FACIES	35	105-132	Pl. 26-32	12 Figs.	--	ERLANGEN 1996

Zechstein 2 Carbonate Platform Subfacies and Grain-Type Distribution (Upper Permian, Northwest Germany)

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KEYWORDS: CARBONATE COMPONENTS - CARBONATE PLATFORM - CARBONATE FACIES - DEPOSITIONAL ENVIRONMENT - SEQUENCE STRATIGRAPHY - POROSITY DISTRIBUTION - UPPER PERMIAN (ZECHSTEIN 2)

SUMMARY

The Upper Permian Zechstein 2 Carbonate (Stassfurt Carbonate, or Ca2) platform facies of Northwest Germany can be subdivided into twelve subfacies types using slabbed cores from fifteen representative wells. Thin section and scanning microscopic analysis further provide subfacies-specific characteristics, based on distribution, size, shape, and spatial arrangement of the grains contained in the different subfacies types. Thirteen grain types can be distinguished within the different subfacies types on the Ca2-platform: 1) one type of oncoid, 2) one type of grapestone, 3) three types of peloids, 4) four types of ooids and 5) four types of aggregate grains. Both presence and composition of grains are indicative of the different subfacies types. There is also a relation between grain composition and porosity of the Ca2-subfacies types. The size and quantity of ooids correlate positively with increasing porosity, whereas an increasing amount of algal structures (algal-lamination) correlates negatively with porosity.

The Ca2-platform carbonates almost exclusively represent highstand systems tract and lowstand systems tract deposits. The presence or absence of type-3 aggregate grains within the grainy shoal and algal-laminated shoal subfacies allows the assignment of these subfacies to highstand (grains absent) or lowstand (grains present) systems tracts deposits. The Ca2-highstand deposits can be subdivided into four shallowing-upward parasequences (PS3 to PS7) bounded by parasequence boundaries (PSB3 to PSB6) and Zechstein sequence boundary ZSB4.

In contrast to macroscopic core studies, microscopic studies to identify Ca2-subfacies types can utilize cutting material. This allows reconstruction of the subfacies distribution on the Ca2-platform, and delineation of potentially porous zones in uncored Ca2 intervals.

INTRODUCTION

In Northwest Germany (Fig. 1), important commercial gas accumulations are found in the Upper Permian Zechstein 2 Carbonate (Stassfurt Carbonate, or Ca2) of the second Zechstein cycle (Stassfurt cycle, or Z2; Fig. 2).

The reservoir rocks are underlain by the Werra Anhydrite (A1) of the first Zechstein cycle (Werra cycle, or Z1) and sealed by the Basal Anhydrite (A2) of the second Zechstein cycle. Welllogs and core analyses show that Ca2 thickness and facies distribution are related to the thickness distribution of the underlying Werra Anhydrite and the overlying Basal Anhydrite. Relatively thin (20 to 80m), dolomitized Ca2-platform facies occur where the A1 sulfate platform is thick (up to approx. 300m). Thick (100 to 250m) upper slope facies and middle slope facies lie basinward of an abrupt decrease of A1 thickness from 300m to less than 100m, but platformward of an abrupt thinning of the A2 from approximately 100m to less than 10m. Dominantly lower slope facies (thickness: 100m to 10m), often containing thin, centimeter-thick intercalations of turbidites, and basinal facies overlie thin A1 anhydrites (thickness: less than 50m) basinward of the steep A2-slope (Fig. 3).

In order to better predict Ca2-reservoir facies distribution a depositional model as well as a sequence stratigraphic framework has been developed (Strohmenger et al., 1993a, 1993b, 1996b; Fig. 2).

By studying 974 thin sections and using scanning electron microscopy (SEM), a component analysis was conducted to evaluate the total spectrum of Ca2-platform grain types and to test the usefullness of grain types in predicting subfacies types.

The aim of the present study is to demonstrate the relationship between grain type, subfacies, and porosity distribution on the Ca2-platform, as well as the influence of intra-Ca2 sea-level fluctuations on distribution of both grains and porosity.

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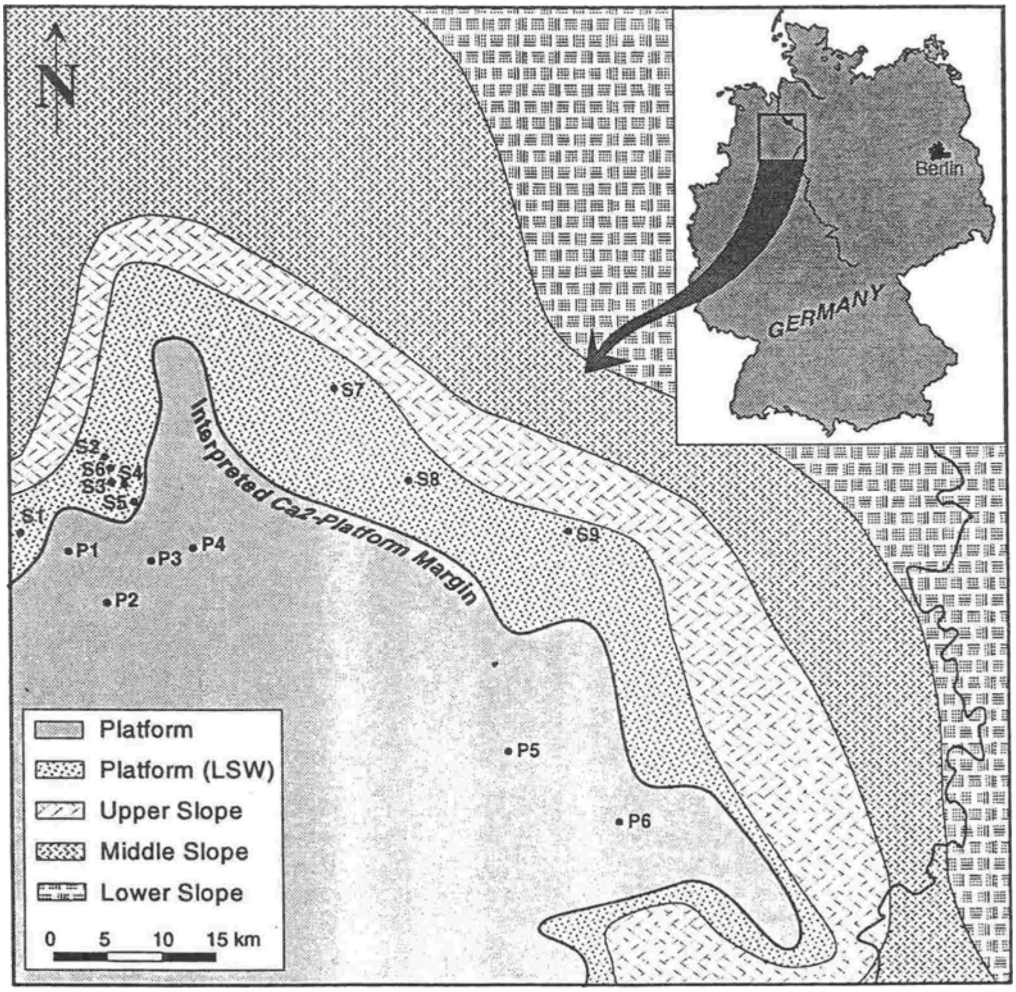


Fig. 1. Location of studied wells (P1 to P6 and S1 to S9). Also shown is the uppermost Zechstein 2 Carbonate (Ca2) facies distribution.

GRAIN-TYPE ANALYSIS OF CA2-PLATFORM FACIES

The platform facies (Main Dolomite) of the Zechstein 2 Carbonate is mainly characterized by peloids and a variety of coated grains (STEINHOFF, 1994; STEINHOFF & STROHMENGER, 1995, 1996). Using thin section and scanning electron microscope (SEM) data, three types of peloids can be distinguished. The coated grains comprise a more complex group of components, consisting of ooids, oncoids, grapestones, and aggregate grains. These four major types of coated grains show various internal structures that led to a subdivision of four types of ooids, four types of aggregates and a single type of oncoid and grapestone. The different internal structures of the components, observed in both highstand and lowstand systems tract deposits, are described in the following section. The development of the different subfacies-specific grain types, as well as commonly observed transitions from one type to another, are briefly discussed and shown on Plates 28 to 32.

Plate 26 — Core slabs of subfacies types of the Ca2-platform facies (Upper Permian, Zechstein 2, Northwest Germany). - Scale for all Figs.: 5 cm

Fig. 1. Supratidal sabkha subfacies evolving from algal tidal-flat subfacies, strongly overprinted by anhydrite-after-gypsum growth. The anhydrite nodules (nodular to chicken-wire anhydrite) grew displacively after the sediment settled but before final lithification. Well S2

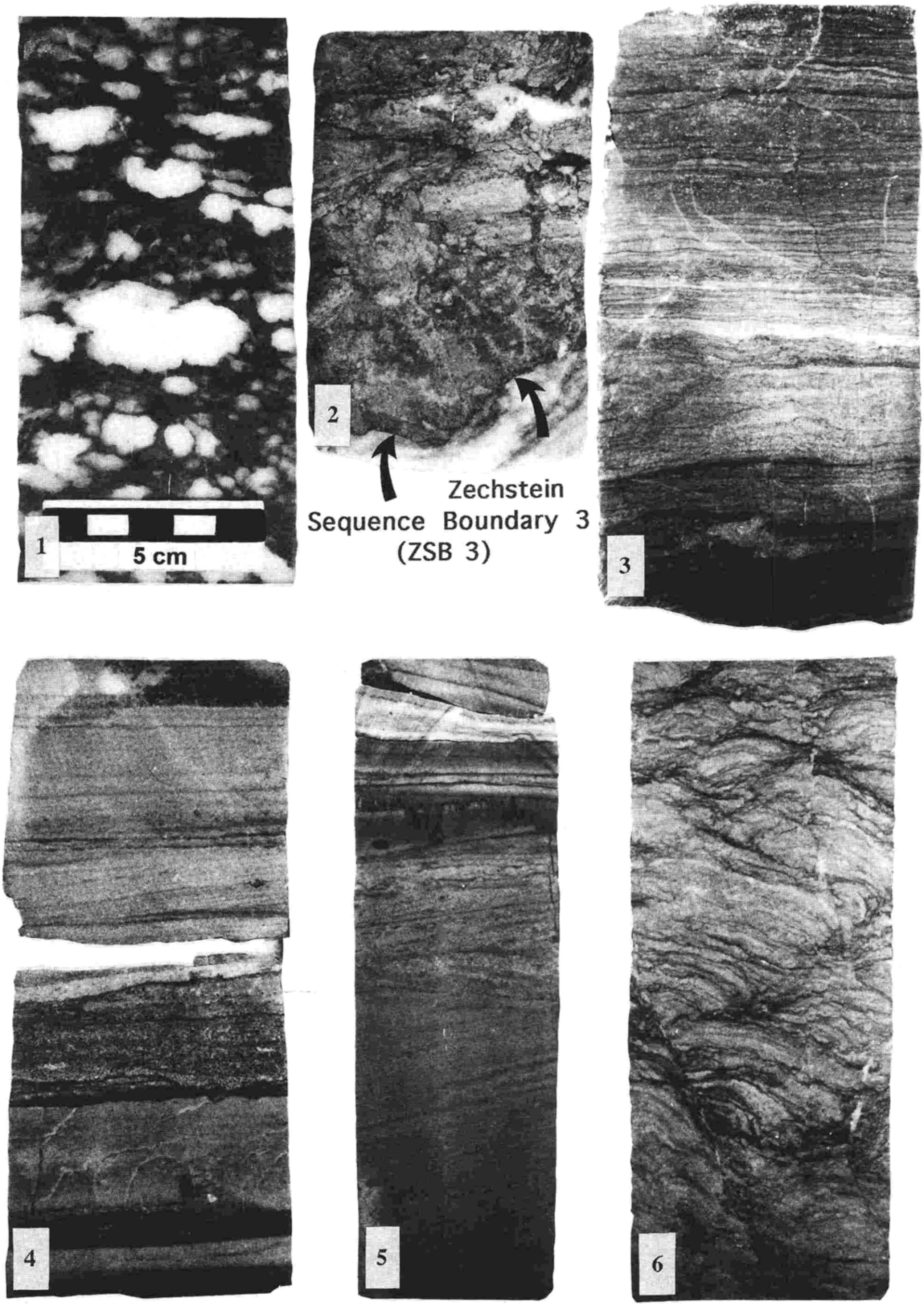
Fig. 2. Transgressive deposit subfacies. Grainstone containing intraclasts that commonly consist of reworked anhydrite material, derived from the underlying Werra Anhydrite (A1). Highly erosive surface at top of Werra Anhydrite (arrow) corresponds to Zechstein sequence boundary ZSB3. Well P2

Fig. 3. Mudstone-dominated algal tidal-flat subfacies, showing crinkled-bedding due to algal growth. Anhydritization of the sediment (compare Pl. 28/3) is quite common and significantly reduces porosity. Well P3

Fig. 4. Tidal-flat subfacies, displaying typically alternating lithofacies. Mudstone (lower part) is overlain by packstone/grainstone interpreted as storm deposits (upper part). Well S2

Fig. 5. Pelletal tidal-flat subfacies with characteristic swash cross-bedding sets. Well S2

Fig. 6. Algal-laminated shoal subfacies. The algal laminae appear as dark and crinkled lamination. Well P4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(ZSB 3)
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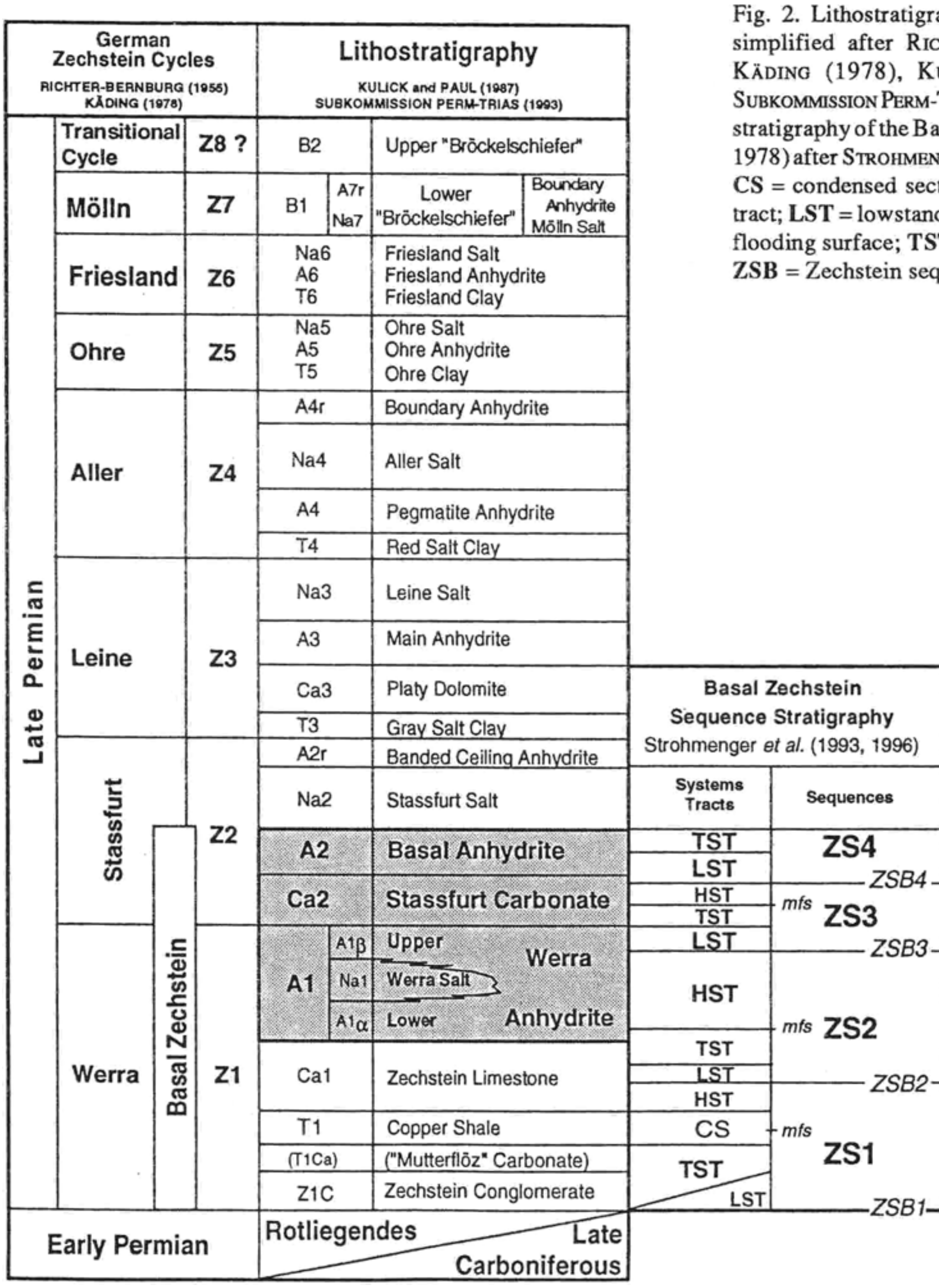


Fig. 2. Lithostratigraphy of the German Zechstein simplified after Richter-Bernburg (1955, 1987), Käding (1978), Kulick & Paul (1987), and Subkommission Perm-Trias (1993). Zechstein sequence stratigraphy of the Basal Zechstein (Sannemann et al., 1978) after Strohmenger et al. (1993a, 1996a, 1996b). CS = condensed section; **HST** = highstand systems tract; **LST** = lowstand systems tract; **mfs** = maximum flooding surface; **TST** = transgressive systems tract; **ZSB** = Zechstein sequence boundary).

Plate 27 — Core slabs of subfacies types of the Ca2-platform facies (Upper Permian, Zechstein 2, Northwest Germany). - Scale for all Figs.: 5 cm

Fig. 1. Protected lagoonal mudstone showing diffuse dark lamination. Well S1

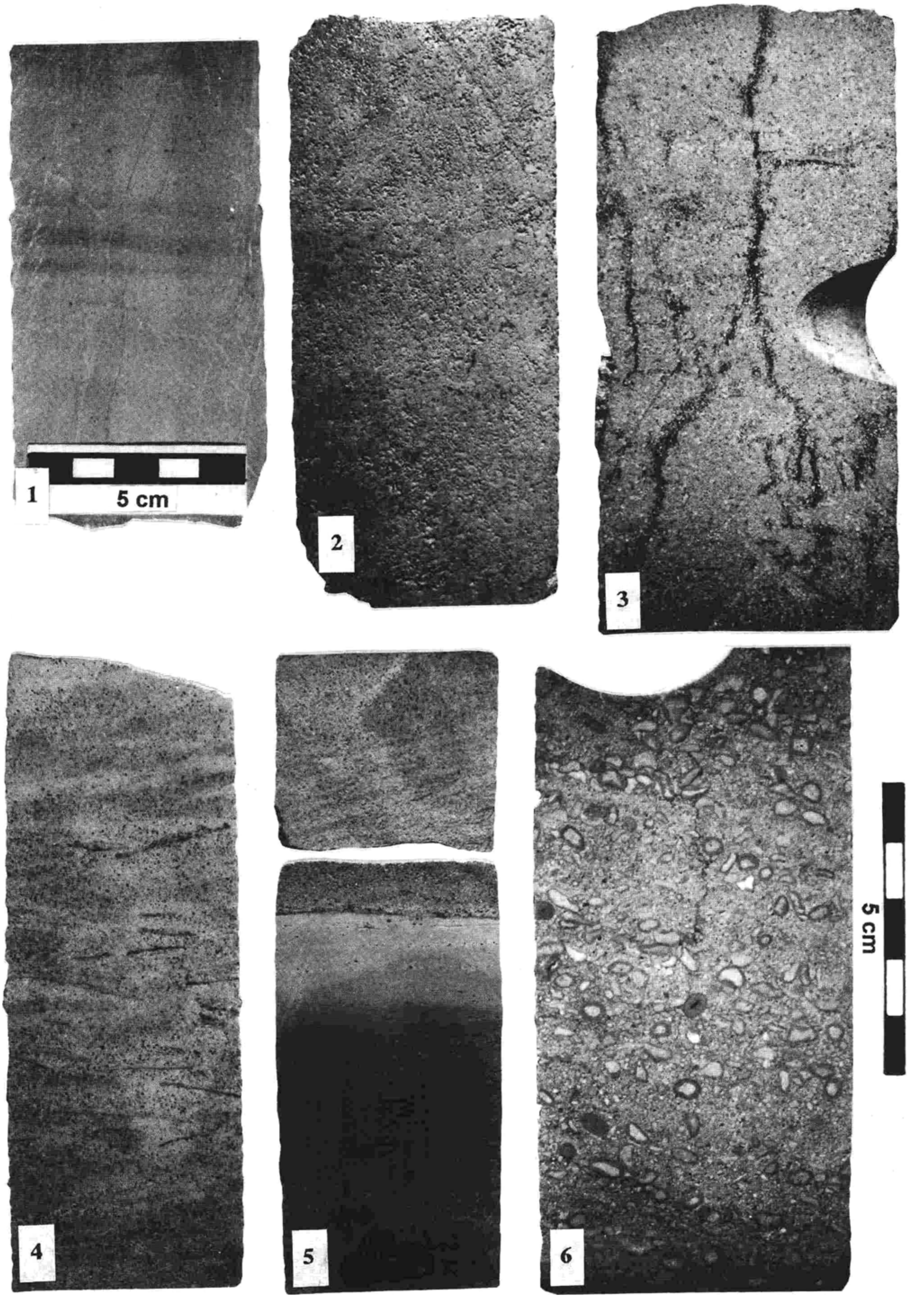
Fig. 2. Grainy shoal subfacies displaying massive-bedding. Well S8

Fig. 3. Ooid shoal subfacies. Ooids are already recognizable macroscopically. Due to micritization the ooids appear whitish in contrast to the slightly darker matrix. The molds appear as dark dots surrounded by the brighter coatings. Well S3

Fig. 4. Ooid bar subfacies showing swash cross-stratification (uppermost and lowermost part), as well as small-scale trough cross-stratification (mid) usually seen in migrating current ripples. Retransported previously lithified (algal) rip up clasts (dark) are confined to the trough cross-bedded sequence. Well S2

Fig. 5. Ooid bar with intercalated muddy ooid inter-bar subfacies. Note the gradual transition of ooid-bearing deposits to muddy sedimentation at the base of the inter-bar in contrast to the erosive contact between mud and the younger conspicuously swash cross-bedded oolite on top. During mud sedimentation ooids of the ooid bar subfacies sporadically became laterally spilled into the inter-bar environment. Well S2

Fig. 6. Beach deposit showing oblique beach-lamination and quite large ooids that are commonly oncoid-like overprinted. Well P5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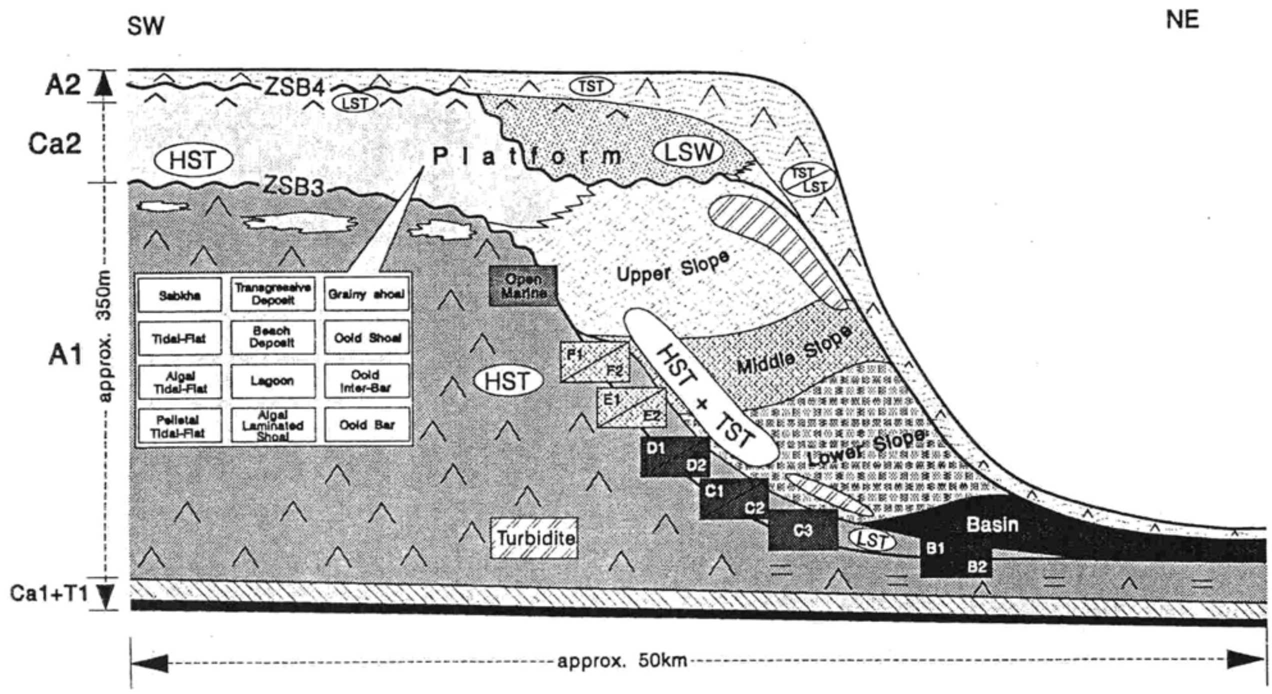


Fig. 3. Schematic sketch of the Zechstein 2 Carbonate (Ca2) facies and subfacies distribution in relation to the underlying paleo-relief formed by the Werra Anhydrite (A1). Also shown is the overlying (sealing) Basal Anhydrite (A2). The Zechstein Limestone (Ca1) and the underlying Copper Shale (T1) are both too thin and uniform in thickness to have any influence on the depositional development of the Zechstein 2 Carbonate. Modified after STROHMENGER et al., 1993b, 1996b. Abbreviations see Fig. 2.

PELOIDS

Peloids (MC KEE & GUTSCHICK, 1969) are rounded to well rounded, spherical to elliptical grains without an internal structure, and characteristically smaller than other components of the same sample. Often their origin remains uncertain. The variety of grain types described by the term peloid is discussed in FLÜGEL (1978, 1982).

Three types of peloids that are more or less subfacies-diagnostic can be distinguished within the platform sediments of the Ca2. Furthermore the ratio of well rounded spherical peloid types (type-1 and -3) to subrounded to angular grains without internal structure (type-2) is useful to identify subfacies types. Intergranular and moldic as well as intercrystalline porosities can simultaneously occur in rocks that are built up of different amounts of peloids (Pl. 31/2-4, and Pl. 32/1)

Type-1 Peloids (Pellets)

These peloids are characteristically well rounded and have an average diameter of approximately 0.1mm, varying between 0.03 and 0.2mm. They display no internal structure (Pl. 29/2). Their origin as biogenic excrements of benthic organisms, such as crustaceans, bivalves, polychaetes and others, is uncertain because remains of organisms are ex-

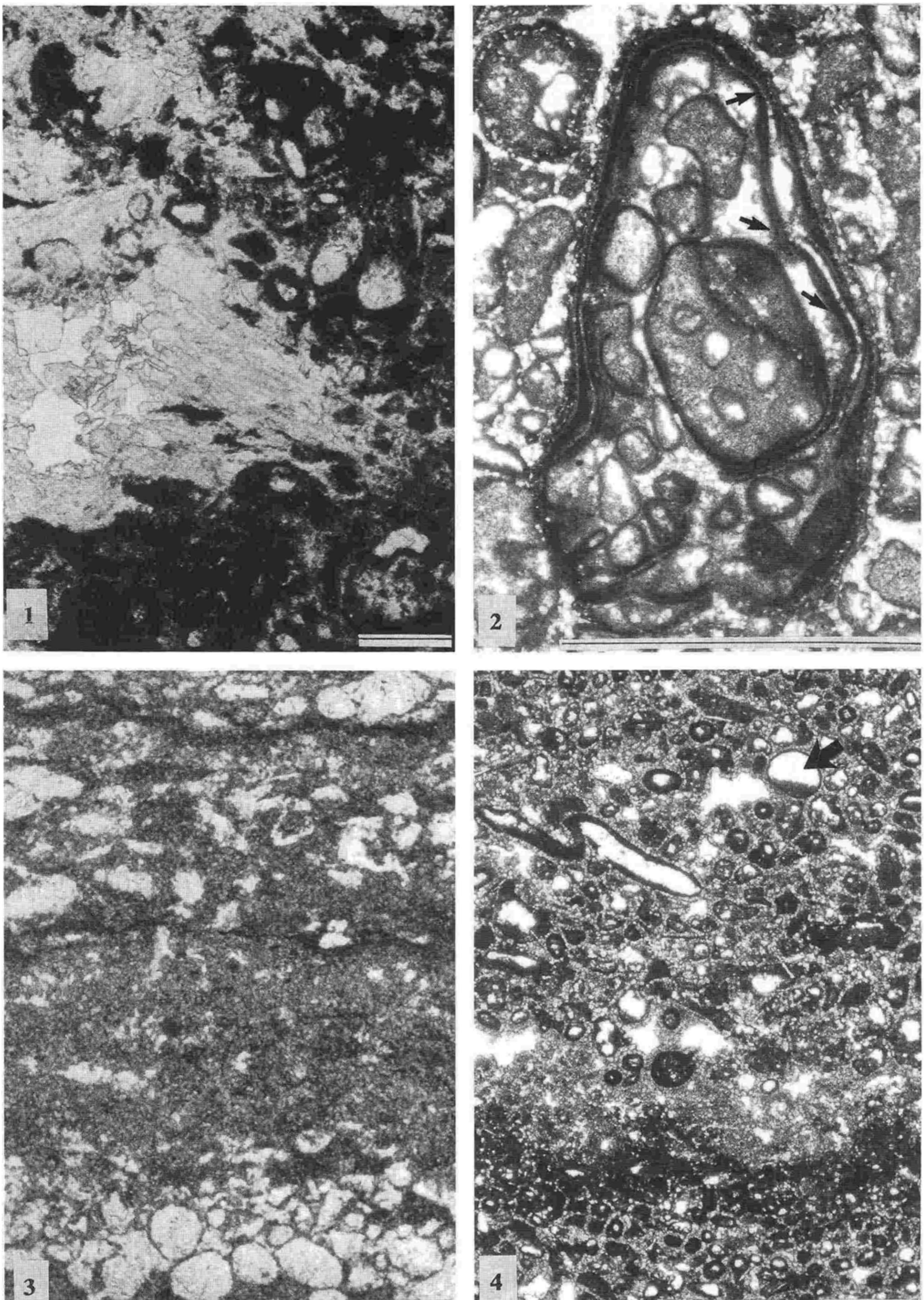
Plate 28 Grain types and grain distribution of the Ca2-platform subfacies types (Upper Permian, Zechstein 2, Northwest Germany). - Scale bar for all Figs.: 0.5 mm

Fig. 1. Typical Ca2-sabkha subfacies. A primary carbonate pack-/grainstone has been displaced/replaced by anhydrite-after-gypsum mineralogy. The latter grew after the sediment was deposited and already partially to wholly lithified. Well S2

Fig. 2. Aggregate grain (type-4 aggregate) containing angular to subangular particles and a carbonate lump. Some coatings of the lump are split off the nucleus and now incorporated withinyounger coatings of the entire aggregate (arrows). This feature indicates a marine vadose environment of origin (compare with Figure 5). Thus, sedimentation under intertidal conditions is inferred. Later, the whole aggregate grain was coated by younger cortices. Well P2

Fig. 3. Succession of an intensely anhydritized algal tidal-flat subfacies. Meteoric fluids apparently caused dissolution of the grains before the blocky- to lath-shaped anhydrite refilled the component molds, thus, protecting them from collapse. Depositional texture is conspicuously varying at thin section scale. Well P1

Fig. 4. Algal tidal-flat succession of different depositional textures and grain types. Geopetal fabric is developed within an ooid mold (arrow). Well P6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tremely rare in the Ca2 of Northwest Germany. TUCKER (1981), TUCKER & WRIGHT (1990), and FLÜGEL (1992) discuss other, partially abiotic, types of pellet formation that also could have formed these grains in the depositional setting of the Ca2. The intensity of rounding of this grain type within the Zechstein 2 Carbonate is between 4 and 5 after PETTIJOHN et al. (1973), and the grains display high sphericity. Components of this type occur most commonly in the pelletal tidal-flat subfacies, but can also be present in adjacent subfacies types.

Type-2 Peloids

These peloids are about 0.04 mm to 1.2 mm in diameter, and have subrounded to more angular shapes (Pl. 30/2). All irregular-shaped grains without an internal structure are grouped with this peloid type. Obviously the origin of type-2 peloids differs from that of type-1 and -3 peloids. Type-2 peloids are interpreted to represent recrystallized intraclasts described as pseudopeloids (FAHRAEUS et al. 1974) and/or lumps (ILLING 1954). The intensity of rounding varies between 0 and 3 after PETTIJOHN et al. (1973). The grains usually developed low sphericity. The grains of this type occur throughout the platform and are therefore contained in every facies type, although in differing abundances.

Type-3 Peloids

Peloids of type-3 are usually rounded to well rounded (Pl. 30/2). The size differs between 0.2 mm and 0.9 mm with an average of approximately 0.4 mm. All peloids larger than 0.4 mm have almost always been observed only in ooid shoals or ooid bearing sediments of the Ca2. For these types of grains, BLATT et al. (1972) proposed the term pelletoid. They are inferred to have formed due to recrystallization of ooids that are characteristically larger than type-3 peloids. The degree of rounding is nearly constant at a level of 5 after PETTIJOHN et al. (1973), and the sphericity is high. Their distribution is about the same as type-2 peloids, although they are much more common in ooid shoal sediments.

COATED GRAINS

Within the majority of Ca2-platform subfacies different types of coated grains such as oncoids, ooids, grapestones, and aggregate grains occur. The distinction of oncoids and ooids often is equivocal because the grain types grade one into the other. Such transition may have evolved due to early compaction of ooids, like spastolites (PETTIJOHN, 1957), or by the quite concentric ooid-like primary fabric of oncoids (STRASSER, 1986). Intragrain porosity of the coated grains is highly variable. Besides molds and intercrystalline porosity, inter-grain as well as an intra-coating porosity can be observed (Pl. 31/1 and Pl. 32). Compaction pressure commonly causes fracturing of the already lithified coated grains, especially in ooid bar subfacies.

ONCOIDS

Carbonate grains with irregular-shaped micritic coatings that are not concentrically orientated around the core, but pinch out laterally, are usually referred to as oncoids. The layered fabric is considered as biogenic in origin, developing while the grains where moved and rotated sporadically. Oncoids originate in marine (shallow subtidal and intertidal) as well as freshwater (lacustrine and fluvial) environments (PERYT, 1983).

The diameters of the oncoids range between 0.5mm and 1.6 mm. Within the Ca2, oncoids are confined to intertidal environments and adjacent subfacies (Pl. 29/1). A special kind of oncoid is recognized within the grainy shoal subfacies in the eastern part of the study area, where type-2 peloids and lumps form the nuclei of the oncoids; previously described as "Algenbeutel" by FÜCHTBAUER (1964; Pl. 32/1). The origin of rarely observed oncoids within the ooid bar subfacies is uncertain, as these components could also be interpreted as spastolites or distorted ooids (CAROZZI, 1961). Therefore oncoids can easily be confused with ooids and thus are not considered as reliable facies indicators. The thickness of the oncoid-type cortex complexes varies between 0.03mm and 0.35mm, while the number of coatings ranges from 1 to 17.

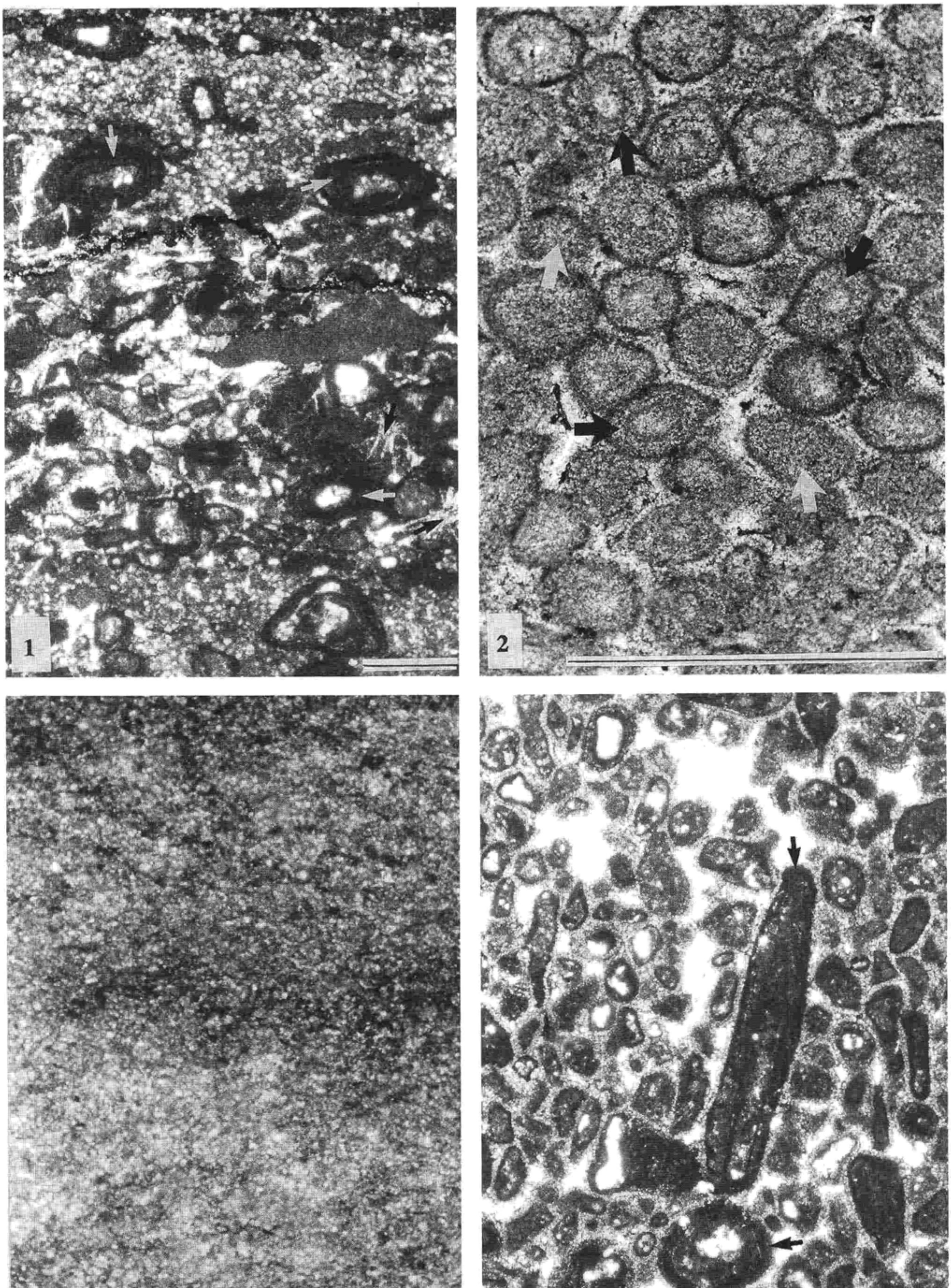
Plate 29 Grain types and grain distribution of the Ca2-platform subfacies types (Upper Permian, Zechstein 2, Northwest Germany). - Scale bar for all Figs.: 0.5 mm

Fig. 1. Bedded structure of tidal-flat subfacies which contains pellets (lowermost part), peloids, ooids, mud intraclasts, and oncoids. Oncoids (white arrows) and gypsum pseudomorphs (black arrows) characteristically occur within Ca2 intertidal environments. Well S2

Fig. 2. Pelletal tidal-flat grainstone. Characteristically single-coated micro-ooids (type-1 ooids, black arrows) and small peloids (type-1 peloids, white arrows) constitute this subfacies type. Due to presence of isopachous cement framing the grains a first lithification under marine phreatic conditions is inferred. Well P2

Fig. 3. Diffusely laminated lagoonal mudstone. No grains are present. Well S1

Fig. 4. Inequigranular algal-laminated packstone, showing irregularly orientated components of subfacies types of higher water energies (arrows, a type-3 ooid at a deeper position and a type-1 aggregate above the ooid). Mud has been winnowed out. A first cement generation is inferred to have formed in a marine phreatic environment. Well P6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GRAPESTONES

Grapestones (Illing, 1954) are described as a special type of composite grain or aggregate grain, built up by intracomponents, resembling a tiny bunch of grapes in spatial arrangement as well as in morphology. Illing (1954) introduced the terms "compound ooids" and "botryoidal lumps" for this type of coated grapestone, which is interpreted to form in environments where ooid grainstones usually form. Purser (1980) considers coated aggregates as a kind of ooid, which Carozzi (1960) describes as "superficial ooids" with a composite grain as core. Within the Ca2-platform facies, the diameter of the grapestones varies between 0.35 mm and 2 mm. They commonly include fewer than five intra-components and rarely display a small amount of micrite. The 1 to 13 cortices form a coating layer all around the nucleus of about 0.03mm to 0.25 mm in thickness. There are significantly fewer coatings on grapestones as on ooids of the same sample (Pl. 30/2). The thickness and shape of the coatings depend on the shape of the nuclei. Grapestones are seen in different shoal subfacies types as well as in ooid bar and transgressive-deposit subfacies of the Ca2-platform.

OOIDS

Ooids (Kalkowsky, 1908; Simone, 1981; Richter, 1983) usually are regularly shaped, well-rounded components with concentric coatings around a core or nucleus. Four types of ooids distinguishable by means of size, shape, and core diameter versus cortex-complex thickness-ratio, are observed in Ca2-platform facies.

Due to dolomitization the previous mineralogy of the ooids cannot be inferred unequivocally. The concentric internal structure of the ooids, however, favors the interpretation that their primary mineralogy was aragonite (Sandberg, 1975; Richter, 1983; Strasser, 1986). The measurement of the preserved dolomitic cortical thicknesses can only be made by SEM analysis (Pl. 31/1 and Pl. 32/2, 3). A comparison of facies-significant data is shown in Figure 4.

Type-1 Ooids

Type-1 ooids (micro-ooids) have an average diameter of approximately 0.1 mm, varying between 0.07 mm and 0.2 mm. They usually display only one coating, but rarely show up to three coatings. The thickness of the cortex complex ranges from 0.03mm to 0.035mm. Type-1 ooids are indicative of the pelletal tidal-flat subfacies (Pl. 29/2 and Pl. 31/1).

Type-2 Ooids

This type of ooid is mainly seen in the eastern part of the study area. The diameter of type-2 ooids ranges between 0.1 mm and 0.4 mm. The average thickness is approximately 0.2 mm. The thickness of the cortex complex ranges between 0.04 mm and 0.1mm and characteristically consists of two coatings, although ooids with up to six coatings occur rarely. The structural fabric of type-2 ooids suggests that they are reworked type-1 ooids in a more highly agitated environment (Strasser, 1986). Most commonly these ooids are observed in the grainy-shoal subfacies type, grading into pelletal tidal-flat subfacies (Pl. 30/1).

Type-3 Ooids

Characteristically, type-3 ooids (Pl. 29/4 and Pl. 30/2) have more coatings than type-1 and -2 (from 2 to 13 coatings with an average of 7). In comparison to ooids of type-1 and -2, the average thickness of the coatings is greater, ranging between 0.05 mm and 0.3 mm. In the range between 0.1 mm and 0.9 mm the most commonly observed size of the ooids is approximately 0.4 mm. Although some variation exists, the nucleus diameter to cortex-complex thickness-ratio is significantly higher in type-3 ooids (about 1 and higher) than in type-4 ooids (usually significantly less than 1) (Pl. 30/2-3 and Pl. 32/2).

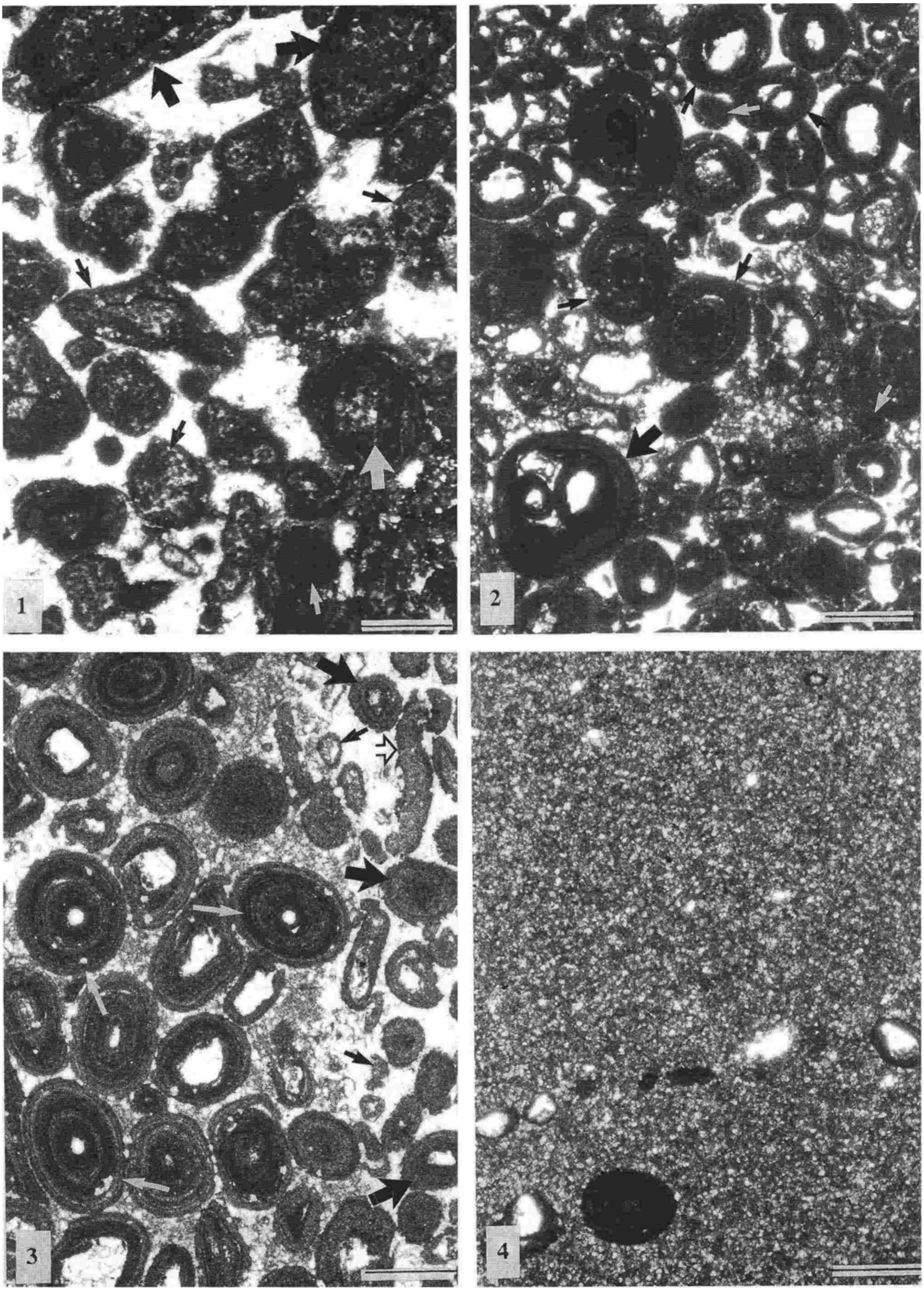
Plate 30 Grain types and grain distribution of the Ca2-platform subfacies types (Upper Permian, Zechstein 2, Northwest Germany). - Scale bar for all Figs.: 5 mm

Fig. 1. "Bioconsolidated" grainy shoal sediment of Ca2-lowstand wedge, predominantly consisting of angular and subangular components of different origin. All grain types (lumps, small black arrows; aggregates, large black arrows; ooids, small white arrow; and oncoids, large white arrow) are more or less intensely micritized (darker rims of the components). Well S8

Fig. 2. Ooid shoal sediment in which all the characteristic component types are contained: type-3 ooids (small black arrows), type-3 peloids (white arrows), and type-1 grapestone (large black arrow). Characteristically, there are more (well)rounded peloids (type-3) than subrounded to angular ones (type-2). Well S3

Fig. 3. Alternation of oo-pelsparite (right) and oomicrite (left). While the latter is consistent with an almost monomict type-4 ooid (white arrows) content and muddy portions between the grains, the oo-pelsparite bears relatively small ooids of more irregular shapes (large black arrows), peloids (small black arrows), and mudclasts (type-2 aggregates; e.g. open black arrow). Due to postsedimentary stresses some ooids became fractured (within the oomicrite). Well P2

Fig. 4. Ooid inter-bar sediment consisting chiefly of carbonate mud. Some peloids and ooids were laterally transported and are arranged along the former depositional surface. Well S5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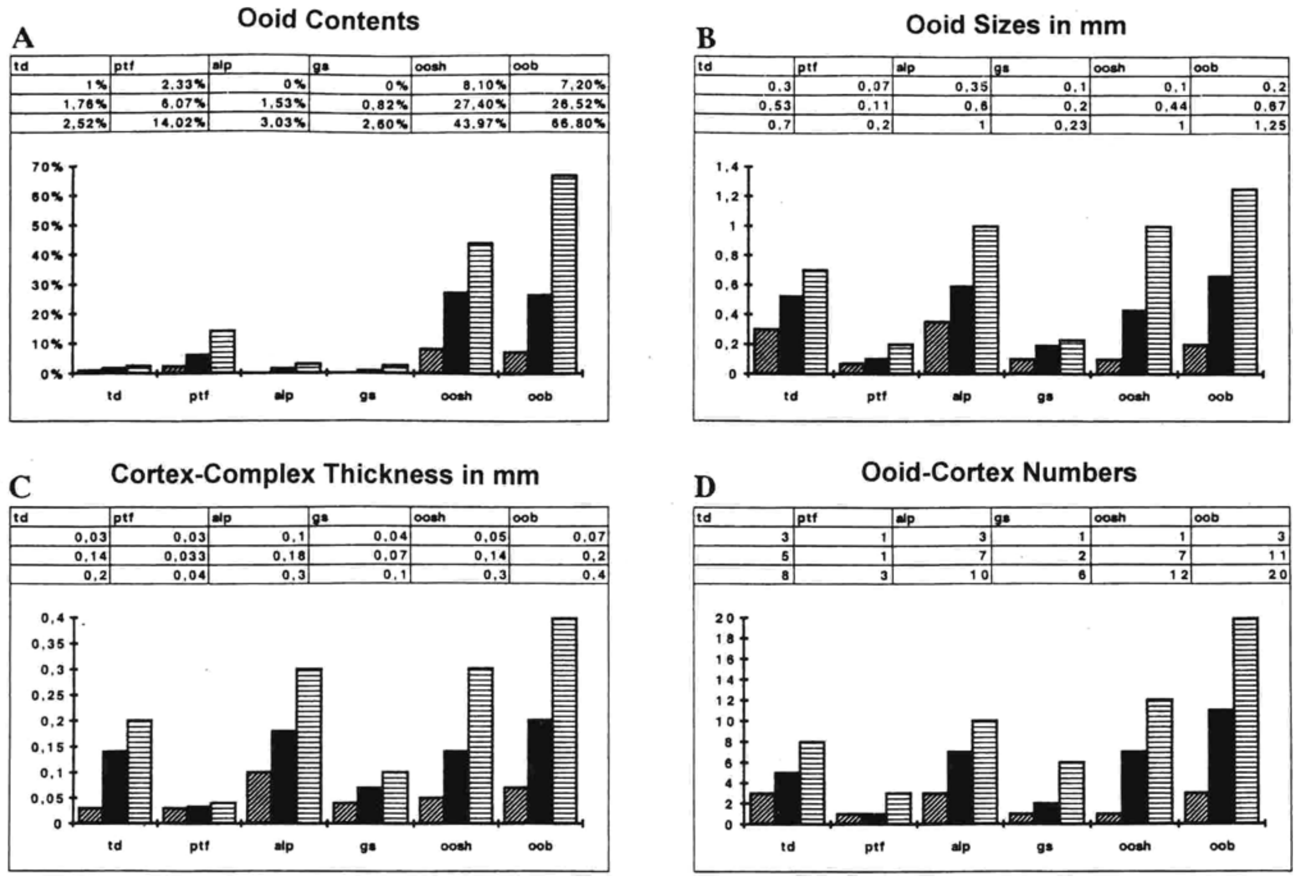


Fig. 4. Ooid data derived from thin section investigations. The histograms show the amount of ooids observed within the different subfacies types in percent as revealed by point counting. The minimum, the average, and the maximum value of the considered feature are shown by three different columns from left to right. Abbreviations are: **alp** = algal-laminated shoal, **gs** = grainy shoal, **oob** = ooid bar, **oosh** = ooid shoal, **ptf** = pelletal tidal-flat, **td** = transgressive deposit.

Type-3 ooids very often display micritic rims or are totally micritized. The intensity of micritization and/or (dolo)recrystallization commonly differs within the cortical complexes. Increasing crystal size causes increasing brightness under the microscope. Macroscopically, the brightness of the ooids behaves in the opposite manner; thus, they appear whitish against the commonly sparitic matrix on slabbed cores (Pl. 27/3). The (superficial) micritization is interpreted to be caused by microbial boring activity during sedimentation (Bathurst, 1966; Margolis & Rex, 1971; Kobluk & Rist, 1977) while the thicknesses of the micritic envelopes reflect the time period (shorter to longer) of interruption of ooid growth.

Type-3 ooids may show pitted contacts (Radwanski, 1965; Radwanski & Birkenmajer, 1977) that generated due to meteoric dissolution caused by seeping freshwater (Clark, 1980). Overpacking was only rarely observed. Carozzi (1960) interprets pitted ooids as a result of early compaction of the sediment. In several oolites of the study area, compressed or broken ooids, sometimes with spalled coatings, do occur, favoring the interpretation of early compaction (Carozzi, 1960, 1961; Wilkinson & Landing, 1978; Wilkinson

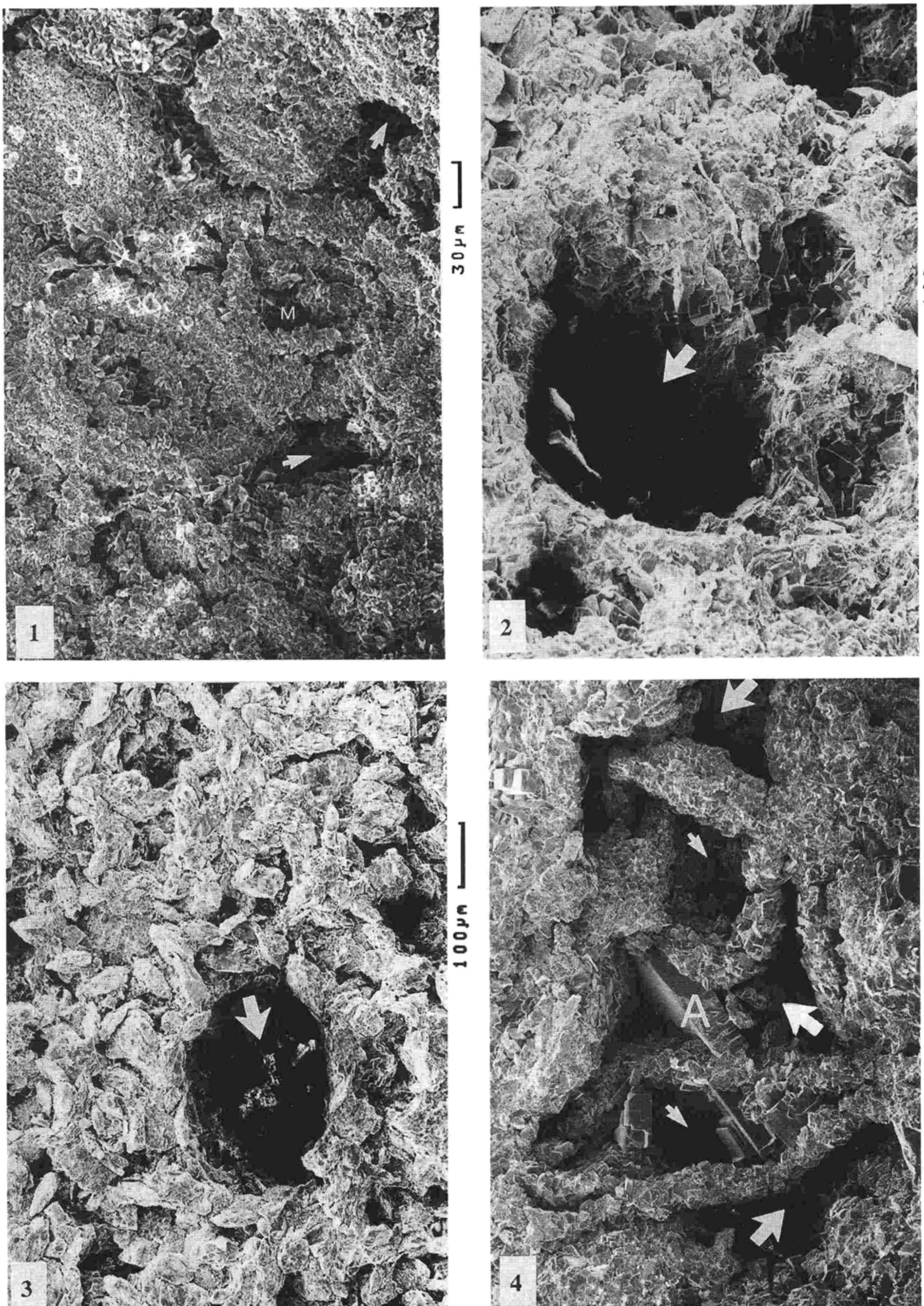
Plate 31 Pore-space development within the Ca2-platform subfacies types (Upper Permian, Zechstein 2, Northwest Germany)

Fig. 1. Two micro-ooids (type-1 ooids) of the pelletal tidal-flat subfacies (middle) displaying both intergranular (white arrows) and moldic (M) porosities. Intracortical porosity is obvious as well (black arrows). Well P5

Fig. 2. Algal-laminated shoal sediment showing component mold (arrow) in a monotonous and rather tight matrix of dolomite rhombs. Well P3

Fig. 3. Component mold (arrow) surrounded by predominantly muddy matrix (algal-laminated shoal subfacies). Relatively high intercrystalline porosity is developed between the dolomitic rhombohedrons. Well P3

Fig. 4. Two components of the grainy shoal subfacies. Moldic (small arrows) as well as intergranular (large arrows) porosity is developed. Anhydrite crystals (A) were growing independently from each other within the molds. Well P4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et al., 1984; RADWANSKI & BIRKENMAJER, 1977; BHATTACHARYYA & FRIEDMAN 1979,1984; PERYT, 1985). Spalled coatings are commonly confined to the outer part of the cortex complex. ROTHE (1969) considers crystallization pressure of evaporitic minerals as a cause for spalling cement crusts of oncoids and ooids. Observed marine phreatic carbonate cements between several coatings of the cortex complex may have had a similar effect (DAVAUD et al. 1990).

Type-3 ooids are characteristic for the ooid shoal subfacies.

Type-4 Ooids

Type-4 ooids display the most complex fabric of all the studied ooids within the Ca2 (Pl. 30/3). The diameter of type-4 ooids ranges between 0.2 mm and 1.25 mm (average size is 0.7 mm). Approximately 3 to 24 coatings form the ooid cortex-complex (Pl. 32/3), while it varies in thickness between 0.07mm and 0.4 mm (average thickness is 0.3 mm). The nucleus diameter versus cortex-complex thickness-ratio is smaller in type-4 ooids than in type-3 ooids (see above). Like type-3 ooids, type-4 ooids show micritization.

Sediments mainly consisting of type-4 ooids also contain ooid fragments that display no further coatings after fracturing (textural inversion, after FOLK, 1962).

Deformed ooids, so-called spastolites (PETTIJOHN, 1957), distorted ooids (CAROZZI, 1961), snouted ooids (RADWANSKI & BIRKENMAJER, 1977) or notched and stretched ooids (CONLEY, 1977) resembling oncoids are also assigned to type-4 ooids. Deformed coatings are considered secondary features by many authors (CAROZZI, 1960, 1961; WILKINSON & LANDING, 1978; WILKINSON et al., 1984; RADWANSKI & BIRKENMAJER, 1977; BHATTACHARYYA & FRIEDMAN 1979, 1984; PERYT, 1985) due to compaction of un- to semilithified ooids, but have, so far, not been observed in recent carbonate sediments (CONLEY, 1977; LOREAU, 1982).

Commonly type-4 ooids are fractured in situ after cementation (Pl. 30) creating internal porosity. Despite later diagenetic processes, in most cases this micro-fracture porosity is preserved.

Pitted ooids (rarely) and spalled ooids occur locally in oolites chiefly composed of type-4 and type-3 ooids. Microporosity developed within ooid cortex-complexes is interpreted to have formed either due to different solubility of different mineralogies (e.g. aragonite and high-Mg-calcite; WILKINSON & LANDING, 1978, LAND et al., 1979, and SINGH, 1987) or due to different ooid microstructures (STRASSER 1986 and STROHMENGER, 1988).

Hemiooids (KALKOWSKY, 1908) or half-moon ooids (CAROZZI, 1963), which supposedly form due to dissolution and characteristically display collapse features, have been observed in type-4 ooids. They are interpreted to reflect an early diagenetic meteoric vadose environment, in which geopetal fabrics have been generated.

This ooid type is a reliable indicator of the ooid bar subfacies.

AGGREGATE GRAINS

Aggregate grains are irregularly shaped components (FLÜGEL, 1978). The intraparticles are bound by cryptocrystalline matrix or sparitic cements. As per TAYLOR & ILLING (1969) these grains show no coatings and are interpreted as forming in shallow marine environments with changing water energies under stable conditions of the seafloor (WINLAND & MATHEWS, 1974). MILLIMAN (1967, 1974) distinguishes lumps and aggregates by their matrix contents. Whereas, lumps contain more than 50% carbonate mud, aggregates contain less than 50%.

Aggregate grains of Ca2-platform sediments are comprised mainly of ooids, peloids, smaller aggregates, and lumps. Another type of aggregates characteristically contains a micritic core. Additionally there are aggregates observed that display portions of matrix of about 50% or slightly more and therefore are transitional between aggregates and lumps after MILLIMAN (1967, 1974). Two of the distinguished four aggregate types show predepositional phases of cementation that typically cause a grain coarsening due to later-stage fixed extra-components. All the aggre-

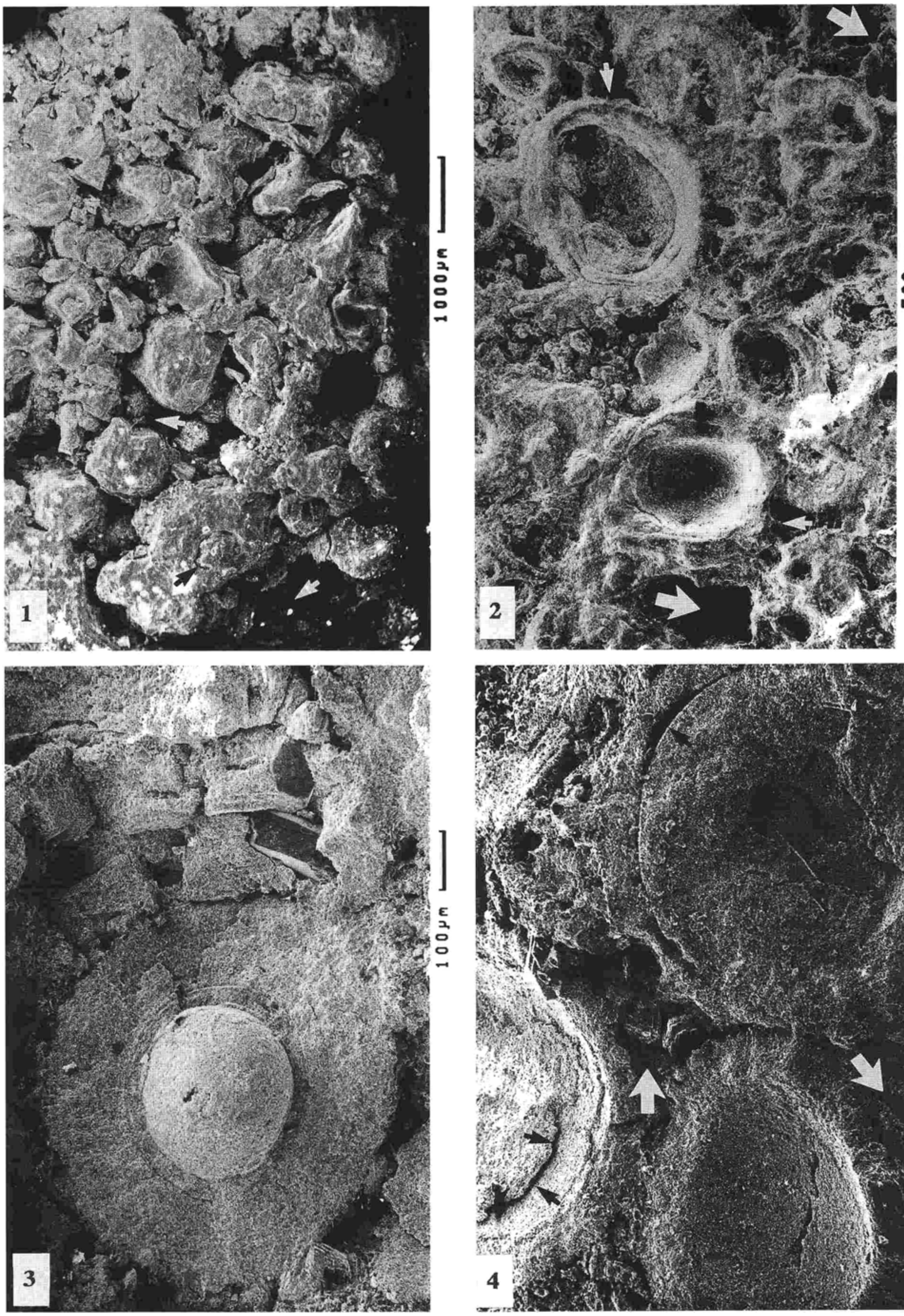
Plate 32 Pore-space development within the Ca2-platform subfacies types (Upper Permian, Zechstein 2, Northwest Germany)

Fig. 1. Oncoid-like overprinted coated grains of a "bioconsolidated" grainy shoal subfacies typical for Ca2-lowstand wedge deposits. The thickness of the coatings varies. Porosity is developed between the components (white arrows) as well as between the cortices (black arrows). Well S8

Fig. 2. Ooid shoal subfacies showing the spatial arrangement of both component and porosity types like moldic (large arrows), intergranular (small arrows), and intercrystalline porosity. In comparison with the grain size the ooids have a relatively large core. Well S3

Fig. 3. A complex medially broken ooid (type-4 ooid) of the ooid bar subfacies displaying nearly the entire amount of the coatings as well as their individual thicknesses. The core is still coated by older cortices and therefore not visible. Well P2

Fig. 4. Ooid arrangement of an ooid bar subfacies. Besides intra-cortical porosity (black arrows) there is also porosity developed between the grains (intergranular, white arrows) as well as between the dolomite crystals (intercrystalline porosity). Well P2


1000µm
1
300µm
2
100µm
3
100µm
4

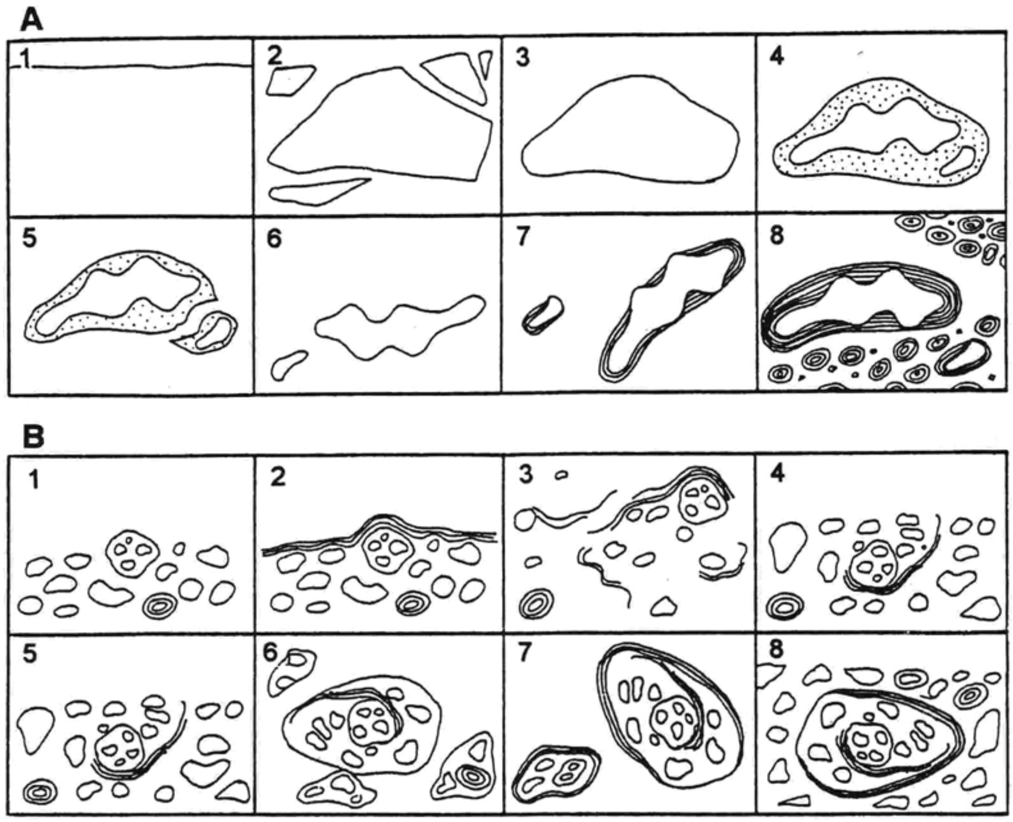


Fig. 5. Schematic sketch showing the formation of aggregate grains. A: Formation of type-1 and -2 aggregates. An already lithified sediment (1: e.g. mud) becomes reworked (2) while the formed fragments (clasts) are rounded (3) and more or less intensely micritized (4). The weak, micritized parts then become eroded in turbulent water regimes whereas the non-micritized parts remain (5 and 6). These intraclasts subsequently become coated by microbial organisms (7). Finally the commonly elongated aggregates are deposited with an orientation parallel to the depositional surface (8). B: Formation of type-4 (steps 1 to 8) and type-3 (steps 5 and 6) aggregates. After deposition of sediment (1) local algal growth fixes the depositional surface (2). The sediment (and the algae) becomes reworked (3), deposited again (4), and cemented (5). The lithified material is subsequently eroded and retransported (6), and coated in an agitated environment (7), before final deposition (8).

gate types that can be distinguished on the Ca2-platform are partially or totally coated.

Type-1 Aggregate Grains

The typically complex type-1 aggregates (Pl. 29/4) are almost always partially to totally coated by a cortical complex that locally exceeds the thickness of the nucleus. The diameter of the aggregate grains varies between 0.6 mm and more than 10 mm. They consist of both carbonate mud, apparently derived from adjacent inter-bar sediments, and ooids from ooid-bar grainstones. The internal grains (ooids) usually do not differ from the surrounding ones, but sporadically show fewer coatings. This indicates that the externally coated grains were coated synchronously to the aggregates, allowing a larger final size in contrast to those that are incorporated or within the aggregate. Thus aggregate grains are interpreted as reworked intraclasts of the ooid bar subfacies.

A very typical feature of type-1 aggregates are the comparatively far protruding protuberances of the core (commonly micritic), while the thicker older coatings primarily refill core depressions and show an onlapping to the flanks of the hollows. The thinner, younger coatings build the outer part of the cortex complex and mostly engulf all of the particle (see Fig. 5A). The thicknesses of these outer coatings may be quite similar to those of ooids of the same subfacies type. During the coating process, locally cemented grains can be intercalated within the cortical complex, reflecting breaks of cortex growth and onset of cementation under quiet water conditions (Dravis, 1979).

The development of the significant morphology of aggregate cores is thought to be due to microbiogenic micritization. The chronology of type-1 aggregate formation is interpreted as follows:

1) Reworking of a mudstone (or wacke-, pack-, and grainstone) of an inter-bar to ooid bar environment causing the formation of mudclasts (or grain-bearing clasts).

2) Marginal micritization of the mudclast (or other types of clasts) that forms the later core shape. Ooids that seem to be more resistant to micritization partially show micro-excavations, most likely done by boring microbes and/or algae (Bathurst, 1966).

3) During reworking of the grains under agitated water conditions, the marginally micritized material becomes eroded and only the non-micritized areas of the core remain. In fact,

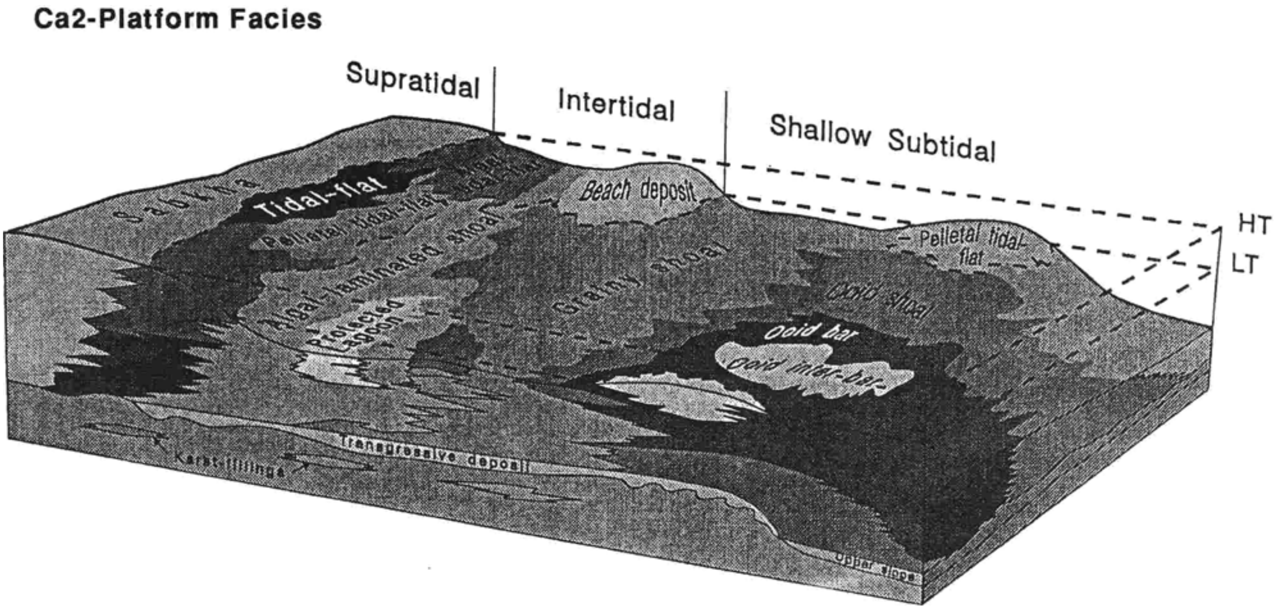


Fig. 6. Block diagram showing the spatial arrangement of the Ca2-platform subfacies types as revealed by investigation of vertical subfacies-type transitions (see Fig. 10). Modified after STROHMENGER et al., 1993b, 1996b.
HT = high-tide sea-level, **LT** = low-tide sea-level.

even fragile, but unmicritized, grains (e.g. chip shaped) are very often not fractured by reworking.

4) If the type-1 aggregate grains stay in an agitated environment, the clasts become coated in a characteristic, relief-filling manner. The youngest coating covers both depressions and protuberances of the core.

The formation of type-1 aggregates is shown in Fig. 5A.

Aggregates of this type are xharacteristic ooid-bar subfacies that are formed in the most agitated water regimes, under marine phreatic conditions.

Type-2 Aggregate Grains

Aggregates of this type range between 0.3 mm and 0.6 mm in diameter, are irregular in shape with respect to ooids, and usually have a core consisting of micrite (Pl. 30/3), while occasionally carbonate grains may be compiled. Some coatings pinch out against protuberances, while others totally surround the core. The formation of type-2 aggregates parallels that of type-1 aggregate grains (Fig. 5A), but the cortices are commonly quite similar to those seen on ooids of the same ooid bar depositional environment.

Type-3 Aggregate Grains

Type-3 aggregates (Pl. 30/1) only include peloids as intra-components and about 50% micritic matrix or sparitic cement. They can display several cementation phases, yielding a significant grain-coarsening. Each cementation phase was usually followed by more or less intense micritization, before the grains were reworked and cemented again (Fig. 5B). The diameter ranges between 0.1 mm and 11.2 mm. Apparently a considerable amount of the peloids of type-2 and -3 is derived from these aggregates by micritization and/or recrystallization. Microbial activities sporadically caused oncoidal overprinting of the grains. Oncoid-like coated aggregate grains are characteristic of the grainy shoal subfacies of Ca2-lowstand wedge depositional environment).

Type-4 Aggregate Grains

Type-4 aggregates, like those of type-3, pass through several reworking and cementation phases prior to final deposition. After each cementation, reworking and often more or less intense micritization of the grain rims is conspicuous (Fig. 5B). The cores contain a varying abundance of grains that occur across the Ca2-platform, such as ooids, peloids, fossils (rarely), and smaller aggregates, or lithified carbonate mud. The diameter of type-4 aggregate grains varies between 0.15 mm and a few millimeters. The coatings are similar to those of type-1 and -2 aggregates, but smoothing of the relief of the cores, prior to final total coating, is rarely observed. Thus, the thickness of the cortical complex reaches about 0.3 mm at a maximum. Furthermore, features like micritic apophyses as well as spalled cortices indicate a temporary marine vadose environment (MAUSFELD, 1987) (Pl. 28/2). Internal cements as constituents of the core, however, have certainly been formed under marine phreatic conditions. Phases of micritization and cementation are commonly displayed.

Type-4 aggregate grains are characteristic components of the transgressive deposit subfacies.

CA2-PLATFORM FACIES

The Ca2-platform facies of Northwest Germany is characterized by twelve subfacies types which all exclusively represent shallow subtidal (some meters of water depth),

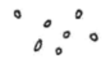
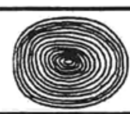
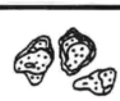
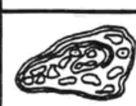
Main Grain Type	Subtype	Form	Subfacies Type
Peloids	Type-1		Pelletal Tidal-Flat
	Type-2		Platformwide Type-2/Type-3 Ratio < 1 → Ooid Shoal
	Type-3		Platformwide Type-2/Type-3 Ratio < 1 → Ooid Shoal
Oncoids	Type-1		Algal Tidal-Flat Tidal-Flat Pelletal Tidal-Flat
Grapestones	Type-1		Platformwide
Ooids	Type-1		Pelletal Tidal-Flat
	Type-2		Grainy Shoal Algal-Laminated Shoal
	Type-3		Ooid Shoal
	Type-4		Ooid Bar
Aggregate Grains	Type-1		Ooid Bar
	Type-2		Ooid Bar
	Type-3		Grainy Shoal (LSW) Algal-Laminated Shoal (LSW)
	Type-4		Transgressive Deposit Grainy Shoal Algal-Laminated Shoal

Fig. 7. Component types of the Ca2-platform and their significance as subfacies indicators. Coated grains such as ooids, oncoids (in part), and aggregates, but also pellets, are the most reliable indicators of certain subfacies types. Components such as peloids (type-2 and-3) and grapestones are found in almost every subfacies environment and therefore are thought to occur platformwide. Subfacies types with no characteristic grain composition such as the ooid inter-bar or the beach subfacies-type which is considered to be rather related to the transgressive deposit, are thus not mentioned in this chart.

intertidal and supratidal depositional environments (Figs. 3 and 6). The descriptions of the subfacies types follow in parts the ones proposed by MAUSFELD (1987), MAUSFELD & ZANKL (1987), MAUSFELD and HUTTEL (1991), BELOW (1992), STROHMENGER et al. (1993b, 1996b) and STROHMENGER & STRAUSS (1996).

The vertical stacking patterns of these subfacies often display two major and two minor shallowing-upward cycles. An ideal shallowing-upward cycle, or parasequence, shows upward gradation from high to moderate energy subfacies, like ooid bar and/or ooid shoal as well as grainy shoal to intertidal subfacies like pelletal tidal-flat, tidal-flat and/or algal tidal-flat.

Figure 7 summarizes the variety of grains and associated subfacies types on the Ca2-platform. The following descriptions of the subfacies types is in order from those representing more quiet water to those representing predominantly agitated water regimes.

SABKHA

Sabkha deposits consist of predominantly crinkly-bedded algal-laminated mudstone subfacies showing contortion and disruption of sedimentary structures due to synsedimentary anhydrite (primarily gypsum) growth. Common features are algal-doming, micro-teepees and nodular

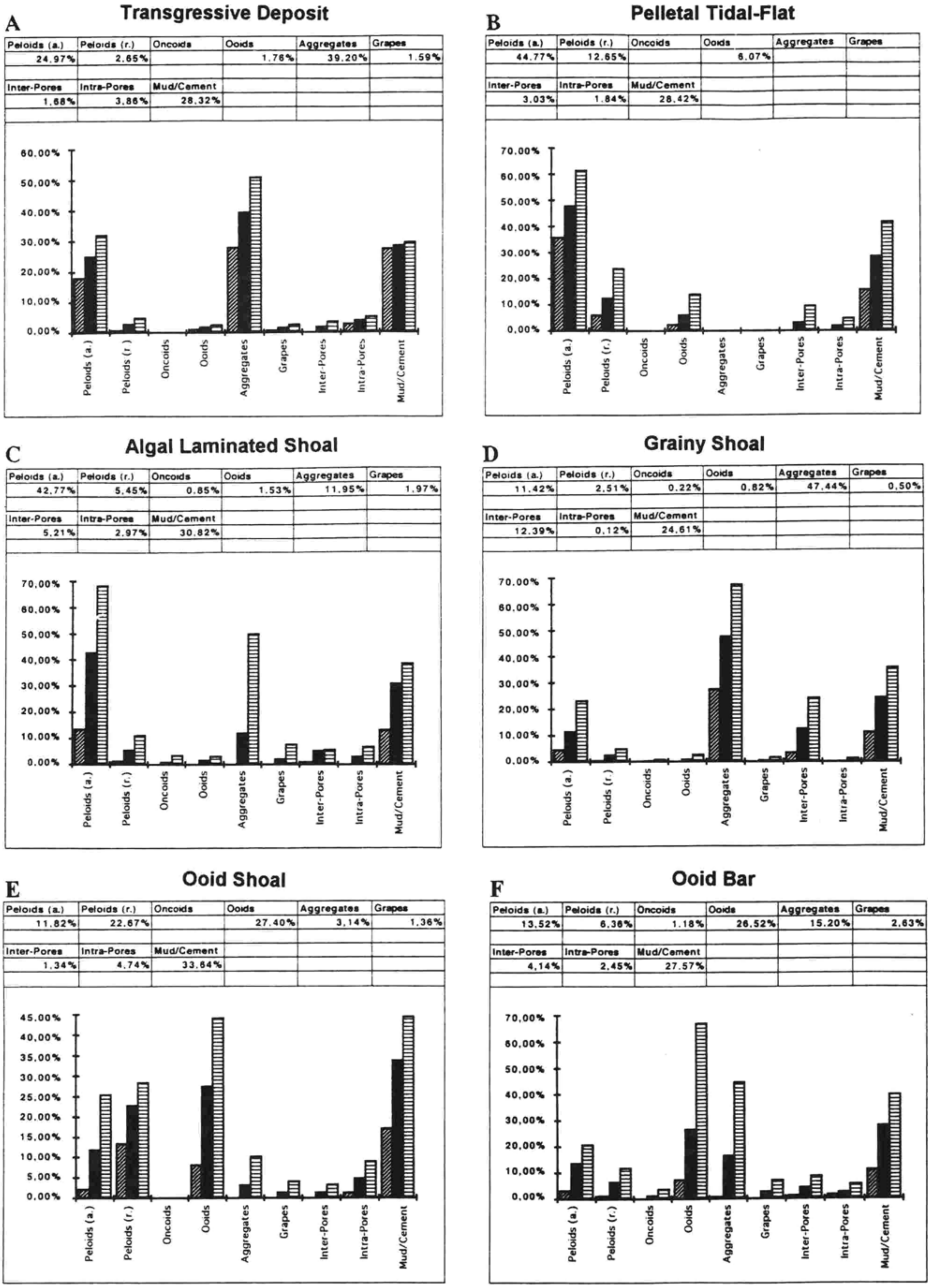


Fig. 8. Comparative compilation of component distribution data. The different histograms display the minimum, average, and maximum (columns from left to right) abundance of grain types as point-counted within the predominantly homogeneous subfacies types of the Ca2-platform. Neither mixed-layered successions concerning depositional texture, according to DUNHAM (1962), which are significant of tidal environments, nor mudstones (characteristic for restricted environments) have been point counted. Abbreviations are: (a.) = subangular to angular, (r.) = rounded to well rounded.

to chicken-wire anhydrite. The lower dolomite-rich part of the A2 corresponds to anhydritized Ca2-platform carbonates which formed during relative sea-level lowstand at the end of the Ca2 time (onset of sabkha conditions on the Ca2-platform; Pl. 26/1 and Pl. 28/1). The sabkha subfacies represents deposits of a supratidal environment under arid to semiarid conditions.

TRANSGRESSIVE DEPOSIT

Coarse-grained shallow water carbonates (packstones/grainstones) commonly showing reworked anhydrite clasts (Pl. 26/2 and Pl. 28/2) comprise the transgressive deposit subfacies. An erosive contact (top A1 sequence boundary) separates these carbonates from the underlying shallow water A1 anhydrites. The transgressive deposits indicate the inundation of the A1-platform causing reworking of the anhydrites (Ca2-maximum flooding). Besides small amounts of ooids and oncoids, peloids (type-2 and-3), as well as type-4 aggregate grains are characteristic for this subfacies. Abundance of the different component types are shown in Figure 8/A.

BEACH DEPOSIT

Ca2-beaches (Pl. 27/6) are relatively coarse grained grainstones/packstones showing swash cross-bedding, graded-bedding, and shingled-bedding as well as typical beach-lamination. It is a rare subfacies type, often related to transgressive deposits (see above). Beach deposits represent a high energy, shallow subtidal to intertidal environment. Graded-bedded intervals may also correspond to channel lag deposits. The component distribution is often very similar to that of the transgressive deposit (Fig. 8/A).

TIDAL-FLAT

This subfacies type comprises centimeter to millimeter thick alternations of mudstones, wackestones/packstones, and packstones/grainstones (Pl. 26/4 and Pl. 29/1). Common sedimentary features are fenestral fabric and mud cracks. Desiccation features, as well as storm deposits (tempestites: intercalated graded beds within finer sediments) indicate an intertidal environment of deposition for the tidal-flat subfacies. Owing to different sources, a great variety of component types may occur. Only oncoids seem to be confined to this and other subfacies, which are interpreted to represent intertidal environments.

PELLETAL TIDAL-FLAT

The pelletal tidal-flat subfacies (Pl. 26/5, Pl. 29/2, and Pl. 31/1) consists of low-angle swash cross-bedded and herringbone cross-bedded packstones/grainstones of fine grained material. Wave ripples associated with small-scale trough-cross-stratification are present, whereas fenestral fabrics and sheet cracks occur relatively rarely. The herringbone cross-stratification indicates bi-directional currents, indicative of the intertidal environment. This subfacies may represent channel levee deposits as well as less agitated shoal sediments of shallow-marine platform environments. The small scale cross-stratifications indicate 3D-ripple development in an intertidal area of the platform with higher water energies, as usually assumed for intertidal deposits. This subfacies is chiefly constituted by micro-ooids (ooid type-1) and type-1 peloids (pellets), although lumps, aggregates, and ooids (type-2 to -4) also occur. Typical abundance and ratios of grain types observed in the pelletal tidal-flat subfacies are shown in Figure 8/B.

ALGAL TIDAL-FLAT

This subfacies type consists of crinkly bedded, algal-laminated mudstones/wackestones and bindstones showing algal doming and micro-tepees (Pl. 26/3 and Pl. 28/3). Fenestral structures and mud cracks, although rare, can be observed. Carbonate components may occur in coarser tempestitic layers. In contrast to the algal-laminated shoal subfacies (see below) a rather parallel algal-lamination of millimeter scale is clearly the predominant sedimentary feature. Although lacking unequivocal desiccation features, the algal tidal-flat subfacies is interpreted to represent deposits of an intertidal, protected environment. Components contained in this subfacies are derived from all over the platform most probably due to spill-overs during temporary storm events. Thus, significant values and/or ratios of certain grain types are lacking.

PROTECTED LAGOON

This is a relatively rare subfacies type in Zechstein 2 carbonates of Northwest Germany. Dominant sedimentary structures are wavy- to cm-bedding (Pl. 27/1 and Pl. 29/3). Bioturbation ranges from rare (Northwest Germany) to abundant (Northeast Germany). Components are characteristically not contained within lagoonal sediments which chiefly consist of carbonate mud. This subfacies type represents a protected to restricted, low energy environment.

ALGAL-LAMINATED SHOAL

The algal-laminated shoal comprises packstones/grainstones mainly consisting of peloids (type-2 and-3), lumps, but also aggregates, ooids, grapestones, and oncoids. Crinkly-bedded algal-lamination is characteristic for this subfacies type (Pl. 26/6). Ooids may become the main components where algal-laminated shoal alternates with ooid shoal subfacies. The algal-laminated shoal subfacies marks the transition between the more protected, intertidal algal tidal-flat subfacies and the moderate to high energy, shallow subtidal grainy and ooid shoal (Pl. 29/4, Pl. 31/2-3). Typical abundance and ratios of grain types observed in the algal-laminated shoal subfacies are shown in Figure 8/C.

GRAINY SHOAL

Sediments (mainly packstones and grainstones) of this subfacies type appear quite homogeneous (massive) and

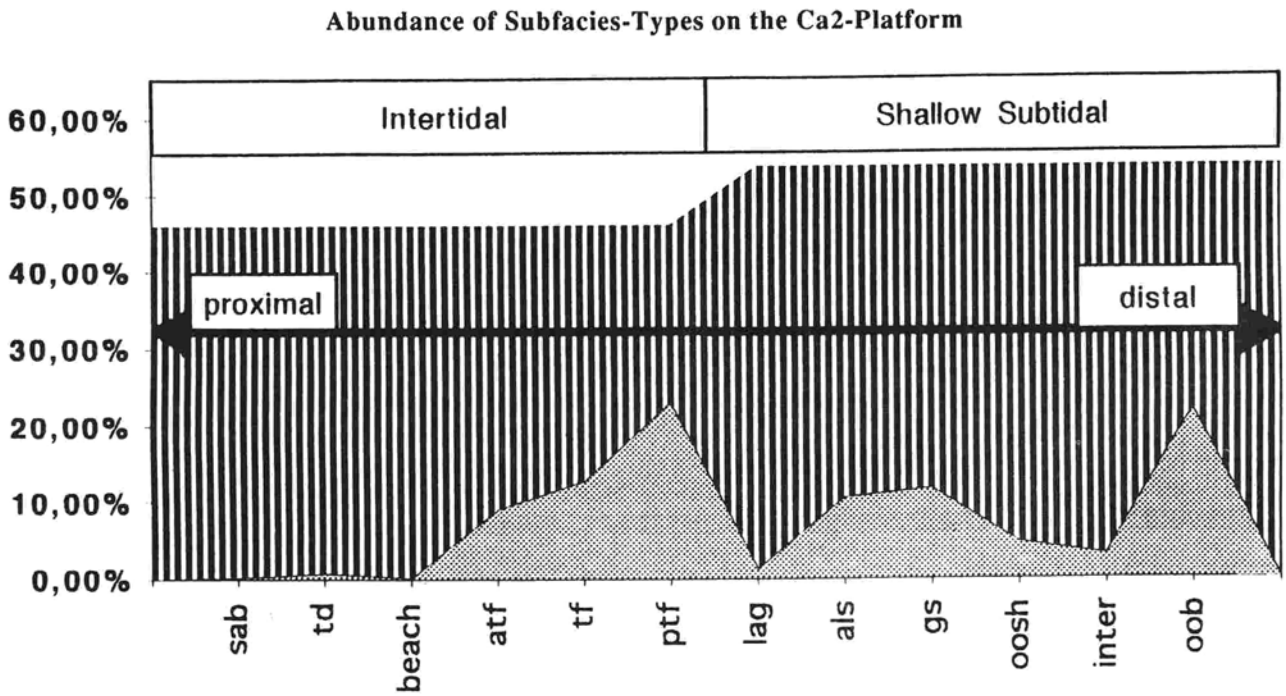


Fig. 9. Graph showing the abundance of subfacies types on the Ca2-platform as recognized in studied well successions. The studied platform succession as a whole represents 100% of which approximately 46% are subfacies types of the intertidal environment and about 53% are represented by subfacies types of the shallow subtidal environment. The curve framing the dotted area displays the percentage amount of each subfacies type while the arrow marks the estimated position of the subfacies types from proximal (landward) to distal (platform-margin) on the Ca2-platform. Abbreviations are: **alp** = algal-laminated shoal, **atf** = algal tidal-flat, **beach** = beach, **gs** = grainy shoal, **inter** = ooid inter-bar, **lag** = protected lagoon, **oob** = ooid bar, **oosh** = ooid shoal, **ptf** = pelletal tidal-flat, **sab** = sabkha, **td** = transgressive deposit, **tf** = tidal-flat.

show no sedimentary structures (Pl. 27/2), although locally some cross-bedding may be observed. Peloids (type-2 and-3) as well as ooids (type-2) are characteristic of the grainy shoal subfacies. Additionally, there are all other grain types of the Ca2-platform contained at different abundances which are considered as allochthonous components derived from adjacent subfacies types. Typical values and ratios of grain types observed in grainy shoal subfacies are shown in Figure 8/D. Grainy shoal sediments of the Ca2-lowstand wedge (Pl. 30/1 and Pl. 32/1) which developed at the end of Ca2 time in Ca2-slope position (Strohmenger et al., 1993a, 1996b) characteristically contain peloids and lumps that are oncoidically overprinted and therefore display irregular coating. In comparison to grainy shoals of Ca2-highstand systems tract deposits, the average grain size within grainy shoals of Ca2-lowstand systems tract (lowstand wedge) deposits increases considerably. The grainy shoal subfacies represents shallow subtidal deposits of a moderate to elevated-energy environment.

OOID SHOAL

Oolitic grainstones to packstones, that are very similar in sedimentary structures and homogeneity, to the grainy shoal subfacies are described as ooid shoal subfacies (Pl. 27/3). In contrast to the grainy shoal subfacies, the ooid (type-3) content ranges from about 10% to 50%. The distinction between the ooid shoal and the grainy shoal subfacies is not sharp and based solely on the amount of ooids (Pl. 30/2 and Pl. 32/2). This subfacies is the only one in which there are more peloids of type-3 than of type-2. Typical abundances and ratios of grain types observed in ooid shoals are shown in Figure 8/E. This subfacies likely represents shallow subtidal deposits of a moderate to elevated-energy environment. The ooid shoal is the lateral equivalent to the grainy and algal-laminated shoal facies.

OOID BAR

Ooid bars are mostly well-sorted ooid grainstones displaying pronounced cross-stratification (planar cross-bedding, herringbone cross-bedding, small-scale trough-cross-bedding, Pl. 27/4). Characteristically, components such as type-1 and -2 aggregates as well as type-4 ooids are indicative of this subfacies type (Pl. 30/3, Pl. 32/3-4). Typical values and ratios of grain types in the ooid bar subfacies are shown in Figure 8/F.

This subfacies type is represented by shallow-water deposits of a high energy environment. Some of the ooid bar sediments may not represent deposits paralleling the platform margin, but rather longitudinal bars of tidal-dominated inlets and/or vast channels.

OOID INTER-BAR

The ooid inter-bar comprises relatively thin-bedded mudstones and/or herringbone cross-bedded peloid packstones/grainstones, alternating with ooid bar deposits (Pl.27/5 and

Pl. 30/4). Ooid inter-bar deposits are restricted to the ooid bar environment and are thought to represent the lateral equivalent of the pelletal tidal-flat subfacies. The ooid inter-bar subfacies may represent channel levee deposits when cross-stratified. The more muddy deposits (mud drapes) indicate protected conditions between and/or behind (back-bars) the ooid bars.

DEPOSITIONAL MODEL

Almost 50% of the studied wells representing Ca2-platform facies are interpreted as intertidal deposits whereas slightly over 50% represent shallow subtidal environments (Fig. 9). The transgressive deposit, beach deposit, algal tidal-flat, pelletal tidal-flat, and tidal-flat subfacies are interpreted as intertidal deposits. Protected lagoonal, algal-laminated shoal, grainy shoal, and ooid shoal, as well as the ooid bar and ooid inter-bar subfacies, are inferred to have formed under shallow subtidal conditions. All these subfacies types have a characteristic composition of grain types, and thus can be distinguished by microscopic investigations.

According to WALTHER's law (WALTHER 1893/94), only subfacies types that were once laterally juxtaposed in their depositional environment can be found superimposed in an undisturbed vertical succession. In a shallow-marine environment with complex lateral subfacies migrations such as the one described here, this law is only partly applicable (MIALL, 1985). With well-defined subfacies types, and considering the abundance of vertical subfacies transitions (STROHMENGER, 1988, ORSAT & STROHMENGER, 1993), however, the general subfacies distribution of the Ca2-platform can be reconstructed.

The number of vertical transitions between the different subfacies types was calculated by means of Markov-chain analysis (KRUMBEIN & DACEY, 1969, HOQUE & NWAJIDE, 1985). The resulting matrix is displayed in Figure 10A. Also shown are the base (Fig. 10C) and top transitions (Fig. 10B). The histograms (Figs. 10B and 10C) graphically display how often transitions have been counted. The height, as well as the similarity of the columns representing base (Fig. 10C) and top transitions (Fig. 10B) provide reliable evidence for the degree of subfacies relationships. Thus, a relatively high affinity between the tidal-flat (tf) and the pelletal tidal-flat (ptf) environment is detected (25 and 29 transitions, respectively). Other higher relationships have been revealed between the grainy shoal (gs) and the algal-laminated shoal (als; 22 and 22 transitions, respectively), the grainy shoal (gs) and the tidal-flat (tf; 16 and 17 transitions, respectively), as well as between the grainy shoal (gs) and the pelletal tidal-flat (ptf; 23 and 19 transitions, respectively). Relatively frequent subfacies transitions also exist between the ooid bar (oobar) and the pelletal tidal-flat (ptf; 12 and 9 transitions, respectively), as well as between the ooid shoal (oosh) and the pelletal tidal-flat (ptf; 14 and 13 transitions, respectively). The relatively frequent transitions between subfacies types representing shallow subtidal and subfacies types representing intertidal environments indicate autocyclic, as well as allocyclic (if correlatable throughout the Ca2-platform) changes of environmental conditions. Algal growth in both the algal-laminated shoal (als) and the algal tidal-flat (atf) points to the relatively high affinity between these two subfacies types. This assumption is confirmed by the abundance of counted top and bottom transitions between these subfacies types (8 and 7 transitions, respectively).

There are exclusively top transitions found from the open marine subfacies (m) to any platform subfacies. This indicates that the system generally prograded once the platform was flooded. The uniform stacking pattern of pelletal tidal-flat (ptf) subfacies which is commonly overlain by algal tidal-flat (atf) subfacies at the end of Ca2 time also implies a characteristically regressive trend allowing algal-fixing of the sediment, which becomes finer as water energy decreases (dashed boxes in Fig. 10/A).

The abundance of the subfacies transitions reveals their spatial arrangement on the Ca2-platform. By this it is possible to assign the different subfacies types to more proximally or more distally orientated subfacies associations, having the sabkha (supratidal, subaerial exposure) and the upper slope facies (subtidal, below fair-weather wave-base) as the two extremes (Fig. 6). Obvious is the relatively high affinity between the different intertidal subfacies types. Only the pelletal tidal-flat additionally displays high affinity to ooid-bearing subfacies types of shallow subtidal environments such as ooid shoal and ooid bar subfacies. This supports the interpretation of the pelletal tidal-flat as the lateral equivalent to the ooid inter-bar subfacies.

Within shallow subtidal environments the grainy shoal quite commonly grades into the algal-laminated shoal in a vertical succession and vice versa. Because algal growth is generally indicative of quiet to moderate water energies the algal-laminated shoal is interpreted to be the proximal (landward) equivalent to the grainy shoal subfacies where algal growth was inhibited due to a more agitated water regime. This assumption is supported by the fact that further algal occurrence is only seen in the algal tidal-flat environment where water energy has furthermore decreased; in a way that only carbonate mud was deposited and sand-sized components are commonly missing. Tepee structures, desiccation cracks and keystone vugs allow the assignment of the algal tidal-flat subfacies to the upper intertidal environment, representing the link between intertidal and supratidal conditions, represented by the sabkha subfacies. Algal remains never occur within the ooid shoal and the ooid bar subfacies, except as rip-up clasts on a cm-scale. These clasts might be retransported by incising channels that cross the different subfacies belts more or less perpendicularly to the platform margin. Because ooid-bearing subfacies types are only rarely interfingered with algal dominated deposits they are interpreted to have formed in a more distal position near the platform margin. The sizes of ooids are inferred to increase with decreasing distance from the platform margin. On the other hand, the ooid bar subfacies type might also represent isolated longitudinal bars of tidal-dominated channels cross-cutting the Ca2-platform perpendicular to the shelf margin. Ooid bars contain the largest ooid sizes within the Ca2 shallow

A	oobar	oosh	gs	als	ptf	atf	tf	td	beach	lag	m
ooid bar (oobar)		2	2	2	12		3				
ooid shoal (oosh)	3		3	4	14	1	2				
grainy shoal (gs)	4	3		22	23	7	16	1			
algal shoal (als)	1		22		3	8	4				
pel. tidal-flat (ptf)	9	13	19	1		13	29		1	9	
alg. tidal-flat (atf)		3	7	7	6		3				
tidal-flat (tf)	3	4	17	4	25	2			1		
trans. deposit (td)			4			2					
beach (beach)			1								
protec. lagoon (lag)					8						
open marine (m)	2				1		2				

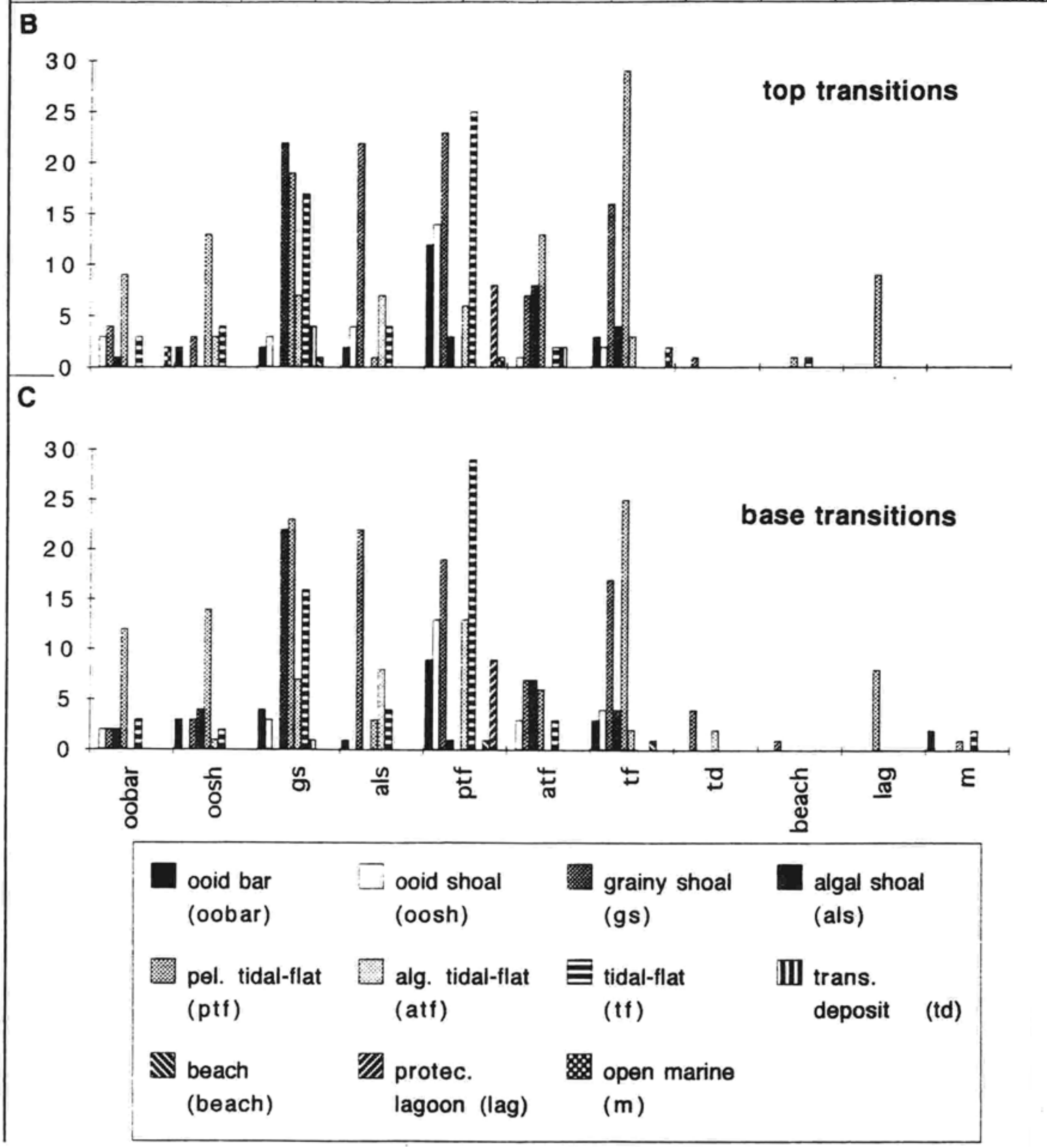


Fig. 10. Vertical transitions of subfacies types observed within the Ca2. A: Matrix displaying the abundance of transitions of the different subfacies types to superimposed ones. B: Histogram showing by which subfacies type a considered Ca2-subfacies is overlain. C: Histogram showing by which subfacies type a considered Ca2-subfacies is underlain. B and C: Length of subfacies-representative columns as well as similarity of length comparing top contacts and base contacts provide reliable evidence for the degree of subfacies relationships. Since, by definition, the ooid inter-bar is interbedded within and exclusively represents transition between ooid-bar units, transitions between ooid inter-bars and ooid bar subfacies types have not been counted.

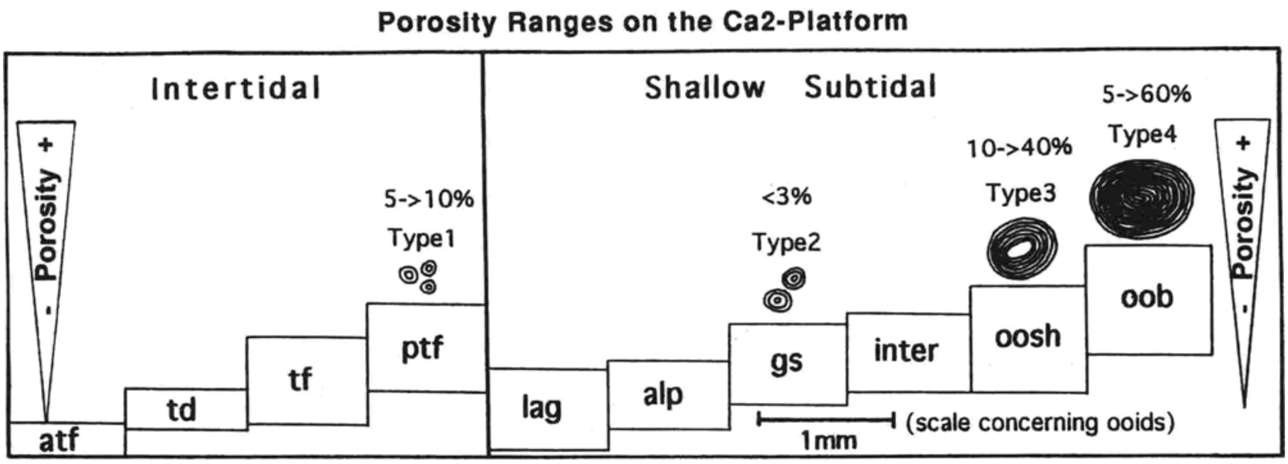


Fig. 11. Porosity development in relation to ooid distribution within the different subfacies types on the Ca2-platform. Porosity generally increases with increase of both ooid size (see scale bar) and ooid abundance (in %). Amount of algal content is negatively correlated with porosity. It should be mentioned that porosities react quite sensitively to later diagenetic processes. Abbreviations see Figure 9.

water carbonates, and display the highest porosities (Fig. 11). Ooids of the ooid-shoal subfacies, which is inferred to be the next subfacies belt proximally to the ooid bars, are significantly smaller than those of the bars.

SEQUENCE STRATIGRAPHIC FRAMEWORK OF CA2-PLATFORM CARBONATES

As mentioned earlier, the Ca2-platform facies is characterized by subfacies types which all represent shallow subtidal to supratidal environments. The vertical stacking patterns of these subfacies display two major and two minor shallowing-upward cycles which can be correlated throughout the entire Ca2-platform. Each of the four small-scale cycles shows upward gradation from high to moderate energy subfacies, like ooid bar and/or ooid shoal subfacies into intertidal subfacies like pelletal tidal-flat and/or algal tidal-flat subfacies (Strohmenger & Strauss, 1996; Stohmenger et al. 1996b; Figs. 3, 6, and 12).

The Zechstein 2 Carbonate encompasses both transgressive and a highstand systems tract of third-order Zechstein sequence ZS3, as well as part of the lowstand systems tract (lowstand wedge) of the overlying fourth Zechstein sequence (ZS4; Fig. 2). The maximum flooding of the Ca2 corresponds to the flooding of the Werra Anhydrite (A1) sulfate platform (Strohmenger et al., 1993a, 1996a, 1996b). The massive to nodular (chicken wire), often algal-laminated, anhydrites of the A1 sulfate platform display a highly erosive surface on top which is interpreted as a sequence boundary (ZSB3; Pl. 26/2). Therefore, in a platform position, A1 shallow subtidal (salina) to supratidal (sabkha) highstand deposits of the second Zechstein sequence (ZS2) are directly overlain by either thin Ca2 peritidal transgressive systems tract and/or highstand systems tract deposits of the third Zechstein sequence (ZS3). In slope position, upper slope mudstones, representing deposits below fair-weather wave-base, can be overlain by intertidal platform subfacies. This abrupt change in subfacies favors the interpretation of a pronounced sea-level fall at the end of Ca2 time. A sequence boundary (ZSB4) is therefore placed on top of the upper slope, open marine subfacies. The overlying platform facies, interpreted as part of the lowstand systems tract (lowstand wedge) of the fourth Zechstein sequence (ZS4), starts with the already mentioned intertidal subfacies at the base (pelletal tidal-flat and/or tidal-flat subfacies) and grades towards the top into shallow subtidal (ooid bar and/or ooid shoal subfacies) and again into intertidal (pelletal tidal-flat and/or algal tidal-flat subfacies) and supratidal (sabkha) subfacies.

The transition of shallow water Ca2 carbonates into the overlying anhydrites of the Basal Anhydriet (A2) is often gradational. Carbonates showing typical Ca2-platform facies (e.g. algal-laminated coated-grain wackestones/packstones and algal bindstones) are often intercalated with algal-laminated anhydrites of the A2. Furthermore, the anhydrites of the A2 often display ghost structures of Ca2 facies. The lower part of the A2 (anhydritized Ca2 facies) is interpreted as the time equivalent to shallow water Ca2 carbonates that overlie upper slope carbonates in a basinward position, corresponding to the described lowstand systems tract (lowstand wedge) of the fourth Zechstein sequence (Figs. 3 and 12). Although sabkha and salina deposits are common in prograding highstand systems tracts (Alsharhan & Kendall, 1994; Handford & Loucks, 1993), most of the A2-sabkha is interpreted to have been formed during lowstand systems tract due to slow rise in relative sea level (Warren & Kendall, 1985). Thus on the Ca2-platform, lowstand systems tract deposits (A2-sabkha: anhydritized Ca2-highstand systems tract) are interpreted to actually occur below the Zechstein sequence boundary ZSB4 (Strohmenger & Strauss, 1996; Stohmenger et al. 1996b). The uppermost part of the A2 (pure, salina-type anhydrites on top of anhydrites showing ghost structures of reworked Ca2 facies) represents the transgressive systems tract of the fourth Zechstein sequence (ZS4, Fig. 12).

The Ca2 is further subdivided into seven mappable higher-order small-scale cycles or parasequences (termi-

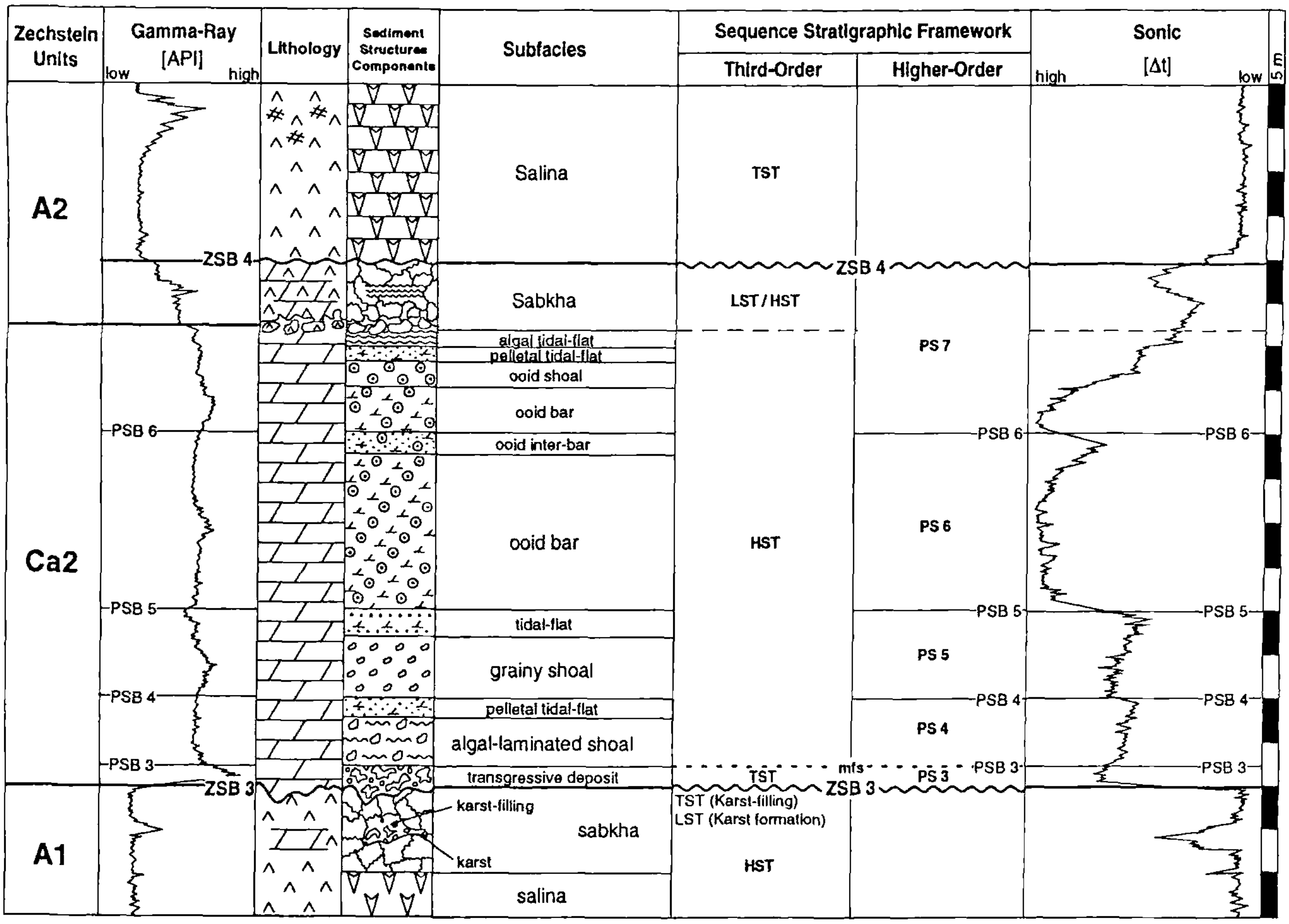


Fig. 12.. Schematic sketch showing Zechstein 2 Carbonate sequence stratigraphic framework (**HST** = highstand systems tract; **LST** = lowstand systems tract; **mfs** = maximum flooding surface; **PS** = parasequence; **PSB** = parasequence boundary; **TST** = transgressive systems tract; **ZSB** = Zechstein sequence boundary; STROHMENGER et al. 1993a, 1996a, 1996b) and idealized subfacies successions.

nology of VAN WAGONER et al., 1987, 1988, 1990) that are recognized by facies/subfacies succession and gamma-ray log response (STROHMENGER et al., 1993a, 1996b; STROHMENGER & STRAUSS, 1996; Fig. 12).

On the studied Ca2-platform only parasequences PS4 to PS7, bound by parasequence boundaries PS4 to PS6, and the Zechstein sequence boundary ZSB4 are completely present (Fig. 12). Parasequences PS1 and PS2 are present only along the Ca2-slope, and, condensed, throughout the Ca2-basin. Parasequence PS3, bound by Ca2-maximum flooding surface (mfs) is only represented by the relatively thin (some centimeters) transgressive deposit subfacies (Figs. 6 and 12).

The sequence stratigraphic framework on the Ca2-platform can be summarized as follows:

- Dominantly highstand systems tract (HST).
- Transgressive systems tract (TST) thin to absent.
- Maximum flooding surface (mfs) corresponds to the flooding of the A1-/Ca2-platform.
- Four parasequences correlatable by means of marine flooding surfaces (parasequence boundaries).
- Exclusively peritidal platform facies.
- Typically porous dolomite.

CONCLUSIONS

Integrating core, thin section, and SEM data allows subdivision of the Zechstein 2 Carbonate platform facies of Northwest Germany into 12 subfacies types. These subfacies types are characterized by sedimentary structures and grain composition.

The platform facies, chiefly consisting of component-rich carbonates, displays onesupratidal, five intertidal, and six shallow-marine subfacies types that can be identified by macroscopic core studies. Due to sea-level changes during carbonate production both vertical and lateral subfacies transitions can be observed. Microscopic studies provide further subfacies characteristics, based on distribution, size, shape, and spatial arrangement of the grains contained in the different subfacies types.

There are four types of ooids present within the platform facies of the Ca2 that show three distinct subfacies-specific criteria. These criteria are size, total thickness of coatings, and number of individual cortices. Furthermore there are four types of composite grains (grapestones excluded), which are subfacies-specific. While type-1 and -2 aggregates suggest shallow-marine environments and those of type-4 are commonly preserved within intertidal successions, type-3 aggregates are formed in both intertidal and shoal sediments. Peloids as well as grapestones are of less importance concerning subfacies characteristics. One exception is the type-1 peloids that have almost a single area of origin; the pelletal tidal-flat subfacies. Oncoids are mostly confined to intertidal or adjacent environments. Retransported components of several subfacies types can be detected within adjacent subfacies, representing allochthonous material. These components can easily be identified by point counting of the studied samples, because their presence alters the characteristic component distribution of each subfacies type.

The carbonate rocks of the Ca2-platform mainly correspond to Ca2-highstand systems tract deposits and show four higher-order shallowing-upward cycles, or parasequences (Fig. 12). It is, so far, not possible to distinguish these parasequences by microscopic analysis. The grainy shoal and/or algal-laminated shoal subfacies of the Ca2-lowstand wedge show, however, significant bioconsolidation during reworking, represented by type-3 aggregate grains. Type-3 aggregate grains therefore can be used to distinguish shallow water highstand systems tract from lowstand systems tract deposits (lowstand wedge).

Each subfacies within the Ca2-platform has a characteristic percentage range of porosity. Predominantly the presence or absence of ooids plays an important role in porespace development. A dependence also seems to occur between the average ooid size and porosity. Porosity generally increases when average sizes of the ooids increase. Thus the best porosities are developed in grainstones consisting mainly of type-4 ooids, found in the ooid bar subfacies type. All non-ooid-bearing sediments (ooid content less than 3%) contain less primary pore space than oolites. Algal growth characteristically decreases porosity (Fig. 11).

Although the Ca2 can be subdivided into subfacies types by macroscopic core studies, microscopic thin section and SEM studies are important for reservoir facies prediction because they are not restricted to core material (nearly never available for the total Ca2 interval). Cuttings, mostly continuously covering the complete Ca2 succession, can successfully be classified. This enables reconstruction of the Ca2-depositional environment, and by this definition of the potentially most porous zones, including intervals where no core material is available.

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