Dynamic stratigraphy as a tool in economic mineral exploration: ultra-pure limestones (Upper Jurassic SW Germany)

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Abstract

Ultra-pure limestones form valuable economic minerals used in the glass, paper, pharmaceutical, chemical and building industries. Both exploration and exploitation of economic materials require predictions of the subsurface stratigraphy. Such predictions are most reliable when the depositional processes creating these deposits are well understood. We present a simple, process-based methodology (‘Dynamic Stratigraphy’) to break down stratigraphic packages into a hierarchy of easily recognisable genetically defined units of various scales. Each scale of analysis at the same time provides critical data on the composition, quality, volumes and preferred occurrence of economic minerals. In this study, Upper Jurassic carbonates of SW-Germany, deposited on a deeper epicontinental ramp, have been re-evaluated, based on newly available borehole data of an exploration programme for industrial minerals, especially for ultra-pure limestones, carried out by the Geological Survey of Baden-Württemberg. About 2.5 km of core were slabbed and continuously studied for micro- and macrofacies, geochemistry, colourimetry (‘whiteness index’) and calibrated to the gamma-ray signatures. In a number of key outcrops stratyal and facies patterns as well as sedimentary geometries were mapped. The carbonate buildups form the most promising rock bodies hosting ultra-pure limestones. Gamma-ray signatures correlate both with major facies types and their bulk chemical composition and are thus useful for an initial evaluation of raw materials properties.

In both major facies associations, (1) the bedded and (2) the massive microbial/sponge buildup facies, distinct sedimentary cycles were recognised, building systematic stacking patterns and a cycle hierarchy. Within the buildup facies, this cyclicity mirrors the ‘whiteness’ and ‘purity’ of limestones. The cycles are used to carry out regional correlations between and across extensive buildup complexes, which are generally regarded as completely massive and homogenous. Based on this, the occurrence and distribution of economically valuable ultra-pure limestone bodies can be understood, and used to develop predictive genetic models.

Dynamic or genetic stratigraphy integrated with petrophysical measurements (colourimetry, gamma-ray logs) leads to more cost-effective techniques of exploration and exploitation. While similar sedimentological concepts are commonly used in the petroleum industry, this study documents their usefulness also in the economic minerals industry.

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1. Introduction

1.1. Scope

Predictive stratigraphic concepts have always played an important role in the hydrocarbon industry (Payton, 1997; Van Waggoner, Mitchum, Campion, & Rahmanian, 1990). This paper aims to show that a process-based stratigraphic approach is also useful in the exploration for raw materials, exemplified by ultra-pure limestones. Understanding the genesis of economic mineral deposits helps to reduce the costs of exploration and development.

We use concepts of ‘dynamic stratigraphy’ (Aigner, Heinz, Hornung, & Asprion, 1999), involving a systematic analysis of sedimentary rock sequence along a hierarchy of spatial and temporal scales, moving from small to larger levels (Fig. 1).

(1) Microfacies analysis identifies generally small-scale primary and secondary textures of limestones as controlled by carbonate-producing biota, water energy

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during deposition, and fluid dynamics during diagenesis. At the same time, microfacies types also mirror the chemical composition and thus the economic potential of the limestones. For instance, low-energy mud- and wackestones tend to contain more insoluble matter and are thus usually less pure than the high-energy pack- and grainstones.

(2) Petrophysical and facies analysis focuses on larger-scale groups of microfacies types that reflect similar depositional and ecological processes. At the same time, these groups of microfacies show comparable physical and chemical parameters such as their gamma-ray signal, whiteness and carbonate content. Thus petrophysical facies types help to characterise the quality of economic minerals.

(3) Architectural analysis reconstructs the three-dimensional geometry of rock bodies as a reflection of the dynamic evolution of depositional environments. These geometries also allow the assessment of the volumes of producible mineral resources.

(4) Sequence analysis provides a genetic framework for the occurrence of rock types within sedimentary sequences and cycles. The cycles record changing environmental conditions (e.g. baselevel dynamics). At the same time, these cycles highlight preferred stratigraphic levels where economic minerals (e.g. ultra-pure limestones) may occur.

(5) Stacking analysis deciphers the way shorter-term stratigraphic cycles change and follow longer-term trends, controlled by various mechanisms (tectonics, eustasy, etc.) During exploration, stacking patterns help to predict the regional occurrence of mineral resources.

(6) Basin-analysis identifies the general patterns of basin paleogeography, dynamics and evolution. It is thus possible to deduce general rules for predicting the distribution of certain facies types that have an economic potential on a basin-wide scale.

Therefore this hierarchical approach provides a logical basis for understanding the small- to large-scale occurrence of ultra-pure limestones

1.2. Geological setting

During the Late Jurassic large parts of the European continent were covered with a shelf sea marginal to the oceanic Tethys in the South (Fig. 2). In the North, this shelf sea was separated from the Boreal Sea by an island archipelago. In the southern, deeper part of this epicontinental shelf sea an extensive siliceous sponge-microbial-reef belt developed. According to Meyer and Schmidt-Kaler (1989, 1990) the Swabian facies as the central part of this reef belt formed a deeper-water area between the shallower Franconian-Southern Bavarian platform in the East and the Swiss platform in the West. To the South, the Swabian facies passed into the Helvetic Basin.
Within the Swabian facies between 400 and 600 m of carbonate rocks were deposited during the Late Jurassic. Two major lithofacies types can be distinguished (Gwinner, 1976; Geyer & Gwinner, 1979):

1. The so-called ‘normal facies’ consists of well-bedded limestones and calcareous marls and
2. The so-called ‘massive facies’ where bedding is either absent, indistinct or very irregular.

The massive limestones are built by microbial crusts (stromatolites and thrombolites) and siliceous sponges and their buildups have been interpreted by various authors as relatively deep and quiet water ‘reefs’, mounds or bioherms (e.g. reviews of Gwinner, 1976; Leinfelder et al., 1994, 1996). The normal facies may either interfinger with the reefs or onlap onto the reefs (Gwinner, 1976; Pawellek, 2001). In the upper parts of the Upper Jurassic, a coral facies developed locally upon the microbial crust-sponge reefs.

1.3. Database and methods

This study is based on sixteen borehole cores (Figs. 2 and 3) each about 100–150 m in length with a total length of nearly 2.5 km. All cores were continuously cut to allow a detailed and a complete logging of macrofacies. From all boreholes gamma-ray logs were available. For microfacies analysis, approximately every meter a peel, a thin section or a polished slab was made. Facies proportion diagrams (Kerans & Tinker, 1997) were established in order to document the cyclicity in a quantitative way. In addition to the borehole cores 53 borehole gamma-ray-logs and 24 quarries were analysed, and four outcrop gamma-ray-logs were measured to integrate the one-dimensional borehole data with the two- and three-dimensional outcrop data.

2. Dynamic stratigraphy

2.1. Microfacies analysis

Upper Jurassic rocks of Southern Germany are generally divided into a bedded and a massive limestone facies association. Both groups include each a number of different microfacies types (Pawellek & Aigner, 2002) due to variable composition and texture. The massive limestones can be further divided into the following main facies types (Fig. 4).
Fig. 3. (a) and (b) Stratigraphic subdivision of the upper Upper Jurassic of the Swabian Alb with the stratigraphic range of the borehole and quarries studied here. (1) Ages from Hardenbol et al. (1998); (2) subboreal ammonite zones from Hantzpergue, Baudin, Mitta, Olferiev, and Zakharov (1998) and Hardenbol et al. (1998); (3) classical stratigraphic subdivision, dating back to Quenstedt (1858); (4) subdivision by the Geological Survey, Villinger & Fleck, 1995; (5, 6) lithostratigraphic subdivision of Villinger and Fleck (1995). Numbers of data points refer to map of Fig. 2.
Thrombolites are rare within massive limestones.

Fig. 4. Facies classification of Upper Jurassic massive limestones of the Swabian Alb using characteristic components. Note that tuberoid limestones and particle-rich limestones are rare within massive limestones.

1. Thrombolites: microbial crusts, characterised by clotted and micropeloidal structure (Aitken, 1967; Schmid, 1996). Terebella sp., Tubiphytes sp. and brachiopods are generally common and siliceous sponges may also occur. The matrix between the thrombolites is normally micritic (mud-wackestones).

2. Sponge-thrombolites and thrombolitic sponge limestones: similar to the thrombolites, but a higher sponge content (sponge-thrombolites are thrombolite dominated, thrombolitic sponge limestones are sponge dominated).

3. Thrombolites/stromatolites: transitional between pure thrombolites and pure stromatolites.

4. Stromatolites: characterised by parallel and macroscopic laminae (Schmid, 1996). Sometimes Tubiphytes sp. is very common in this facies type. The matrix between the stromatolites is generally built by particle-rich limestones, formed by peloids, bioclasts and rare oolites.

5. Marly, micritic sponge limestones with abundant stromatolites: sponge float- to rudstone; the matrix between the sponges consists of marl, marly limestone or micrite.


(7) Particle-rich sponge limestones: sponge float- to rudstone, where the matrix consists of particle-rich packstones.

Tuberoid and particle-rich limestones do not only occur in massive limestones but also in bedded limestones.

The bedded limestones can be further divided into the following (micro-) facies types (Fig. 5)

1. Marls and marly limestones, building units of several decimeters up to several tens of meters.

2. Well bedded limestones. Centimeter to decimeter thick lime mudstones alternating with thin marl interbeds or partings.

3. Debris-limestones. Clasts of sponges, microbial crusts, reworked intraclasts and rarely corals form the main components. The size of components and their composition is highly variable.

Table 1

<table>
<thead>
<tr>
<th>Facies type</th>
<th>Gamma-ray value of each facies type (1) in this table the average amplitude as well as the maximum range are represented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marls and marly limestones</td>
<td>○ 18–33 (max. = 9–59)</td>
</tr>
<tr>
<td>Well-bedded limestones</td>
<td>○ 11–18 (max. = 7–32)</td>
</tr>
<tr>
<td>Intraclast-bioclast limestones</td>
<td>○ 6–10 (max. = 3–20)</td>
</tr>
<tr>
<td>Tuberoid limestones</td>
<td>○ 6–8 (max. = 5–20)</td>
</tr>
<tr>
<td>Marly and strongly styloitic sponge limestones</td>
<td>○ 5–8 (max. = 4–18)</td>
</tr>
<tr>
<td>Thrombolites and sponge thrombolites</td>
<td>○ 4–8 (max. = 2–18)</td>
</tr>
<tr>
<td>Breccias</td>
<td>○ 2–8 (max. = 1–20)</td>
</tr>
<tr>
<td>Tuberoid sponge limestones</td>
<td>○ 5–7 (max. = 4–18)</td>
</tr>
<tr>
<td>Thrombolitic sponge limestones</td>
<td>○ 3–7 (max. = 2–21)</td>
</tr>
<tr>
<td>Micritic sponge limestones</td>
<td>○ 3–9 (max. = 2–21)</td>
</tr>
<tr>
<td>Particle-rich sponge limestones</td>
<td>○ 4–6 (max. = 3–27)</td>
</tr>
<tr>
<td>Coral debris limestones</td>
<td>○ 4–5 (max. = 3–6)</td>
</tr>
<tr>
<td>Particle-rich limestones</td>
<td>○ 3–5 (max. = 2–19)</td>
</tr>
<tr>
<td>Stromatolites/thrombolites</td>
<td>○ 3–5 (max. = 2–10)</td>
</tr>
<tr>
<td>Stromatolites</td>
<td>○ 3–5 (max. = 2–10)</td>
</tr>
</tbody>
</table>
Particle-rich limestones. Consisting mainly of rounded intraclasts, peloids and ooids, with a dominantly packstone, and (rarely) patchy grainstone texture. In this facies tubular tempestites (Tedesco & Wanless, 1991; Wanless, Cottrell, Tagett, Tedesco, & Warzeski, 1995; Wanless, Tedesco, Tyrell, & 1998) can commonly be observed.

Most micrite-dominated limestone types, deposited under lower energy conditions contain some clay and thus have less economic potential. In contrast, higher-energy facies types such as stromatolitic and particle-rich limestones are ultra-pure carbonate rocks.

2.2. Facies and petrophysical analysis

The facies and microfacies types mentioned above cannot discriminated solely based on petrophysical parameters. However, facies groups do show similar petrophysical characteristics such as gamma-ray signals and whiteness indices. In this paper, the petrophysically significant facies groups are discussed; they relate directly to raw materials properties.

The radioactivity of Upper Jurassic carbonates of SW Germany is caused by clay minerals (Below, 1988). This implies a simple correlation between gamma-ray and facies. Several facies types have similar gamma-ray values and thus form distinct petrophysical facies groups (Tables 1 and 2, Fig. 6)

(4) Particle-rich limestones. Consisting mainly of rounded intraclasts, peloids and ooids, with a dominantly packstone, and (rarely) patchy grainstone texture. In this facies tubular tempestites (Tedesco & Wanless, 1991; Wanless, Cottrell, Tagett, Tedesco, & Warzeski, 1995; Wanless, Tedesco, Tyrell, & 1998) can commonly be observed.

Most micrite-dominated limestone types, deposited under lower energy conditions contain some clay and thus have less economic potential. In contrast, higher-energy facies types such as stromatolitic and particle-rich limestones are ultra-pure carbonate rocks.

<table>
<thead>
<tr>
<th>Facies type</th>
<th>Ultra-pure limestones</th>
<th>Normal massive limestones</th>
<th>Debris limestones</th>
<th>Well-bedded limestones</th>
<th>Marls and marly limestones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average values</td>
<td>3–5 cps</td>
<td>5–7 cps</td>
<td>5–7 cps</td>
<td>11–18 cps</td>
<td>18–33 cps</td>
</tr>
<tr>
<td>Range of values</td>
<td>1–17 cps</td>
<td>2–17 cps</td>
<td>1–17 cps</td>
<td>7–30 cps</td>
<td>15–58 cps</td>
</tr>
</tbody>
</table>

Fig. 6. Gamma-ray signatures of the five major facies groups.
limestones and tuberoid sponge limestones has very similar average gamma-ray values, as the ‘normal’ massive limestone group. However, they can be distinguished very easily in cores from massive limestones.

(4) The bedded limestones have a wide range of cps values (8–26) with an average of 11–18 cps.

(5) The marls and marly limestones have much higher average gamma-ray values (18–33 cps) than all other facies groups.

X-ray fluorescence analysis of collective samples was used to analyse the CaO content of each facies type. The CaCO₃ content was then calculated from the CaO content (Table 3). Plots of the same five facies groups as above are shown in Fig. 7 and Table 3:

1. Ultra-pure limestones with an average CaCO₃ content of 99%. In contrast to ‘normal’ massive limestones and debris limestones, which rarely may have a CaCO₃ content of 99%, the CaCO₃ content of ultra-pure limestones are usually not below 98%.

2. ‘Normal’ massive limestones with an average CaCO₃ content of 97–98%.

3. Debris limestones with an average CaCO₃ content of 93–99%.

4. Bedded limestones with an average CaCO₃ content of 88–93%.

---

Table 3

<table>
<thead>
<tr>
<th>Facies type</th>
<th>CaO-content (%)</th>
<th>CaCO₃-content (calculated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marls and marly limestones</td>
<td>41–45</td>
<td>73–81</td>
</tr>
<tr>
<td>Well-bedded limestones</td>
<td>49–52</td>
<td>88–93</td>
</tr>
<tr>
<td>Intraclast-bioclast limestones</td>
<td>54–55</td>
<td>97–98</td>
</tr>
<tr>
<td>Tuberoid limestones</td>
<td>54–55</td>
<td>97–98</td>
</tr>
<tr>
<td>Marly and strongly stylolitic sponge limestones</td>
<td>54 (max. = 53–56)</td>
<td>97 (max. = 95–99)</td>
</tr>
<tr>
<td>Thrombolites and sponge thrombolites</td>
<td>54–55 (max. = 53–56)</td>
<td>97–98 (max. = 95–99)</td>
</tr>
<tr>
<td>Breccias</td>
<td>52–56 (max. = 45–56)</td>
<td>93–99 (max. = 81–99)</td>
</tr>
<tr>
<td>Tuberoid sponge limestones</td>
<td>54 (max. = 54–55)</td>
<td>97 (max. = 97–98)</td>
</tr>
<tr>
<td>Thrombolitic sponge limestones</td>
<td>55 (max. = 54–57)</td>
<td>98 (max. = 97–100)</td>
</tr>
<tr>
<td>Micritic sponge limestones</td>
<td>55 (max. = 54–57)</td>
<td>98 (max. = 97–100)</td>
</tr>
<tr>
<td>Particle-rich sponge limestones</td>
<td>56 (max. = 55–57)</td>
<td>99 (max. = 98–100)</td>
</tr>
<tr>
<td>Coral debris limestones</td>
<td>56 (max. = 53–56)</td>
<td>99 (max. = 95–99)</td>
</tr>
<tr>
<td>Particle-rich limestones</td>
<td>56 (max. = 55–57)</td>
<td>99 (max. = 98–100)</td>
</tr>
<tr>
<td>Stromatolites/thrombolites</td>
<td>55–56 (max. = 54–57)</td>
<td>98–99 (max. = 97–100)</td>
</tr>
<tr>
<td>Stromatolites</td>
<td>56 (max. = 55–57)</td>
<td>99 (max. = 98–100)</td>
</tr>
</tbody>
</table>

---

Fig. 7. CaO content of the five facies groups.
5. Marlsl and marly limestones with an average $\text{CaCO}_3$ content of 73–81%.

Average cps values were calculated for each core interval that was bulk-sampled for CaO measurements. These average cps values correlate very well with the CaO content (Fig. 8). With the help of the determined regression line ($y = -1.2x + 72$), it is possible to make a rough estimate the carbonate content (Table 4).

The determination of the whiteness index ($Y$) by means of an industrial colourimeter plays an important role in the raw material industry to assess the quality of limestones (Dimke, 1997). In this study the whiteness index was measured each 20 cm along slabbed and cleaned cores (Table 5). Plots of the same five facies groups as above are shown in Fig. 9 and Table 6.

1. Ultra-pure limestones with an average whiteness index of 60–81.
2. ‘Normal’ massive limestones with an average whiteness index of 56–69.
5. Marlsl and marly limestones with an average whiteness index of 44–50.

The five facies groups can be easily distinguished by their average whiteness index, but each group does show a significant range of values (Fig. 9). This is caused by two types of small-scale rock heterogeneities: (1) by dark components (e.g. sponges) that occur in the ultra-pure limestones as well as in other limestones, and (2) by secondary diagenesis (e.g. Liesegang rings, Mn-dendrites, etc.).

### Table 4
Estimation of the CaO/CaCO$_3$-content predicted from the gamma-ray values

<table>
<thead>
<tr>
<th>Cps</th>
<th>CaO-content ($%$)</th>
<th>CaCO$_3$-content ($%$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>56</td>
<td>99</td>
</tr>
<tr>
<td>10</td>
<td>52</td>
<td>93</td>
</tr>
<tr>
<td>15</td>
<td>48</td>
<td>86</td>
</tr>
<tr>
<td>20</td>
<td>43</td>
<td>77</td>
</tr>
<tr>
<td>25</td>
<td>39</td>
<td>70</td>
</tr>
<tr>
<td>30</td>
<td>35</td>
<td>63</td>
</tr>
<tr>
<td>35</td>
<td>31</td>
<td>55</td>
</tr>
<tr>
<td>40</td>
<td>27</td>
<td>48</td>
</tr>
</tbody>
</table>

### Table 5
Whiteness-index ($Y$) of each facies type

<table>
<thead>
<tr>
<th>Facies type</th>
<th>Whiteness index ($Y$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marlsl and marly limestones</td>
<td>56–66 (max. = 34–84)</td>
</tr>
<tr>
<td>Well-bedded limestones</td>
<td>51–61 (max. = 33–69)</td>
</tr>
<tr>
<td>Intraclast-bioclast limestones</td>
<td>60–71 (max. = 39–79)</td>
</tr>
<tr>
<td>Tuberoid limestones</td>
<td>55–61 (max. = 49–66)</td>
</tr>
<tr>
<td>Marly and strongly stylolitic sponge limestones</td>
<td>58–63 (max. = 37–67)</td>
</tr>
<tr>
<td>Thrombolites and sponge thrombolites</td>
<td>56–66 (max. = 34–85)</td>
</tr>
<tr>
<td>Breccias</td>
<td>53–70 (max. = 34–83)</td>
</tr>
<tr>
<td>Tuberoid sponge limestones</td>
<td>60–66 (max. = 32–70)</td>
</tr>
<tr>
<td>Thrombolitic sponge limestones</td>
<td>58–69 (max. = 34–83)</td>
</tr>
<tr>
<td>Micritic sponge limestones</td>
<td>58–69 (max. = 34–83)</td>
</tr>
<tr>
<td>Particle-rich sponge limestones</td>
<td>67–77 (max. = 40–83)</td>
</tr>
<tr>
<td>Coral debris limestones</td>
<td>60–74 (max. = 51–76)</td>
</tr>
<tr>
<td>Particle-rich limestones</td>
<td>64–80 (max. = 37–84)</td>
</tr>
<tr>
<td>Stromatolites/thrombolites</td>
<td>60–81 (max. = 51–85)</td>
</tr>
<tr>
<td>Stromatolites</td>
<td>67–80 (max. = 49–85)</td>
</tr>
</tbody>
</table>
Fe-impregnations) producing dark spots in the original white ultra-pure limestones.

A crossplot of whiteness index \( Y \) against gamma-ray values (Fig. 10) shows that with increasing cps amplitudes the whiteness index decreases. Because of the dispersion of the small-scale variations as mentioned above, some scatter is apparent.

In order to even out the small-scale variations in whiteness (measurements taken every 20 cm along cores), an average whiteness index over core intervals that were bulk-sampled for CaO-determinations was calculated. A cross-plot between this average whiteness-index and the measured CaO-content shows a linear relationship (Fig. 11).

### 2.3. Architectural analysis

For the raw materials industry three-dimensional rock geometries (geobodies) are very important for calculating reserve volumes and planning mining operations. Facies associations and their relationships to each other were thus analysed in outcrop studies. In the Upper Jurassic of the Swabian Alb three different geobodies can be distinguished: small- and large-scale biohermal bodies, wedge-like talus bodies and businal bodies, which fill the space between the bioherms (Pawellek, 2001; Pawellek & Aigner, 2003). The best exploration targets for ultra-pure limestones are the large-scale bioherms (Fig. 12; Kimmig et al., 2002; Borel, 2000). Large-scale bioherms have mostly dome-like to conical shapes with a diameter generally more than 100 m up to kilometers and a height up to 120 m (Dietl & Schweigert, 1999; Gwinner, 1958, 1976; Wendt, 1980; Ziegler, 1977). In all scales of bioherms, phases of expansion, retreat and vertical build-up (analogous to progradation, retrogradation and aggradation) can be recognised.

Ultra-pure limestones are found in aggrading and prograding bioherms, while phases of retrogradation mostly include more clay and are thus less attractive industrial targets. In the western Swabian Alb ultra-pure limestones are also found in particle-rich limestones, shed off from the bioherms into the surrounding basins (Borel, 2000). This is stratigraphically limited to the particle-rich limestones of the Malm e.

#### Table 6

<table>
<thead>
<tr>
<th>Facies group</th>
<th>Whiteness index ( Y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-pure limestones</td>
<td>( \Theta = 60–81 ) (max. = 37–85)</td>
</tr>
<tr>
<td>Normal massive limestones</td>
<td>( \Theta = 56–69 ) (max. = 34–85)</td>
</tr>
<tr>
<td>Debris limestones</td>
<td>( \Theta = 53–71 ) (max. = 32–83)</td>
</tr>
<tr>
<td>Well-bedded limestones</td>
<td>( \Theta = 51–61 ) (max. = 33–69)</td>
</tr>
<tr>
<td>Marls and marly limestones</td>
<td>( \Theta = 44–50 ) (max. = 19–67)</td>
</tr>
</tbody>
</table>

---

**Fig. 9.** Whiteness-index \( Y \) frequency distribution of the five major facies groups.

**Fig. 10.** Correlation between whiteness-index \( Y \) and gamma-ray values (data from borehole Ro 7920/B1).
2.4. Sequence analysis

On a regional scale the following facies belts (Fig. 13) can be observed across the studied outer carbonate ramp system (inner ramp not exposed): a zone of thick-bedded particle-rich limestones with stromatolites, followed by a zone of large bioherms and talus deposits, followed by basinal bedded limestones and marls (details see Pawellek Fig. 11. Correlation between whiteness-index \( Y \) and CaO-content, for 13 different wells (abbreviated Ro 7920/B1, Ro 7821/B1, Ro 7821/B2, Ro 7820/B1, Ro 7624/B1, Ro 7624/B2, Ro 7623/B4, Ro 7425/B1, Ro 7525/B1, Ro 7525/B2, Ro 7525/B3, Ro 7525/B4, Ro 7524/B1).

Fig. 11. Correlation between whiteness-index \( Y \) and CaO-content, for 13 different wells (abbreviated Ro 7920/B1, Ro 7821/B1, Ro 7821/B2, Ro 7820/B1, Ro 7624/B1, Ro 7624/B2, Ro 7623/B4, Ro 7425/B1, Ro 7525/B1, Ro 7525/B2, Ro 7525/B3, Ro 7525/B4, Ro 7524/B1).

Fig. 12. Architecture and geometries of facies bodies and sequence hierarchy in the Gerhausen-Altental quarry (located on Fig. 2, number 37). The gamma-ray-log was measured in a borehole which was drilled 10 m behind the quarry wall. This cross-section is characterised by an overall retrogradation of massive limestones building large dome-shaped bioherms. Retrogradation does not happen gradually, but is punctuated by subordinate retro- and progradation steps marked by wedges of bioherm debris and olistoliths. These subordinate steps are controlled by the genetic sequences. In addition, medium-scale sequences with medium-scale retrogradation and progradation can be recognised. The bioherms mostly consists of microbial crusts and sponges. Ultra-pure limestones are limited to the lower dome-like bioherms and disappear in the upper part with increasing retrogradation of the bioherms.
Shallowing and deepening phases would theoretically produce vertical facies successions forming regular cycles (Fig. 13). Cores, logs and outcrops do reveal such reoccurring motifs of vertical facies successions on several scales of cyclicity (Pawellek, 2001; Pawellek & Aigner, 2003). Many of these cycles show symmetrical facies successions that are composed of shallowing-upward and deepening-upward halfcycles, bounded by gradational contacts (turnarounds).

A whole suite of sedimentological, palynological and palaeocological criteria were used to delineate these deepening-upward or shallowing-upward halfcycles (Pawellek, 2001; Pawellek & Aigner, 2003). Each criterion on its own may not indicate variations in waterdepth, but taking several criteria together gives more confidence in the interpretation of trends in relative waterdepth. Variations in the content of ooids, the size, roundness and sorting of all components, the occurrence of sparitic and micritic matrix, the clay content, organism succession, microbialite types and morphology within the cycles are interpreted to reflect variations in hydrodynamic energy most likely related to changes in water depth. An upward increase in ooid content, sparitic matrix, size, roundness and sorting of the components going hand in hand with a decrease in micrite and clay is interpreted as an increase of depositional energy. A reverse increase in micrite and clay and a decrease in ooids, sparitic matrix, roundness and sorting of the components is interpreted to record a decrease in hydrodynamic energy. Changes in content of the marine and continental phytoclasts-ratio helps to substantiate the shallowing-upward or the deepening-upward trends.

Parallel to these sedimentological and palynofacies variations, trends in the biota were observed, especially in the content of siliceous sponges, and in the type and growth habit of microbial crusts. The interpretation of these variations is difficult but provide some clues. According to many authors thrombolites, built mostly by light independent microbes, are most widespread in deeper water zones. Thrombolites are often found in aphotic zones (Dromart, Gaillard, & Jansa, 1994; Herrmann, 1996; Keupp, Jenisch, Herrmann, Neuweiler, & Reitner, 1993; Keupp et al., 1996; Leinfelder, 1993, 1994; Leinfelder Nose, Schmid, & Werner, 1993; Leinfelder et al., 1996; Rehfeld, 1996; Reitner, Wörheide, Thiel, & Gautret 1996;

Cycles with a thickness between four and ten meters can be regionally correlated. They are referred to as ‘genetic sequences’ (cf. Busch, 1971; Cross et al., 1993; Cross & Lessenger, 1998; Frazier, 1974; Galloway, 1989; Galloway & Hobday, 1996; Homewood, Guilloucheau, Eschard, & Cross, 1992; Homewood, Mauriaud, & Lafont, 2000; Sonnenfeld, 1996; Wheeler, 1964). ‘Genetic sequences’ are defined as generally meter-scale elementary stratigraphic cycles which can be regionally correlated and that record phases of shallowing followed by deepening.

Seven different types of genetic sequences have been distinguished in the Upper Jurassic of the Swabian Alb (Pawellek, 2001, Pawellek & Aigner, 2003).

Within genetic sequences ultra-pure limestones are most wide-spread around the zones of maximum depositional energy (maximum relative shallowing) (Fig. 14). When hydrodynamic energy is at the highest clay particles are prevented from setting. Generally, the highest probability for ultra-pure limestones is within the bioherm cycles and within the particle-rich limestone—cycles (Fig. 15).

2.5. Stacking analysis

Commonly several stacked genetic sequences build one medium-scale sequence (Fig. 16, Pawellek, 2001; Pawellek & Aigner, 2003). The thickness of the medium-scale sequence varies between ten and several tens of meters. Several medium-scale sequences form large-scale sequences (Fig. 17). Large-scale cycles are more than 100 m thick. In many cases the gamma-ray log is an useful tool to identify the cycle stacking patterns. Similar stacking patterns became obvious during the outcrop studies.

This stacking pattern controls the overall stratigraphic distribution of ultra-pure limestones (Figs. 15–17). The large-scale shallowing and deepening sequences cause the general expansion or retreat of ultra-pure limestones over the study area.
Fig. 15. Schematic sketch to illustrate the preferred occurrence of ultra-pure limestones within sequences. Generally the best quality and the widest distribution of ultra-pure limestones occur in stratigraphic positions with maximum depositional energy, i.e. relative shallowing.
2.6. Basin analysis

The general basin-fill architecture of the Upper Jurassic of the Swabian Alb based on regional log-correlation shows that depo-centers migrate through time from West to East (Fig. 18, Pawellek & Aigner, 2003). In Malm δ₁–₃ the depo-center is located in the western Swabian Alb. In Malm δ₄ and lower Malm ε the depositional center migrates to the East and in upper Malm ε and Malm ζ the depo-center reaches the Eastern Swabian Alb. As mentioned above, the ultra-pure limestone facies group consists mostly of biohermal or near biohermal facies types (stromatolites, stromatolites/thrombolites, particle-rich sponge limestones, coral debris limestones). The particle-rich limestones, not restricted to bioherms, migrate as a separate ‘facies belt’ from West to East behind the bioherms.
Based on these observations, the following stratigraphic and paleogeographic distribution of ultra-pure limestones is apparent:

1. The first ultra-pure limestones (in biohermal facies) appear within Malm d3 on the western Swabian Alb.
2. Within Malm d4 and Malm e ultra-pure limestones are most wide-spread. They can be found on the western Swabian Alb (mostly in particle-rich limestone facies) as well as on the middle and eastern Swabian Alb (in biohermal and/or in particle-rich limestone facies).
3. Ultra-pure limestones disappear in the western, middle and eastern Swabian Alb at different times. On the western Swabian Alb no ultra-pure limestones can be found above Malm e. On the middle Swabian Alb ultra-pure limestones reach the Malm e/Malm ξ boundary, and on the eastern Swabian Alb ultra-pure limestones can still found in Malm ξ1 (in biohermal facies).
4. Above Malm ξ1 no ultra-pure limestones appear in the area of the Swabian Alb.

3. Conclusions

1. Upper Jurassic carbonates of the Swabian Alb reflect the deeper parts of an epicontinental carbonate ramp. Along this ramp system a variety of micro-facies types could be distinguished. Due to their different components, their chemical composition, gamma-ray signatures and whiteness, their economic potential is highly variable. The hierarchical, process-based approach of ‘dynamic stratigraphy’ provides a framework for understanding the occurrence of ultra-pure limestones resources on various scales.
2. The micro-facies types could be grouped into five groups (ultra-pure limestones, ‘normal’ massive limestones, debris limestones, well bedded limestones, marls and marly limestones) with similar physical and chemical properties. Stromatolites, stromatolites/thrombolites, particle-rich limestones, particle-rich sponge limestones and coral debris limestones make up the economically most important facies class containing ultra-pure limestones.
3. In each main facies group, gamma-ray values, carbonate content and the whiteness index show close relationships. Because of that, gamma-ray logs are a useful tool for quality estimations on their economic potential.
4. The facies types build the following characteristic types of geobodies: (a) lens-like, conical, pillar-shaped or dome-like bioherms, (b) wedge-shaped talus bodies and (c) basin-fill bodies, which fill the space between bioherms. Ultra-pure limestones occur mostly in biohermal dome-like geobodies. Particle-rich limestones, however, build sheet-like or wedge-shape geobodies.
5. Stratigraphically, distinct sedimentary cycles (‘genetic sequences’) could be recognised. These genetic sequences record variations in depositional energy, most likely related to changes in waterdepth. Ultra-pure limestones are most widespread in relatively high-energy facies types.
6. Stacks of several genetic sequences build medium- and large-scale sequences. This stacking controls...
Fig. 18. West-East stratigraphic cross-section through the study area of the Swabian Alb. Ultra-pure limestone-bearing depositional centers can be observed, which migrate from the Malm d to the Malm e from West to East. Well numbers refer to Figs. 2 and 3a and b.
the regional stratigraphic distribution of ultra-pure limestones. Overall shallowing leads to an expansion of ultra-pure limestones, while overall deepening leads to their general disappearance.

(7) A basin-wide stratigraphic cross-section based on borehole data reveals the migration of ultra-pure limestone bearing facies belts and a very low-angle progradation to the East. Within the study area, ultra-pure limestones are limited to the stratigraphic section between Malm 3 and Malm 4.

4. Uncited reference


Acknowledgements


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