generally dominated by dinoflagellate cysts and reach an absolute abundance maximum of  $4.1 \times 10^4$  particles per gram of sediment in sample Au-61. The absolute abundance of degraded debris shows a well-pronounced cyclical pattern with relatively strong differences between absolute

abundance minima and maxima. The maximum absolute abundance of this group also occurs in sample Au-61, where  $7.6 \times 10^4$  particles per gram of sediment are recorded (Fig. 6).

**Oxygen Isotopes.**—Oxygen isotope values range from  $-5.39$  to  $-2.07\text{‰}$  (Fig. 5). The  $\delta^{18}\text{O}$  fluctuations co-vary with the absolute abundances of total palynoclasts, total terrigenous debris, terrigenous palynoclasts, terrigenous palynomorphs, marine palynomorphs, and degraded debris. Less negative  $\delta^{18}\text{O}$  values occur predominantly in intervals of increased absolute abundances in all these groups, whereas more negative  $\delta^{18}\text{O}$  values occur in intervals of reduced absolute abundances. This correlation is expressed most clearly in the topmost 40 m of the core (upper part of the Lacunosamergel Fm. and the lower part of the Untere Felsenkalk Fm.), where sampling intervals are smallest (Fig. 6).

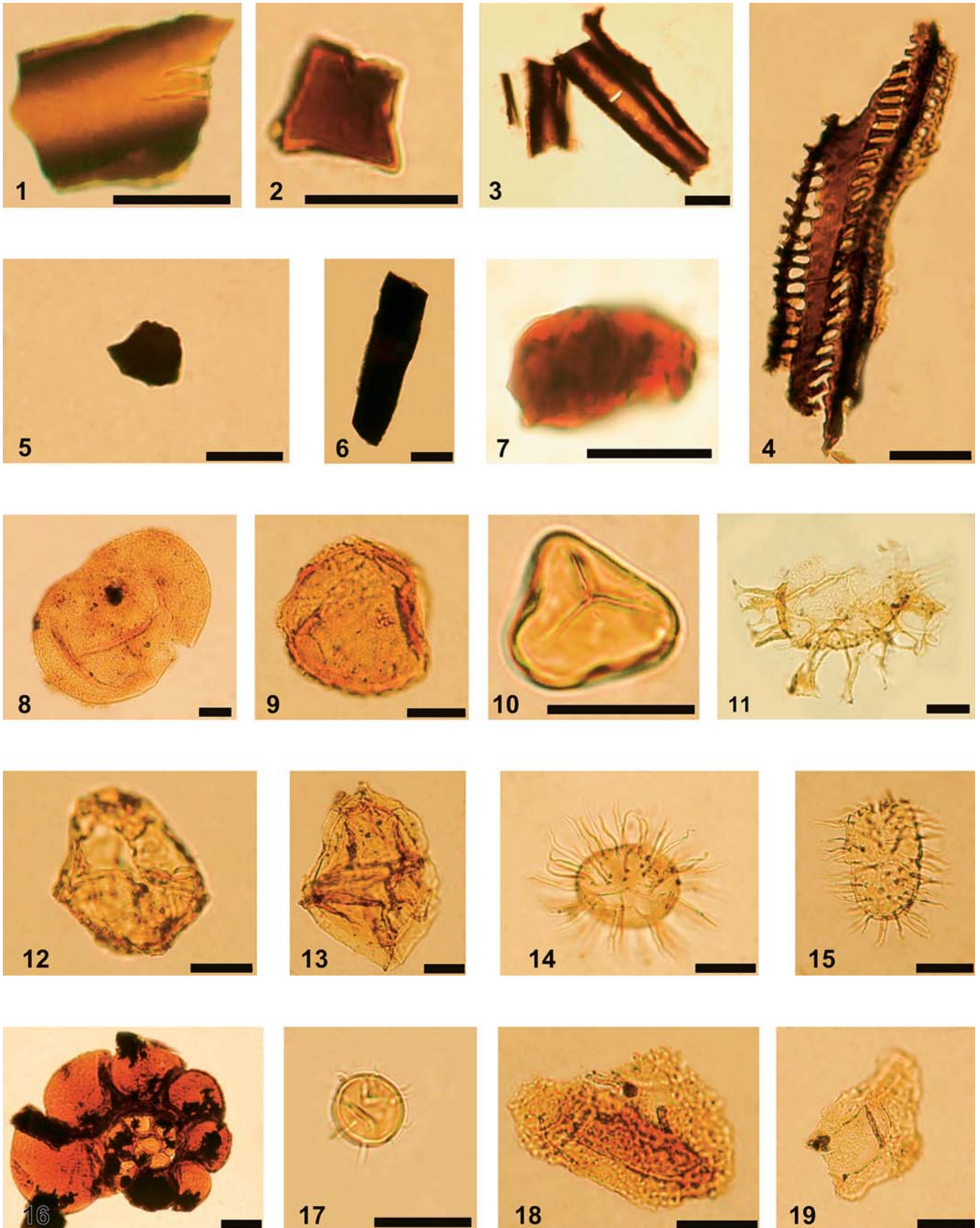
**Sedimentology.**—Core Auendorf Ro 7324/B2 displays a facies succession typical for the Swabian Marl Basin. The base of the core is dominated by carbonate-rich deposits of the Wohlgeschichtete Kalk Formation. These consist mainly of well-bedded limestones with thin intercalated marls. The relative thicknesses of marlstone interlayers compared to the limestone beds increase upcore from the Wohlgeschichtete Kalk Fm. towards the Lacunosamergel Fm. In the Lacunosamergel Fm., packages of marls and marly limestones up to several meters thick alternate with tuberoid debris limestones and bioclast-intraclast debris limestones. The uppermost 17 m of the core belong to the Untere Felsenkalk Fm. and are again more limestone-dominated. They consist of tuberoid debris (i.e., sponges and microbial crusts; cf. Fritz 1958; Hiller 1964; Ruf et al. 2005a) limestones with a bed thickness of up to 2.1 m alternating with relatively thin (i.e., less than 0.5 m thick) marls (Fig. 6). A detailed sedimentological characterization of core Auendorf Ro 7324/B2 has been provided by Ruf et al. (2005a).

Within the sampling resolution of this study, sedimentary sequences of two different orders are distinguished (Fig. 6). Sequences with thicknesses of 5 to 10 m (e.g., in the core interval between 28.4 and 21.9 m) are formed by marly limestones at the base, passing into “clean” limestones that are overlain by marly limestones and marlstones. These small-scale sequences are stacked to form medium-scale sedimentary sequences with thicknesses of 15 to 25 m that are especially well pronounced in the Lacunosamergel Fm. (e.g., between 48 and 31.6 m of the core; Fig. 6). These medium-scale sedimentary sequences are composed of marly mudstones at the base. Towards the top, the marl layers become thinner and the limestones thicker, culminating in an about 5-m-thick succession of tuberoid debris limestones. The tuberoid debris limestones pass into marly mudstones and marls.

#### Core Wiesensteig B 908

**Palynofacies.**—All 35 palynofacies samples processed from core Wiesensteig B 908 yielded diverse palynofacies associations in good preservation. As seen in core Auendorf Ro 7324/B2, absolute abundances of total palynoclasts, total terrigenous debris, terrigenous palynoclasts, terrigenous palynomorphs, marine palynomorphs, and degraded debris show in-phase cyclic variations (Fig. 7). Two cycle hierarchies are discerned: smaller-scale cycles with lengths between 5 and 8 m are stacked into medium-scale cycles with lengths between 12 and 15 m.

For all palynoclast groups, maximum absolute abundances are reached in sample Ws-22 (Fig. 7). Here, absolute abundances of particles per gram of sediment are  $2.9 \times 10^6$  for total palynoclasts,  $2.35 \times 10^6$  for terrigenous debris,  $2.28 \times 10^6$  for terrigenous palynoclasts,  $5.9 \times 10^4$  for terrigenous palynomorphs,  $2.6 \times 10^5$  for marine palynomorphs, and  $3.2 \times 10^5$  for degraded debris. As in core Auendorf Ro 7324/B2, the “marine palynomorphs” group is composed mainly of dinoflagellate cysts.



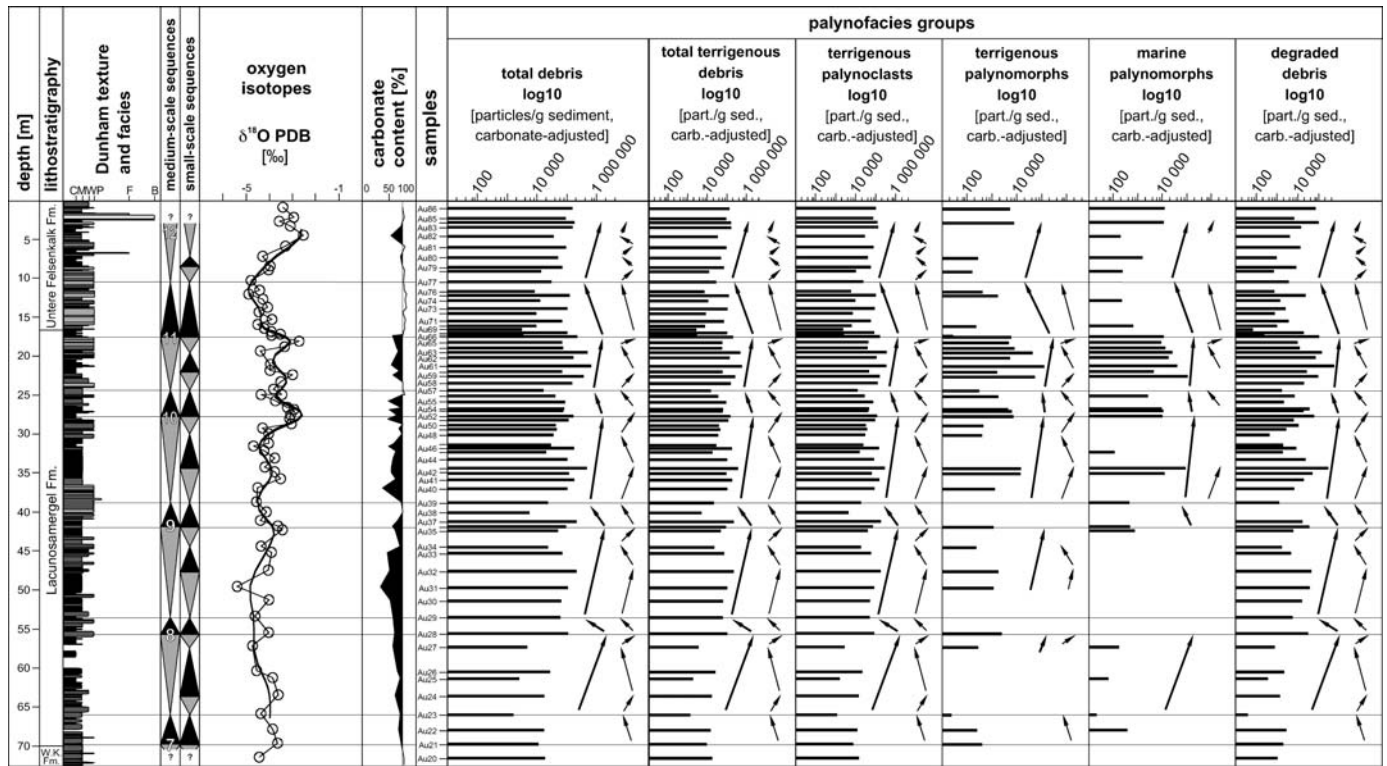


Fig. 6.—Sedimentological, oxygen isotope, and palynofacies data from core Auendorf Ro 7324/B2. Palynofacies data comprise absolute abundances (carbonate-adjusted) of total debris, total terrigenous debris, terrigenous palynoclasts, terrigenous palynomorphs, marine palynomorphs, and degraded debris. See Figure 4 for a definition of palynoclast groups and Figure 8 for a key to symbols.

**Oxygen Isotopes.**—The oxygen isotope record, with values ranging from  $-4.95$  to  $-2.41\text{‰}$  (Fig. 7), shows an overall trend from less negative to more negative values from the base to the top of the core. As seen in core Auendorf Ro 7324/B2, there is an obvious correlation with the records of palynoclast groups, with less negative  $\delta^{18}\text{O}$  values occurring during intervals of increased absolute palynoclast abundances (Fig. 7), and more negative  $\delta^{18}\text{O}$  values coinciding with reduced palynoclast abundances.

**Sedimentology.**—The basal part of core Wiesensteig B 908, comprising the upper part of the Lacunosamergel Fm., is marl-dominated (Fig. 7). Towards the boundary between the Lacunosamergel Fm. and Untere Felsenkalk Fm., the thickness of marl beds decreases and limestone successions up to 5 m thick are intercalated in the marl beds. These limestones are mainly mudstones and tuberoïd debris wackestones. The Untere Felsenkalk Fm. is dominated by tuberoïd debris and intraclast-bioclast limestones (see Ruf 2005 for detailed sedimentological information).

Similar to core Auendorf Ro 7324/B2, sedimentary sequences of two different scales can be distinguished. Small-scale sedimentary sequences with thicknesses between 5 and 8 m (e.g., between 53 and 48 m) are composed of marly mudstones at the base passing into “clean” limestones that are overlain by marly mudstones and marlstones. These small-scale sedimentary sequences are stacked into medium-scale sequences with thicknesses between 15 and 30 m.

DISCUSSION

*Determination of Palynofacies Sequences*

With regard to absolute, carbonate-adjusted abundances, all palynoclast parameters in the cores Auendorf Ro 7324/B2 and Wiesensteig B 908 show an in-phase, cyclical distribution pattern (Figs. 6, 7, 8). The possibility that this distribution pattern may reflect variable oxidation of the palynofacies assemblages, therefore representing a diagenetic rather

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Fig. 5.—Examples of constituents of the different palynoclast groups used in this study. Scale bar equals  $20\ \mu\text{m}$ . 1 = brown wood, equidimensional (“terrigenous palynoclasts” group; sample WS 38-2; coordinates 123,8/15,7); 2 = brown wood, equidimensional (“terrigenous palynoclasts” group; AU 61-2; 128,9/8,2); 3 = brown wood, blade-shaped (“terrigenous palynoclasts” group; AU 53-2; 121,8/9,5); 4 = structured plant material (“terrigenous palynoclasts” group; AU 63-1; 134,2/11,8); 5 = black debris, angular-equidimensional (“terrigenous palynoclasts” group; AU 61-2; 129,4/6,8); 6 = black debris, blade-shaped (“terrigenous palynoclasts” group; AU 53-2; 134,9/19,5); 7 = resin (“terrigenous palynoclasts” group; AU 80-2; 127,5/18,2); 8 = bisaccate pollen grain (“terrigenous palynomorphs” group; AU 42-1; 122,8/13,4); 9 = monosaccate pollen grain (“terrigenous palynomorphs” group; WS 22-1; 115,1/2,5); 10 = trilete spore (*Deltoidospora* sp.; “terrigenous palynomorphs” group; AU 63-1; 137,5/10,1); 11 = chorate dinoflagellate cyst (*Systematophora* sp.; “marine palynomorphs” group; AU 42-1; 131,5/3,6); 12 = proximate dinoflagellate cyst (*Leptodinium* sp.; “marine palynomorphs” group; WS 22-2; 137,8/17,6); 13 = cavate dinoflagellate cyst (*Endoscrinium* sp.; “marine palynomorphs” group; WS 22-2; 134,4/7,9); 14 = chorate dinoflagellate cyst (*Cleistosphaeridium* sp.; “marine palynomorphs” group; WS 22-2; 127,5/2,7); 15 = proximochorate dinoflagellate cyst (*Prolixosphaeridium* sp.; “marine palynomorphs” group; WS 22-2; 140,3/10,6); 16 = foraminifer test lining (“marine palynomorphs” group; AU 59-1; 131,3/14,4); 17 = acanthomorph acritarch (“marine palynomorphs” group; AU 43-2; 117,2/11,1); 18 = degraded debris (“degraded debris” group; AU 22-1; 121,9/17,0); 19 = degraded debris (“degraded debris” group; WS 22-2; 140,6/9,4).

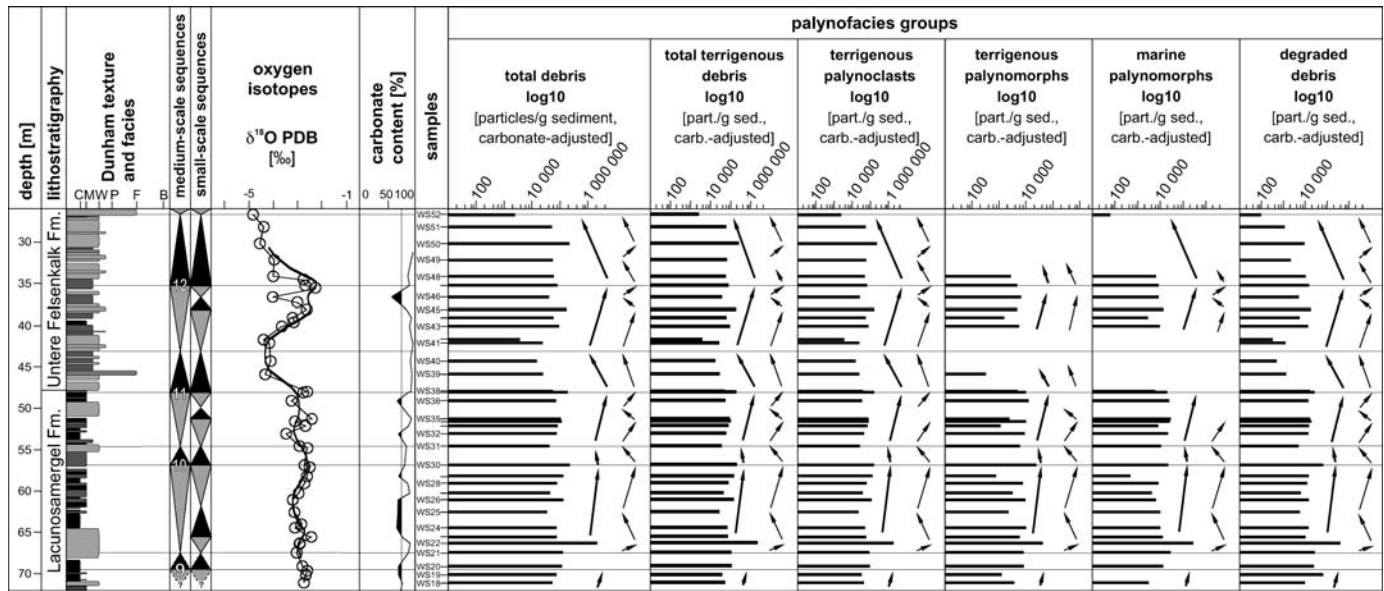


FIG. 7.—Sedimentological, oxygen isotope, and palynofacies data from core Wiesensteig B 908. Palynofacies data comprise absolute abundances (carbonate-adjusted) of total debris, total terrigenous debris, terrigenous palynoclasts, terrigenous palynomorphs, marine palynomorphs, and degraded debris. Oxygen isotope data depicted by triangles are from Braun (1999). See Figure 4 for a definition of palynoclast groups and Figure 8 for a key to symbols.

than an original signal, appears unlikely. This is due to the distribution of strongly oxidation-prone palynofacies constituents in the sample material. Foraminifer test linings, which are highly sensitive to oxidation (Versteegh, personal communication 2004), occur in samples with both very high and very low absolute palynoclast abundances (Link 2005). If oxidation had altered absolute palynoclast abundances, one would expect findings of foraminifer test linings to be restricted to intervals of high absolute palynoclast abundances. Similarly, the distribution pattern of amorphous organic matter (AOM), another easily oxidized palynofacies constituent, also does not show a correlation to the absolute abundances of palynoclasts. Instead, AOM is present in all samples, with AOM peaks occurring in samples both with low and high absolute palynoclast abundances (Link 2005). Hence, the distribution pattern of oxidation-prone palynofacies constituents shows that oxidation cannot have caused the observed cyclical distribution patterns. In addition, nearly all palynofacies samples contain finely distributed framboidal pyrite. If oxidation had affected the palynofacies associations, it should also have oxidized the pyrite (e.g., Brenner 1988). This leads us to conclude that the observed cyclical distribution patterns are based on primary signals and can yield paleoenvironmental information.

Terrigenous palynoclasts (as represented by the terrigenous debris, terrigenous palynoclast, and terrigenous palynomorph groups) are a proxy for terrestrial input into the marine system, with maximum absolute abundance representing maximum terrestrial influence (e.g., Van der Zwan 1990; Hart et al. 1994; Tyson 1995; McCarthy et al. 2004). Changes in the abundance of terrigenous palynoclasts in marine settings are commonly ascribed to fluctuations in shoreline distance and/or runoff (e.g., Traverse 1988; Tyson 1995). Because both proxy data (e.g., Abbink et al. 2001 and references therein) and general-circulation-model simulations (Valdes and Sellwood 1992; Valdes 1993; Valdes et al. 1995) suggest that dry climate conditions persisted during the Kimmeridgian in Europe, runoff variations seem very unlikely to have played a strong role in influencing terrigenous palynoclast abundances. Hence, we interpret the highest values of terrigenous palynoclasts to indicate a sea-level lowstand, whereas the lowest values are indicative of a sea-level highstand. According to the concept of genetic stratigraphy (Homewood 1996; Cross and Lessenger 1998), in a predominantly sea-level-controlled

clastic system an increased terrigenous input occurs in the fall hemisphere, while decreasing terrestrial influence is characteristic for the rise hemisphere. Absolute abundance peaks of terrigenous palynoclasts in this concept would indicate the fall–rise turnaround. Based on these premises, information on sea-level change can be deduced from the palynofacies sequences that are expressed in the cores Auendorf Ro 7324/B2 and Wiesensteig B 908 (Figs. 6, 7).

Our data show fluctuations in the absolute abundances of terrigenous debris by two orders of magnitude (Figs. 6, 7). Based on the concept outlined above, these intervals are interpreted to reflect intervals of low and high sea level. Typical absolute abundances of terrigenous debris interpreted to characterize sea-level lows are on the order of  $3.4 \times 10^5$  and  $1.9 \times 10^5$  particles per gram of sediment for the cores Auendorf Ro 7324/B2 (sample Au-43) and Wiesensteig B 908 (sample Ws-45), respectively. In contrast, typical absolute abundances of terrigenous debris interpreted as characterizing sea-level highs are  $4.9 \times 10^3$  for core Auendorf Ro 7324/B2 (sample Au-38) and  $2.8 \times 10^3$  for core Wiesensteig B 908 (sample Ws-42), and are thus two orders of magnitude lower. These differences would require major shifts in shoreline distance, a scenario that seems inconsistent with the commonly accepted view that short-term sea-level change during the greenhouse world of the Late Jurassic was on the order of only several meters (e.g., Sahagian and Jones 1993). This apparent contradiction is resolved, however, through the geometry of the carbonate ramp in the Upper Jurassic Marl Basin in SW Germany. Here, the dip of strata is so low that already a relatively minor change in sea level causes significant shifts in shoreline position. Based on a dip of  $0.002^\circ$ , a value realized in numerous carbonate ramps (e.g., Shaw 1964; Irwin 1965; Burchette and Wright 1998), a sea-level change of 2 m causes a shoreline displacement of 57 km (compare Ruf et al. 2005b). Hence, the observed differences in absolute abundances of terrigenous debris between situations of sea-level high and sea-level low are compatible with a minor sea-level change.

#### *Terrestrial Influence on the Marine System*

The absolute abundance records of marine palynomorphs relative to the non-carbonate fraction of the sediment are in phase with those of the

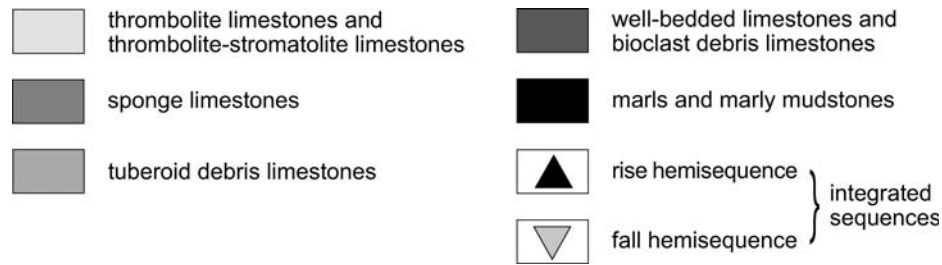


FIG. 8.—Key to symbols on datasheets for the cores Auendorf Ro 7324/B2 (Fig. 5) and Wiesensteig B 908 (Fig. 6).

terrigenous palynoclast groups (i.e., terrigenous debris, terrigenous palynoclasts, and terrigenous palynomorphs). Because our records of absolute abundance are carbonate-adjusted, variations in carbonate production (which could have led to a dilution or enrichment of palynoclast abundances) can be ruled out as a potential cause for the observed distribution pattern. Hence, a coupling between the terrestrial realm (as represented by terrigenous palynoclasts) and the marine realm (as represented by marine palynomorphs) is probable.

Terrigenous palynoclasts in marine settings not only reflect sea-level change, as discussed in the section “Determination of Palynofacies Sequences,” but also can serve as a proxy for the nutrient flux from the land into the marine system (e.g., Tyson 1995; McCarthy et al. 2004). The distribution of marine phytoplankton is strongly controlled by the availability of nutrients (e.g., Falkowski et al. 2000). Dinoflagellates, whose organic-walled cysts dominate the marine palynomorphs in both cores, are one of the most abundant groups of marine phytoplankton in epicontinental settings from the Triassic onwards and are sensitive productivity indicators, with higher nutrient levels generally coinciding with increased abundances of dinoflagellate cysts (see Pross et al. 2004; Pross and Brinkhuis 2005; and Sluijs et al. 2005 for reviews). Based on the above, the increased absolute abundances of terrigenous palynoclasts are proposed to represent intervals of enhanced nutrient input from terrestrial settings. As a response to enhanced nutrient availability, the absolute abundances of marine palynomorphs also increased. This implies that marine productivity in the Swabian Marl Basin during the Late Jurassic was strongly controlled by the nutrient flux from the surrounding landmasses. The nutrient flux, in turn, was closely related to the distance to the coast and thus to sea-level change. Similar conclusions were reached by Munneke and Westphal (2004), who proposed a sea-level control on marine productivity during the Kimmeridgian in the Swabian Marl Basin based on changes in shallow-water aragonite formation.

Further evidence for this scenario is provided by the observation that marls tend to yield higher absolute abundances of both terrigenous debris and marine palynomorphs than limestones (Figs. 6, 7). Because the absolute abundances are carbonate-adjusted, the reduction of absolute palynoclast abundances through carbonate dilution in limestone-dominated intervals can be ruled out. This implies that the marls were deposited in relatively proximal settings (i.e., during early sea-level rise). Limestones, in contrast, were formed in relatively distal settings (i.e., during intervals of high sea level). The rise–fall turnaround is situated in limestone-dominated intervals.

Our observation is in contrast to the data of Pawellek and Aigner (2003a) from a stratigraphically higher interval in the Upper Jurassic of SW Germany compared to this study. These authors concluded that an increase in the clastic fraction represents more distal conditions, deposited as background sediment in deeper-water zones where carbonate production was limited. However, Pawellek and Aigner (2003a) investigated only six samples for their palynological signal, where percentages of marine palynomorphs were higher in marlstone-dominated intervals than

in limestone-dominated intervals. Absolute and carbonate-adjusted values were not available for that study, so that the coupling between the terrestrial and marine systems (as represented by terrigenous palynoclasts and marine palynomorphs, respectively) could not be evaluated. Our observation is in accordance with the classical sequence stratigraphic concept that intervals with highest clastic input (i.e., marlstone-dominated intervals) are interpreted to represent sea-level lows or early rises (e.g., Van Wagoner et al. 1988). It is also supported by the view of Pittet and Strasser (1998), Pittet et al. (2000), and Bartolini et al. (2003). These authors concluded that carbonates were deposited in the Swabian Marl Basin as a result of export of carbonate from shallow areas within the Helvetic Platform (Fig. 1) during times of relative sea-level highs.

#### Determination of Integrated Sequences

As outlined in the “Determination of Palynofacies Sequences” section, the carbonate-adjusted palynofacies data from the cores Auendorf and Wiesensteig exhibit two different hierarchies of cycles. The first hierarchy consists of small-scale sequences with thicknesses of 3–7 m. The second hierarchy is represented by medium-scale sequences which are 5 to 20 m thick and consist of stacked small-scale sequences (Figs. 6, 7).

Both sequence hierarchies documented in the palynofacies data are also recorded in the oxygen isotope curves. Relatively heavy  $\delta^{18}\text{O}$  values tend to co-occur with high absolute abundances of all palynoclast groups and vice versa. Hence, we use this consistent pattern in order to determine integrated sequences that then can be used to gain information on the depositional environment.

Because the correlation between lithostratigraphic unit and ammonite biozone boundaries is well established for the Upper Jurassic of SW Germany (Deutsche Stratigraphische Kommission 2002), the duration of the medium-scale sequences encountered can be estimated. Core Auendorf Ro 7324/B2 comprises the boundaries between the Wohlgeschichtete Kalk, the Lacunosamergel, and the Untere Felsenkalk formations. These boundaries coincide with the boundaries between the planula/platynota and divisum/acanthicum ammonite zones, respectively. Based on the age estimates of 154.1 Myr for the planula/platynota and 152.62 Myr for the divisum/acanthicum ammonite zone boundaries (Fig. 2; Hardenbol et al. 1998), and the presence of four lower-order sequences in the corresponding part of core Auendorf Ro 7324/B2 (Fig. 6), an average duration of ca. 370 kyr can be calculated per lower-order integrated sequence. Given the dating uncertainties of zonal boundaries, this may indicate a potential link to the 400 kyr eccentricity cycle of the Earth’s orbit (cf. Strasser et al. 2000).

#### Correlation of Cores Auendorf and Wiesensteig

The medium-scale sequences identified in cores Auendorf Ro7324/B2 and Wiesensteig B 908 correlate well over a distance of about 9 km (Fig. 9). Control for this correlation has been provided by Ruf et al. (2005a). Based on a compilation of stable-isotope records and gamma-ray

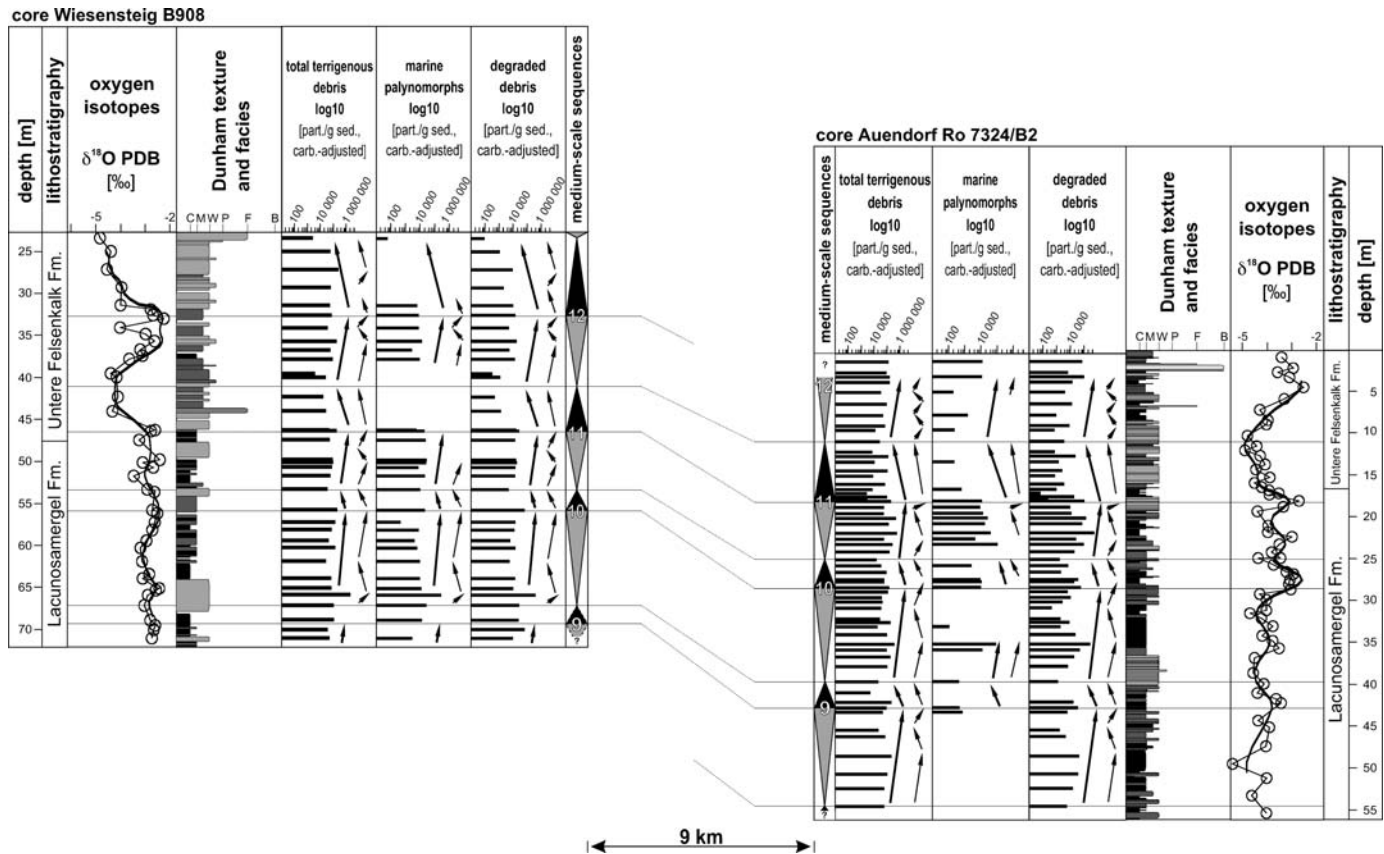


FIG. 9.—Correlation of cores Auendorf Ro 7324/B2 and Wiesensteig B 908 based on genetic sequences developed. See Figure 4 for a definition of palynoclast groups and Figure 8 for a key to symbols.

logs and utilizing a prominent basin-wide marker bed, the so-called “Glaukonitbank” of Late Kimmeridgian age as a reference level, these authors demonstrated that the medium-scale sequences in the Upper Jurassic of SW Germany can be correlated over distances of more than 100 km. An allocyclic control on the formation of medium-scale sequences is strongly suggested by the well-established local and regional correlation of segments of the stable-isotope curves corresponding to the sequences. Hence, the possibility of correlating medium-scale sequences between the cores Auendorf Ro7324/B2 and Wiesensteig B 908 provides a prerequisite for the establishment of an integrated model for environmental change as presented below.

#### *Integrated Model for Environmental Change*

As described above, the  $\delta^{18}\text{O}$  values from micrite areas in the cores Auendorf Ro 7324/B2 and Wiesensteig B 908 exhibit a trend to heavier values in intervals of enhanced absolute palynoclast abundances of both terrestrial and marine origin (Figs. 6, 7). This picture emerges most clearly for the upper part of core Auendorf, where a high-resolution dataset is available (Fig. 6).

The  $\delta^{18}\text{O}$  signal of bulk carbonate samples as presented in this study has often been considered an unreliable paleotemperature and paleosalinity proxy because precipitation of calcite cement during burial diagenesis causes the bulk  $\delta^{18}\text{O}$  signal to shift to lighter values (e.g., Schrag et al. 1995). However, the Upper Jurassic of SW Germany has been only subjected to very shallow burial without severe alteration (Reinhold 1998). Because diagenetic processes can operate even at shallow depths, the reliability of the  $\delta^{18}\text{O}$  data needs further evaluation. A

strong indication for the presence of original trends in the  $\delta^{18}\text{O}$  signal is provided by the fact that  $\delta^{18}\text{O}$  records from the Upper Jurassic of the Swabian Marl Basin can be correlated over distances of  $> 100$  km (Ruf et al. 2005a; see above). This observation is in accordance with the view that the isotopic composition of carbonates deposited in the Swabian Marl Basin records the changes in paleoenvironmental conditions on the adjacent shallow Helvetic Platform (Bartolini et al. 2003). Moreover, cross-plots of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  bulk carbonate measurements from various sections in the Oxfordian and Kimmeridgian of the Swabian Marl Basin have revealed no significant correlations, therefore corroborating the view that diagenesis has not strongly affected the isotopic composition (Ruf et al. 2005b). Hence, although diagenetic overprints have to be taken into account, we conclude that the original trends in our  $\delta^{18}\text{O}$  records have been preserved. A paleoenvironmental interpretation seems possible, especially if the comparison of  $\delta^{18}\text{O}$  trends with those of other proxies yields a consistent picture.

Independently of these aspects, the significance and applicability of bulk-rock  $\delta^{18}\text{O}$  records has been demonstrated by several studies. For instance, Weissert and Erba (2004) presented bulk-rock  $\delta^{18}\text{O}$  records from Upper Jurassic to mid-Cretaceous pelagic carbonate sections. Although they refrained from translating the  $\delta^{18}\text{O}$  signal into accurate sea-surface temperatures owing to the effects of burial diagenesis, the  $\delta^{18}\text{O}$  records still yielded valuable, albeit only qualitative, information on temperature trends. For the mid-Cretaceous of the Vocontian Basin and the Mazagan Plateau (DSDP Site 545), Herrle et al. (2003b) showed that bulk-rock samples exhibit  $\delta^{18}\text{O}$  fluctuations similar to those recorded in pristine foraminifera from the Blake Nose Plateau (ODP Site 1049C). Therefore, Herrle et al. (2003b) concluded that original trends in the  $\delta^{18}\text{O}$

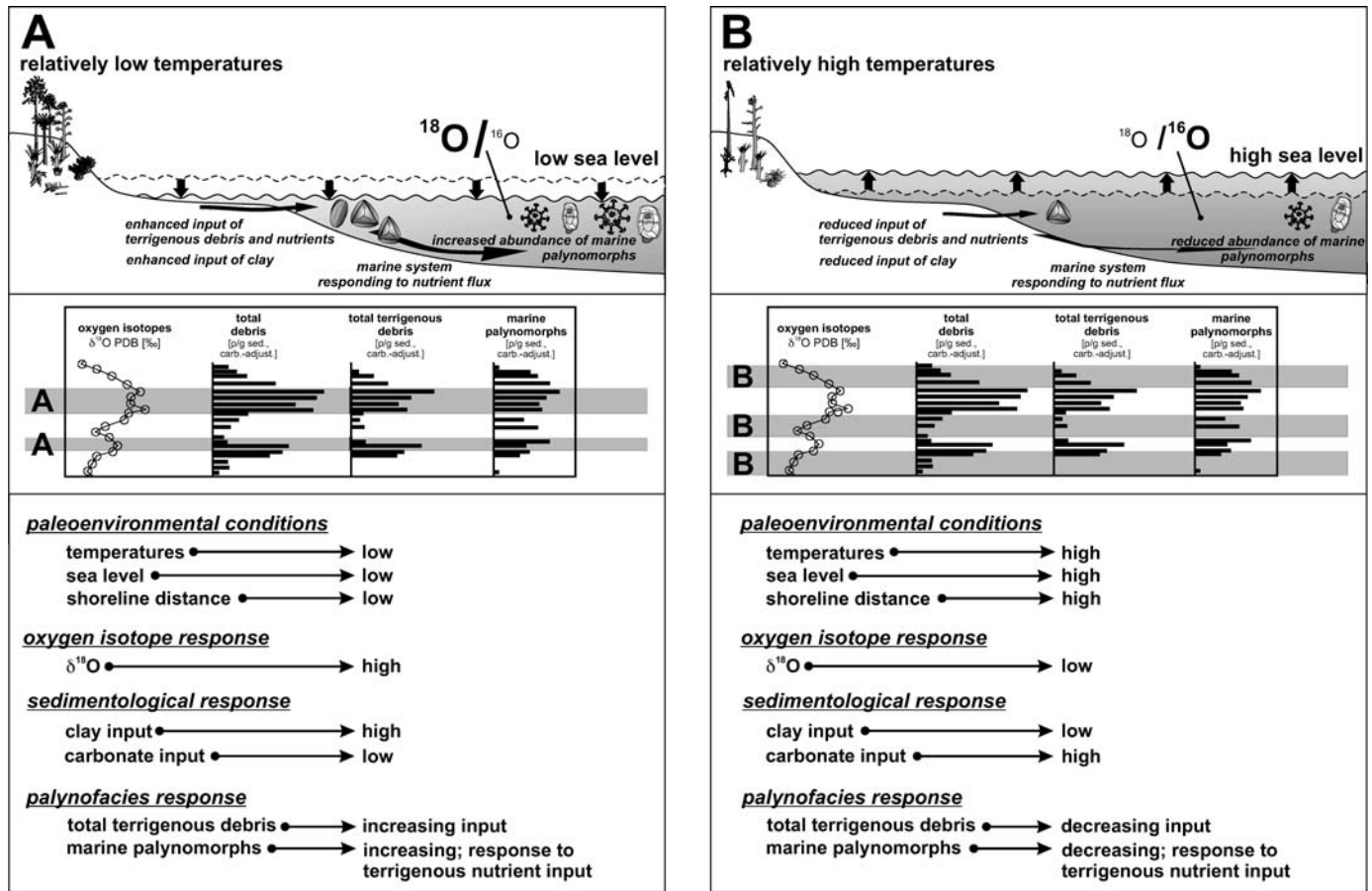


Fig. 10.—Schematic model for palynofacies, sedimentological, and oxygen isotope response to environmental change in the deeper part of the carbonate ramp in the Late Jurassic Swabian Basin (top part), idealized curves for oxygen isotopes and for total debris, total terrigenous debris, and marine palynomorph absolute abundances (middle part), and summary of oxygen isotope, sedimentological, and palynofacies response to prevailing paleoenvironmental conditions (bottom part). **A**) During times of relatively low temperatures and low sea level, enhanced input of terrestrial palynoclads and terrigenous clay coincides with increased  $\delta^{18}\text{O}$  values. Enhanced input of terrigenous palynoclads is considered to reflect enhanced input of land-derived nutrients, which then led to high absolute marine palynomorph abundances. **B**) During times of relatively high temperatures and high sea level, reduced input of terrestrial palynoclads and enhanced carbonate production coincides with decreased  $\delta^{18}\text{O}$  values. Owing to a reduced input of land-derived nutrients, absolute marine palynomorph abundances are reduced.

bulk records had been preserved. From analyses of a late Quaternary deep-sea core retrieved off Somalia, Shackleton et al. (1993) showed that the  $\delta^{18}\text{O}$  bulk record reproduced the marine isotope stages well, and therefore the  $\delta^{18}\text{O}$  bulk approach is a valuable tool for high-resolution oxygen isotope stratigraphy.

Based on a comparison with the palynofacies dataset, freshwater input into the Swabian Marl Basin from the surrounding land masses such as the Massif Central, the Rhenish Massif, or the Bohemian Massif (Fig. 1) is ruled out as a cause for the observed  $\delta^{18}\text{O}$  trends. As discussed above, intervals of enhanced terrestrial input are characterized by increased absolute abundances of terrigenous palynoclads. These intervals, however, exhibit heavier instead of lighter  $\delta^{18}\text{O}$  values, which would be expected to result from an increased flux of isotopically lighter freshwater. Another case against a significant freshwater signature in the  $\delta^{18}\text{O}$  values is the arid climate that prevailed in Europe during much of the Late Jurassic (see the palynological study of Abbink et al. 2001 and references therein). Summarizing the information from the available proxy data, the climate became increasingly drier during the Oxfordian until arid conditions were reached in the Kimmeridgian. This picture is consistent with the results of general-circulation-model simulations for the Kimmeridgian, which also predict at least seasonally arid conditions in Europe (Valdes and Sellwood 1992; Valdes 1993; Valdes et al. 1995).

Thus, strong runoff, which would be necessary to explain lighter  $\delta^{18}\text{O}$  values through a freshwater link, is not compatible with the climatic boundary conditions in Europe during the Kimmeridgian. Hence, temperature change emerges as a prominent factor to have determined the  $\delta^{18}\text{O}$  signal. This implies that enhanced input of terrigenous debris occurred when temperatures were lower. In turn, reduced input of terrigenous debris occurred during times of higher temperatures.

Based on the palynoclast, oxygen isotope, and sedimentological data from the cores Auendorf Ro 7324/B2 and Wiesensteig B 908, we propose a model for climate- and sea-level-induced environmental change in the Swabian Marl Basin during the Late Oxfordian and Kimmeridgian (Fig. 10A, B). Cooler temperatures (as indicated by relatively heavy  $\delta^{18}\text{O}$  values) caused a lowering of the sea level (as characterized by high absolute abundances of terrigenous palynoclads) where clay input was relatively high (as indicated by the dominance of marlstones in the respective intervals). The examined cores were situated in relatively proximal positions within the Swabian Marl Basin. Because absolute palynoclast abundances and clay input represent tracers of terrestrial input, the flux of terrigenous nutrients into the marine realm was enhanced. The terrestrial input was probably derived from the Rhenish Massif (Meyer and Schmidt-Kaler 1989), a view that is consistent with southbound currents during the Late Jurassic in SW Germany (Ricken

1985; Gygi 1986). The enhanced flux of terrigenous nutrients caused a shift to more trophic conditions, resulting in increased phytoplankton productivity, evidenced in our dataset by increased absolute abundances of marine palynomorphs (Fig. 10A). In contrast, warmer temperatures (as indicated by relatively light  $\delta^{18}\text{O}$  values) caused higher sea level (as characterized by low absolute abundances of terrigenous palynoclasts). Rise–fall turnarounds are characterized by minima of absolute terrigenous palynoclast abundances. Owing to the more distal position of the examined cores to the coastline during that time, the input of terrigenous nutrients into the marine realm was reduced. This caused a shift to less trophic conditions, resulting in a reduction of phytoplankton productivity as evidenced by reduced absolute abundances of marine palynomorphs (Fig. 10B).

The sea-level changes may be controlled by climate fluctuations coupled to insolation changes. Based on shallow-water Upper Jurassic and Lower Cretaceous carbonate sections from Switzerland, France, Germany, and Spain, Pittet (1996), Strasser and Hillgärtner (1998), and Strasser et al. (1999, 2000) argued that commonly observed sequences represent an effect of the 400 kyr eccentricity cycle. In order to explain the sea-level change in the absence of major ice shields that could have provided significant glacio-eustatic fluctuations (e.g., Frakes et al. 1992; Eyles 1993), a thermal expansion of the surface and/or deep waters, changes in the water balance of lakes and aquifers, or a combination of these factors is suggested (Strasser et al. 1999; Strasser et al. 2000). These explanations, however, do not consider the effect of varying concentrations of greenhouse gases in the atmosphere, which according to model simulations would potentially have caused the formation of a large Southern Hemisphere ice sheet and thus could well explain meter-scale sea-level fluctuations as a response to insolation change in the eccentricity band (Valdes et al. 1995).

The average duration of the medium-scale integrated sequences in core Auendorf can be estimated at ca. 370 kyr (see Section “Determination of Integrated Sequences”), which appears reasonably close to the value of 400 kyr for the second eccentricity cycle given the magnitude of dating uncertainties. Hence, we suggest that the driving factor for the environmental changes described in our model are eccentricity-related insolation differences that caused sea-level changes, with higher insolation leading to a sea-level rise and lower insolation to a sea-level drop. This would imply that the regional record of sea-level and temperature fluctuations in the epeiric Swabian Marl Basin reflects climatic changes that occurred on a global scale.

#### CONCLUSIONS

Two cores from the distal part of the Swabian Marl Basin in the Upper Jurassic (Late Oxfordian and Kimmeridgian) of SW Germany were studied. Palynofacies, oxygen isotope, and sedimentological data were examined in order to elucidate the environmental processes controlling the formation of deeper carbonate-ramp deposits. The most salient results of our study are as follows:

- (1) Methodologically, the calculation of absolute palynoclast abundances with regard to the non-carbonate fraction of the sediment (“carbonate adjustment”) makes it possible to avoid the effect of dilution of the palynofacies signal through carbonate precipitation. This can be instrumental in the interpretation of the original signal.
- (2) Carbonate-adjusted absolute abundances of terrigenous palynoclasts are used as proxies for shoreline distance and thus for sea-level change. The strong differences in absolute abundances of terrigenous palynoclasts between intervals of high and low sea level are explained through the geometry of the Late Jurassic carbonate ramp of SW Germany, where even small (on the order

of meters) sea-level change leads to a large (on the order of tens of kilometers) shoreline displacement.

- (3) Carbonate-adjusted absolute abundances of marine palynomorphs show an in-phase distribution pattern with that of terrigenous palynoclasts. Because terrigenous palynoclasts reflect terrestrial input into the marine system and as such also mirror the land–sea flux of nutrients, a close coupling between the terrestrial and marine realms via a nutrient link is suggested. Times of increased availability of land-derived nutrients were characterized by increased phytoplankton productivity and vice versa. Based on the observation that sea-level lows (as evidenced by high absolute abundances of terrigenous palynoclasts) co-occur with relatively heavy  $\delta^{18}\text{O}$  values and vice versa, intervals of low sea level were characterized by relatively low temperatures and vice versa.
- (4) Marl-dominated intervals tend to yield higher (carbonate-adjusted) absolute abundances of both terrigenous debris and marine palynomorphs than do limestone-dominated intervals. This implies that the marl-dominated intervals were deposited in relatively proximal settings (i.e., during early sea-level rise) and limestone-dominated intervals formed in relatively distal settings (i.e., during intervals of high sea level).
- (5) The (carbonate-adjusted) absolute abundance records of the various palynoclast groups allow the recognition of two sequence hierarchies that are also recognized in the oxygen isotope record. The first category consists of small-scale sequences 3–7 m thick, and the second category consists of medium-scale sequences 5–20 m thick. Limestone–marl alternations on a decimeter scale were not studied in this work; we focused on the higher-order sequences.
- (6) The integrated palynofacies and oxygen isotope sequences are correlated between the two cores studied. Based on estimates of the duration of ammonite zones taken from the literature, the sequences have a duration of ca. 370 kyr. This suggests a possible link to the second (400 kyr) eccentricity cycle of the Earth’s orbit. The driving factor for the formation of sequences as evidenced in our records might be sought in eccentricity-related insolation differences that caused sea-level changes, with higher insolation leading to a sea-level rise and vice versa.

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