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Compaction-formed platy limestone from the Middle Cambrian Zhangxia Formation (Western Hills, China): towards a new classification for bedded limestone

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Abstract Remarkable bedding features occur in Middle Cambrian platy limestone of the Western Hills close to Beijing in NE-China, which are intercalated in a sequence of shallow water carbonates (mudstones, storm deposits, oolitic grainstones). The platy limestone beds (up to 5 cm thickness) have undergone complex diagenetic compaction and pressure solution. Varying facies types are characterized by wavy, stylolitic boundaries with different thickness of clay accumulation and common lateral pinch out. Cross-cutting relationships of stylolites commonly destroy primary bed-surfaces. This indicates an intimate interfingering resulting in an indenting fabric of primary separated facies types. Nevertheless, primary sedimentary boundaries can be recognized. There occur varying types of compaction features documented by different stylolite types with varying amplitudes and thickness of clay-enrichments (parallel clay seams, stylolamination, stylo-nodular and stylo-brecciated structures with multi-grained seams). Bedded limestone of the type documented, generally belong to the limestone family of Plattenkalk, Lithographic Limestone or platy limestone, which can form in different environments. Consequently, using these names without detailed data on some specific parameters (e.g. thickness, surface morphology, composition of allochems, particle and crystal size) results in more confusion and hinders the comparison of Plattenkalk, Lithographic Limestone and platy limestone from different locations throughout the earth history. Therefore, a classification is proposed here which is based on macroscopic, microscopic, and sub-microscopic parameters. Plattenkalk and platy limestone are considered to form the two main groups. Plattenkalk beds are laterally consistent and have parallel, horizontal surfaces. Platy limestone can pinch out laterally and reveals irregular and inclined bed surfaces. Single beds in both can have different thickness, internal structure (e.g. micritic, microsparitic) and fabric (e.g. homogeneous, nodular), particle content and other variations (e.g. chemical, mineralogical). These parameters should be added to the basic name and used in a system similar to Folk's limestone classification. Lithographic Limestone is defined as a subgroup of Plattenkalk with well-defined parameters. A consequent use of this classification will also help to understand fossil preservation and/or non-preservation in different types of Plattenkalk, Lithographic Limestone, and platy limestone.

Keywords Platy limestone · Lithographic Limestone · Plattenkalk · Middle Cambrian · China · Compaction

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Introduction

Plattenkalk, Lithographic Limestone and platy limestone are in the focus of the International Symposium on Lithographic Limestone and Plattenkalk. But, how is Plattenkalk defined? Swinburne and Hemleben (1994) discuss the various types and define it as "a flat, tabular, thinly bedded (cm–dm scale) and finely laminated (mm or submillimetric scale) limestone, composed predominantly of fine-grained lime mud, or micrite which has undergone early cementation". Furthermore, Lithographic Limestone is described as one very narrowly defined type of Plattenkalk (Swinburne and Hemleben 1994; Röper 2005). Meanwhile, there was a wide variety of Plattenkalk presented during the different Symposiums on Lithographic Limestone and Plattenkalk. From ideal Plattenkalk of the Solnhofen type to limestone, which separates in not well-defined plates with irregular bed surfaces; all is included in the term Plattenkalk. However, a closer look to the microfacies shows, that this *broad non-definition* covers different types which comprise very tight homogeneous mudstones, peloidal packstones, and grainstones with primary varying amounts of siliciclastic detrital input. Swinburne and Hemleben (1994) summarize that "…though Plattenkalks seem physically very similar, the origin of each may have been quite different".

Munnecke et al. (2008) have shown that the sedimentary matrix of Plattenkalk has received markedly less attention compared with varying palaeontological aspects. Even the nomenclature of Plattenkalk successions is not clearly defined. Röper (2005) states that "the term Plattenkalk, in the past was restricted to workable slabs of intermediate thickness, has been transferred to all carbonate marine sediments, in which bioturbation partially or completely stopped, and thus the primary lamination and fine stratification of the sediments was preserved". Munnecke et al. (2008) conclude that this excludes limestone used for lithography because they do not exhibit lamination. But very fine, faint lamination can occur as documented by Koch (2007). Although the term "platy limestone" seems to be an overwhelming alternative, it seems to be too wide.

On the basis of these points we analyzed Middle Cambrian platy limestone from the Western Hills close to Beijing (China) which are separating in plates of some centimetre thickness when quarried. They reveal intensive compaction features influencing and vanishing primary very different microfacies types of a shallow marine environment. Consequently, they do not fit in any description and/or interpretation of Plattenkalk given until now.

Throughout this study, the term "platy limestone" will be used in the sense of Röper (2005), Munnecke et al. (2008). In the final discussion we propose a classification based on published data on Plattenkalk, Lithographic Limestone and platy limestone as well as on our own data.

Geologic frame

The North China Carbonate Platform comprises strata from the Early Cambrian to the Late Ordovician (about 530–460 Ma). Up to 2,000 m of limestone and dolomite were deposited reflecting changes in depositional environments, palaeoclimate, relative sea-level, tectonic uplift and subsidence. The Early Paleozoic Carbonate Platform is situated in NE China, with the city of Beijing in the northeastern part and the city of Xian on the southern margin (Fig. 1). It covers an area of about 1,500 km east–west and 1,000 km north–south extension. The regional geology and the tectonic development are described by Yang et al. (1986), Meyerhoff et al. (1995), Wang and Mo (1995), Meng et al. (1996), Wang (1985).

Two megasequences (transgressive–regressive cycles), which are separated by a major palaeokarst zone (Meng et al. 1997), can be distinguished within the strata of the North China Carbonate Platform. The first sequence comprises Lower Cambrian to Lower Ordovician strata and the second Middle and Upper Ordovician strata. The Early Paleozoic Carbonate Platform consists of nine depositional sequences, generally 50–150 m thick.

During the Lower Cambrian flooding of the Huabei Craton, phosphorites and phosphatic sandstones were deposited that are overlain by carbonates, mudrocks, and evaporites (Mantou Formation). The Middle Cambrian is subdivided into the Maozhuang, Xuzhuang and Zhangxia Formations (Fig. 2). A continued long-term relative rise in sea-level occurred in Cambrian times and resulted in the transgressive part of the first megasequence on the platform, reaching from the basal Mantou Formation to the Zhangxia Formation (Fig. 2). The Middle Cambrian Xuzhuang Formation follows above with a conformable boundary to the underlying Maozhuang Formation. The Xuzhuang Formation reaches 120 m in thickness and can be subdivided in a lower part predominantly consisting of mudrocks with thin bioclastic and oolitic limestone, and an upper part composed of oolitic limestone with thin shale interbeds indicating sedimentation on a shallow water carbonate platform. The upper boundary is marked by a basal lag deposit of the overlying Zhangxia Formation, which reaches 160 m thickness in the Beijing area and is characterized by abundant oolitic limestone, storm deposits, calcirudites, skeletal peloidal limestone, micritic limestone and dolomite. The Zhangxia Formation can be subdivided in a lower marly unit and an upper unit dominated by oolites (Figs. 3, 4). Storm beds are common in the lower part, and are developed as graded, cross-laminated limestone of low thickness alternating with dolomitic shales.

After a phase of tilting of the North China Carbonate Platform to the north, cross-stratified grainstones and stromatolitic-thrombolitic bioherms are most obvious (Meng et al. 1997). During the Upper Cambrian and Lower Ordovician fine-grained limestone, dolomite and intertidal sediments were deposited, documenting the regressive part

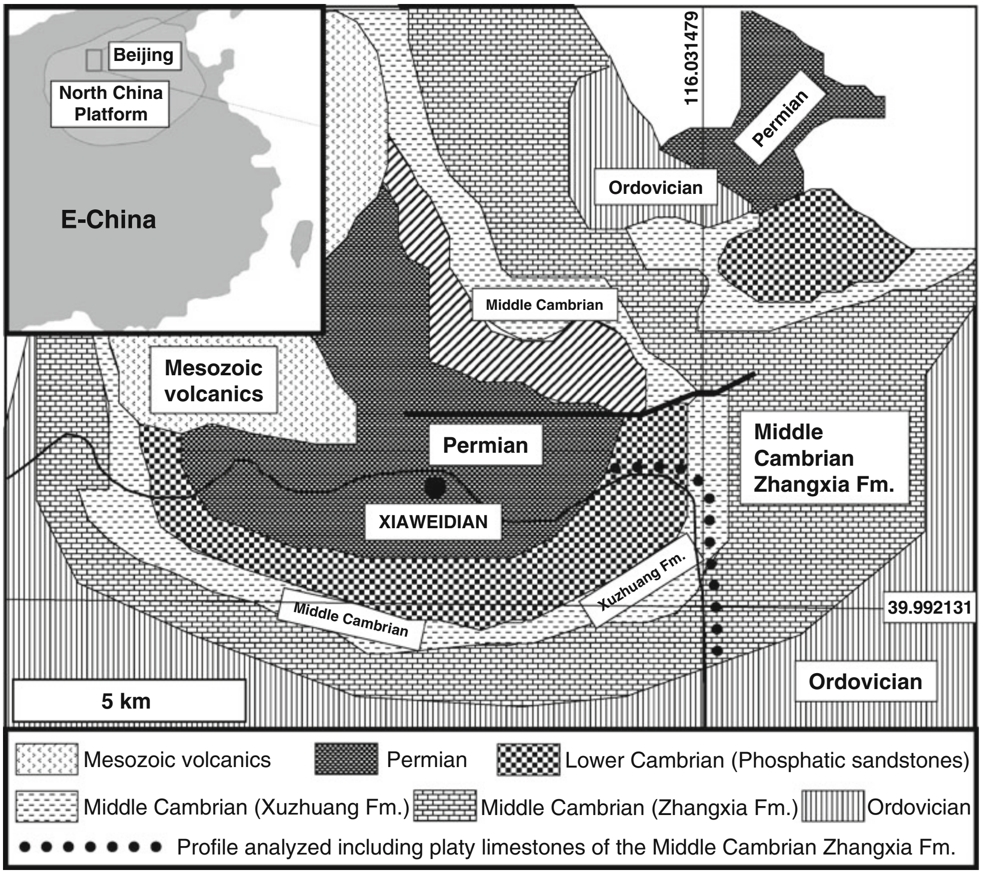

Fig. 1 Geographical setting and simplified geological map of the study area indicating Mesozoic volcanics, Lower Cambrian (Mantou and Maozhuang Formation), Middle Cambrian (Xuzhuang Formation), Middle Cambrian (Zhangxia Formation), Ordovician, and Permian units (modified after Meng et al. 1996)

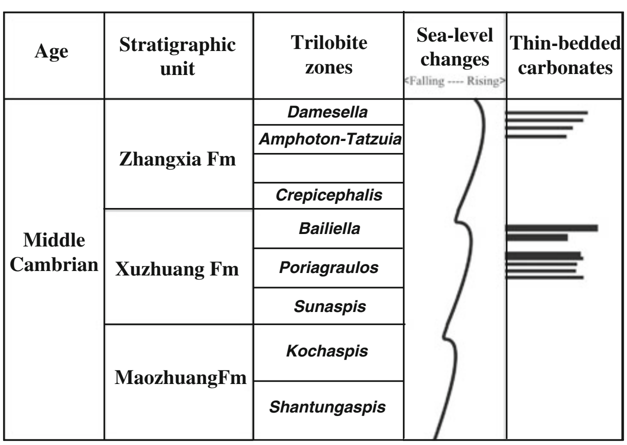

Fig. 2 The occurrence of the thin-bedded carbonates (platy limestone) in the Middle Cambrian including names of formations and trilobite zones (altered from Meng et al. 1997)

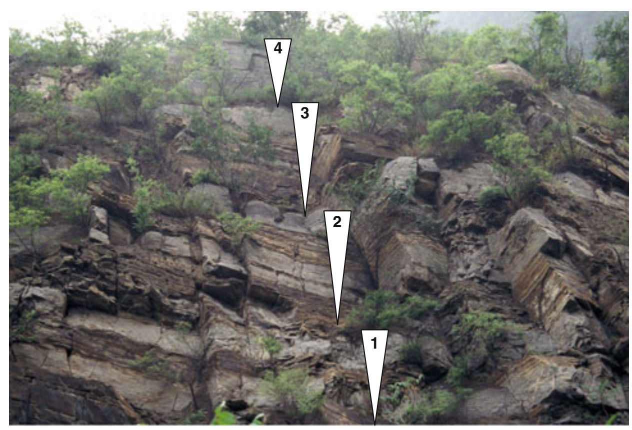

Fig. 3 The carbonates in the outcrop of about 40 m height revealing alternations of fine-bedded *grey-coloured* limestone and *brownish*, thin-bedded zones. The wall corresponds to cycles 1–3 and incomplete cycle 4 as defined by Meng et al. (1997). The thicker bed at the *top* of cycle 2 with round weathering features predominantly consists of cross-bedded oolitic grainstones (compare with Fig. 4)

of the first megacycle. The Middle–Upper Ordovician megasequence overlying is predominantly composed of shallow-water carbonates with thick evaporite units that are not described in detail in the present paper. The stratigraphic frame of the Middle Cambrian of the Moazhuangian to Zhangxia formations is defined by eight trilobite zones (Fig. 2).

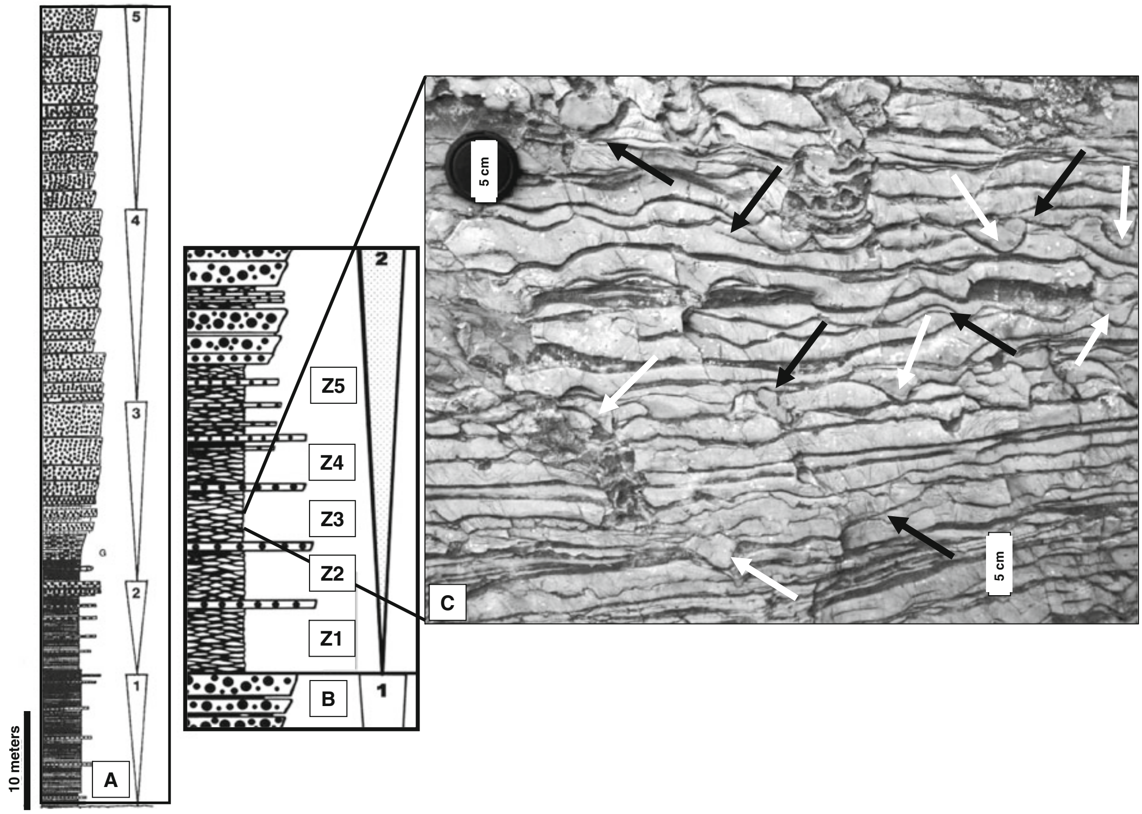

Fig. 4 **a**, **b** The nodular, platy limestone analyzed occurs between oolitic packstones and grainstones of the 1st and the 2nd cycle in the Zhangxia Formation (thickness of cycle 2 is about 12 m). **b** The zones Z1–Z5 were analyzed for different facies types occurring in single limestone beds. **c** In zone Z3 the depicted representative section contains all characteristic sedimentary features. Note the common pinch-out (*black arrows*) of beds within a lateral distance of some centimetres to decimetres, which results in the characteristic wavy texture of the platy limestone. Furthermore, cross-cutting features occur (*white arrows*) with symmetric and asymmetric boundaries. *Parallel* boundaries of single beds occur rarely (modified from Meng et al. 1997)

Studied outcrops and methodology

The Western Hill outcrops are located approximately 20 km west of Beijing 40°00′21″ N, 116°01′54″ E), in the Yanshan orogenic zone. The area is characterized by high mountains, which expose cyclic sedimentary sequences of Cambrian carbonate rocks. Steep walls of bedded limestone of the Zhangxia Formation occur on the flanks of narrow valleys (Fig. 3). Even from longer distance alternations of fine grey limestone beds with brownish thin-bedded units can be distinguished.

The thin-bedded, nodular, platy limestone is inter bedded between oolitic packstones and grainstones of the 1st and the 2nd cycle of the Zhangxia Formation. They were first analyzed macroscopically in the field: repetitions of varying facies types occur in the different thin-bedded limestone layers of zones Z1—Z5A, exhibiting a clear cyclic pattern (Figs. 3, 4). They are predominantly composed of peloidal-oolitic packstones and grainstones, oolitic grainstones, intraclastic packstones and grainstones, peloidal mudstones, silty, clayey mudstones, and pure mudstones. Furthermore crystalline dolomite and limestone, dolomitized to various degrees, can be recognized.

In many parts of the outcrops close to Xianweidian and about 40 km west besides the railway to Qingbaikou well-bedded limestone, very thin-bedded limestone and platy limestone can be observed. The sequences also reveal local small patch reefs (stromatolitic-thrombolitic bioherms) of 0.5 to about 3 m thickness, which pinch out laterally within decimetres into platy limestone or even into clay/marl sediments. Also beds of some decimetre thickness are intercalated resulting in a cyclic appearance of the Middle Cambrian sequence.

A representative succession of 2 m thickness of zone Z3 (Fig. 4) was selected for further analyses of the genesis of the platy limestone. Selected individual layers and small units of this succession were analysed in the field and characteristic facies types were sampled for thin section analysis.

The Middle Cambrian platy limestones are characterized by wavy, stylolitic boundaries between single beds revealing different thickness of clay accumulation (Fig. 4).

Most characteristic are cross-cutting relationships of stylolites which only locally allow horizontal parallel surfaces of the beds. Most obvious is the lateral pinch out of beds with a maximum of 5 cm thickness within a lateral distance of some centimetres to decimetres.

Microfacies and diagenesis

The microfacies analysis allows to recognize lateral and vertical variations within single layers and commonly also within the scale of a thin section. This data can be transformed to the macroscopic appearance of single beds, of their lateral and vertical interfingering and pinch out. The analysis carried out do not allow to elucidate the diagenetic history of the Middle Cambrian carbonates throughout (e.g. the dolomitization, dedolomitization, and silicification) without additional analysis (e.g., chemistry, isotopes, cathodoluminescence). Only some insights from selected samples of the interval analyzed can be presented. Consequently the diagenetic conclusions just give a first impression of the complexity of the processes. Three major microfacies types can be observed.

Oolitic grainstones

Oolitic grainstones with well-preserved ooids and tangential microstructure of ooid-cortices commonly occur in thicker layers and also in thin intercalations (Fig. 5a). The cores of the ooids are composed of peloids and of fragments of echinoids and molluscs. These ooids are not dissolved and therefore are interpreted to be of primary Mg-calcite mineralogy as described by Strasser (1986), Strohmenger et al. (1987) from Upper Jurassic limestone in France and Slovenia.

The ooids show well-developed radial textures of light-coloured triangular zones alternating with dark zones within an inner thick sequence of cortices which is covered by thin seams to be of black, probably organic matter (Fig. 5a, b). Nevertheless tangential relic textures can be recognized. These light-coloured radial textures are interpreted as recrystallisation and aggrading neomorphism of inner cortices. Subsequently outer cortices were formed which reveal no alteration. Therefore a change of water chemistry during the formation of ooids is assumed with a time gap between the two types of cortices. The ooids reveal relatively smooth cement seams (Fig. 5a, b) consisting of characteristic bladed crystals of primary Mg-calcite mineralogy (Fig. 5b) as described by Schroeder (1979), Longman (1980). Due to synsedimentary compaction outer cortices of some ooids split off, exactly at the surface of the inner zone of cortices, which was covered by black material, locally forming elongated intraparticle pore spaces. Similar features were reported by Rothe (1969) from Zechstein carbonates in NW-Germany. Subsequently marine cement seams were formed within these elongated secondary pores as well as around ooids.

Fitting of grains in packstones and grainstones (Fig. 5e) is another process, which commonly is ascribed to an early freshwater influx (Strohmenger et al. 1987; Flügel 2004). During this process the point-contacts of single grains undergo intensive dissolution. Consequently they are transformed to elongate and/or even to sutured grains contacts with enrichment of insoluble residues.

Locally relics of micritic matrix are found in intergranular pores (Fig. 5b), which are now recrystallized to microsparite. Melim et al. (2002) summarize many observations of latest studies on the Bahama Platform and conclude that the microspar is a cement as also reported by Munnecke et al. (1997). These findings are in contradiction to the widely accepted interpretation that microspar is the product of recrystallisation due to an early freshwater influx (Folk 1965).

Other ooids were completely dissolved. The oomolds were subsequently filled by small and very large dolomite rhomboedra first and subsequently by coarse crystalline to blocky calcite in the relic pore space (Fig. 5c). These ooids are interpreted to be of primary aragonitic mineralogy. The dissolution must have occurred after an early lithification so that the sedimentary structure did not collapse and the oomolds remained open.

Ooids of a primary alternating Mg-calcite/aragonite mineralogy reveal similar diagenetic textures (Fig. 5d). There, the primary Mg-calcite core (peloid, intraclasts) was transformed to fine-crystalline dolomite, the outer aragonitic cortices were dissolved completely. Consequently bimineralic ooids as described by Strasser (1986) from Purbeckian sediments occurred during the Middle Cambrian of NE China as also reported by Chow and James (1987) from Middle and Upper Cambrian platform carbonates in western Newfoundland (Canada). They reflect changing chemical conditions in a shallow marine environment as described throughout the earth history (Tucker 1984; Wilkinson et al. 1984; Moore et al. 1986; Strasser 1986; Chow and James 1987; Heydari and Moore 1994; Strohmenger et al. 1987; Swirydczuk 1988). Moreover, primary relic textures are commonly preserved when Mg-calcite is stabilized to calcite according to Oti and Müller (1985), Koch and Rothe (1985).

The dolomitization of Mg-calcite peloids, which formed cores of ooids probably also occurred in the early phase of Mg-calcite stabilization (Fig. 5d). It must have occurred before the outer sequence of ooid cortices was dissolved and subsequently dolomite was precipitated in the newly formed partial oomolds.

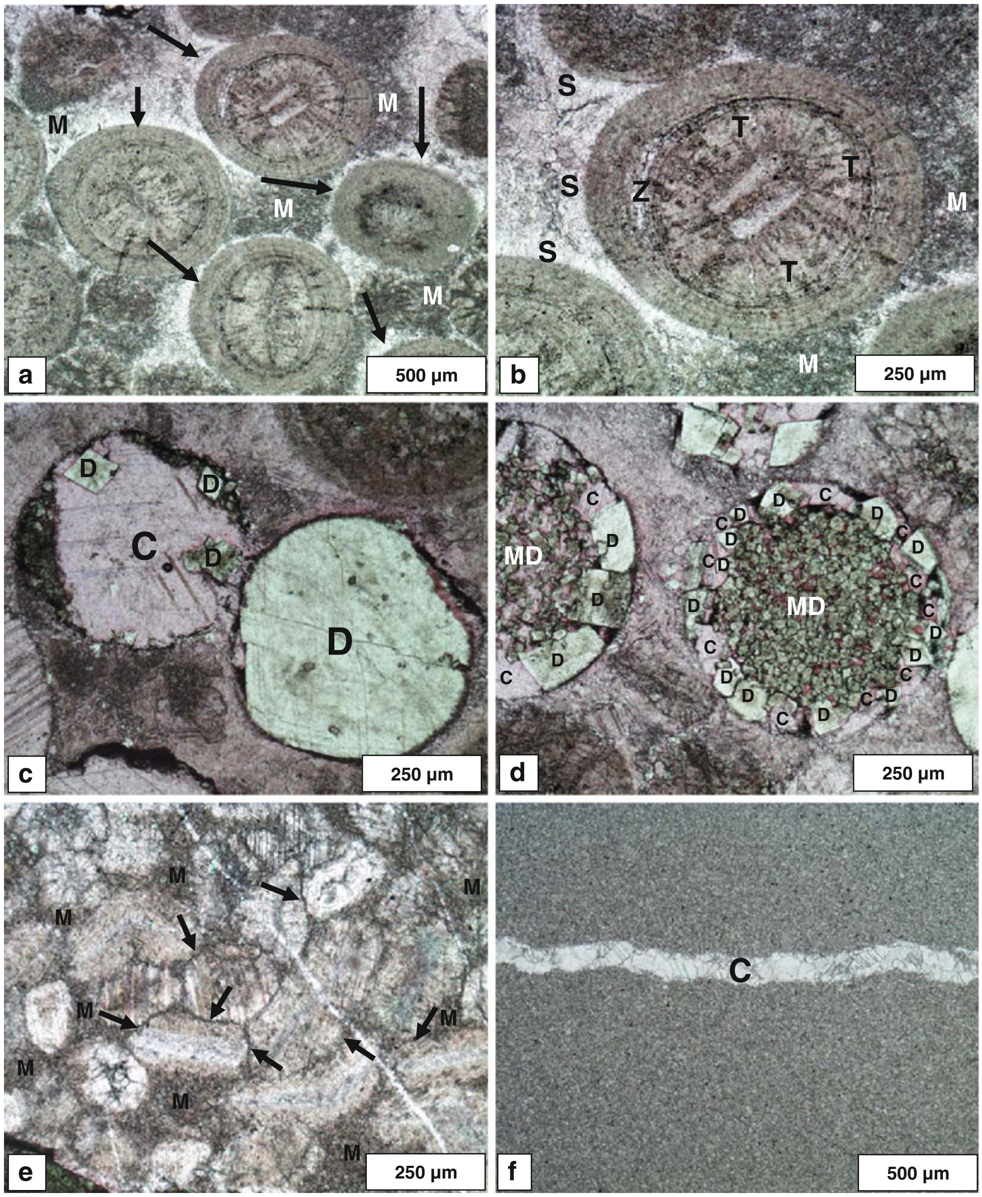

Fig. 5 **a** Oolitic grainstone with well-preserved ooids and two types of ooid-cortices. *Inner* cortices reveal recrystallisation of primary tangential micro textures to radial light-coloured textures. Outer cortices predominantly preserved their primary tangential textures. Ooids are surrounded by isopachous marine cement seams (*arrows*; Mg-calcite). Locally relics of micrite (M) recrystallized to microspar can be found. **b** Early compaction resulted in deformation and split off of outer cortices forming intraparticle pore space which was filled by marine cement (Z). Note common light-coloured triangular recrystallisation-areas (T) in the inner zone of primarily tangential cortices. Note also cement seams with relic textures of former bladed Mg-calcite (S). **c** Some ooids were completely dissolved. The oomolds first were filled by smaller and very large dolomite rhombohedra (**d**). The relic pore space subsequently was cemented by coarse granular calcite (**c**). **d** Composed ooids show the dissolution of outer cortices (primary aragonite), cementation of these molds by dolomite (D) and calcite (C), and the formation of microcrystalline dolomite (MD) in the inner part (primary Mg-calcite). **e** Fragments of echinoids and other fossils in a primary matrix-rich packstone were intensively compacted and reveal sutured grain contacts (*arrows*). **f** Pure mudstones are locally traversed by fractures filled with granular calcite (C)

Echinoid packstones

Echinoid packstones containing also other fossil fragments like molluscs and unknown biogenic fragments (Fig. 5e) are characterized by intense micro-sutured stylolitic grain contacts. The monocrystals of echinoid fragments are very resistant against pressure solution. Consequently the matrix of the packstone is predominantly dissolved, resulting in enrichments of clay flasers between particles. Increasing compaction and pressure solution will result in increasing sutured grain contacts between particles (Fig. 5e). In other limestone without micrite, echinoid fragments commonly reveal thin syntaxial overgrowth as described by Evamy and Shearman (1965, 1969). Syntaxial overgrowth commonly was interpreted as formed during an early freshwater influx (Longman 1980; Walkden and Berry 1984) which in most cases need free, open interparticle pore space for their development. But latest studies on Bahamian sediments indicate that granular cements and also syntaxial overgrowth can be formed from slightly altered marine pore waters. Melim et al. (2002) name an early diagenesis under such conditions "marine-burial diagenesis" to distinguish it from both, the well-documented near-surface marine diagenesis characterized by hardgrounds and/or marine cementation, and deeper burial diagenesis characterized by compaction, pressure solution, and late cements. This diagenesis in marine pore fluids mimics many aspects of diagenesis in meteoric pore fluids, most notably by producing a low-Mg calcite limestone with blocky spar, neomorphism, microspar and moldic porosity. Dissolution of aragonitic bioclasts in Cretaceous rudists limestone during early organic oxidation underlines these new findings (Sanders 2003).

Pure, non-fossiliferous micrites

Pure non-fossiliferous micrites only reveal extension veins (Fig. 5f; horizontal, vertical, subvertical) corresponding to varying tectonic stress-stages. These fractures are now cemented by coarse-granular calcite.

Silicification is only locally obvious. A first generation of minor authigenic silica occurs within fragments of echinoids and some molluscs. It is partly mimicking the primary shell structures and reveals idiomorphic crystal terminations of quartz. A second generation of authigenic silica is bound as micro-nodules and as fibrous silica flasers to fractures and is also enriched along stylolites because of high pressure solution stability.

Clay enrichments at primary boundaries and stylolitic contacts between varying facies types of small-scale sedimentation units are most characteristic for Middle Cambrian platy limestone of NE China. Locally alternations of silty, clayey micrite with fine-grained bioclastic detritus and recrystallized pelsparite (Fig. 6a) occur. Furthermore, vertical alternations and lateral interfingering of silty, slightly pyritic marlstone, overlain by slightly silty, pyritic clay-bearing microsparite rich in detrital chlorite, and silty, recrystallized mudstones can be found.

Marked features of differential compaction can be observed especially in clayey sediments (Fig. 6b). A clay-rich sediment (mudstone-wackestone) with minor amounts of biogenic particles (small molluscs and some gastropods of up to 3 mm in size) was deposited primarily.

In this limestone small dolomite rhombohedra were formed which later were altered to dedolomite present now as tiny brown spots in dark grey clay enrichments. A peloidal micrite was deposited above (Fig. 6b) which is now preserved as slightly recrystallized limestone with thin clay flakes and some traces of microfossils (calcispheres?). Around gastropods, which were dissolved soon after deposition and cemented by granular calcite, marked differential compaction occurs (Fig. 6b).

Within the same carbonate layer (bed) different facies types can be recognized which are separated by stylolites (Fig. 6c). Locally relics of pure micrite were squeezed between other microfacies types. Further pressure solution will result in the complete disappearance (dissolution) of such relics. Many of these features can be found within one thin section or separated in different microfacies types, which are bordered against each other by stylolites (Fig. 6d).

Different limestone types are separated by stylolitic clay-rich accumulations of 0.01–1 mm thickness (Fig. 6e). There occur mudstones, fossiliferous mudstones, biogenic packstones, and biogenic bearing mudstones as well as silty marls and silty claystone. The matrix rock is composed of a slightly silty wackestone–packstone, which is nearly completely composed of very fine debris of fossils and carbonate crystals (10–100 μm). Furthermore, dark fragments of clayey carbonate occur which are laminated and contain also very fine fossil debris.

Locally also fragments of recrystallized micrite and of wackestone–packstone rich in microfossil fragments occur. All this indicates complete dislocation and penetration of varying facies types (intensive pressure solution) primarily deposited as specific sedimentary layers above and aside of each other.

Two different generations of extension veins occur at last. They are separated by marked stylolites (Fig. 6f). The first generation of fractures clearly was formed before stylolitization. The extension veins are up to 50 μm wide and are filled by coarse granular calcite. They are commonly interrupted and dislocated by stylolites. A second generation of fractures, which commonly occurs in "swarms" was formed after stylolitization. These fractures are smaller than the first generation and filled by fine-granular calcite and penetrate the stylolites without interruption.

The diagenetic events described above can be summarized and ordered in a relative time sequence (Fig. 7). It has to be stressed that this was established on the base of microscopic analysis only.

Mesogenetic shallow and deep burial compaction

Stylolites are common throughout the profile. The amplitudes are ranging between few millimetres and 2.5

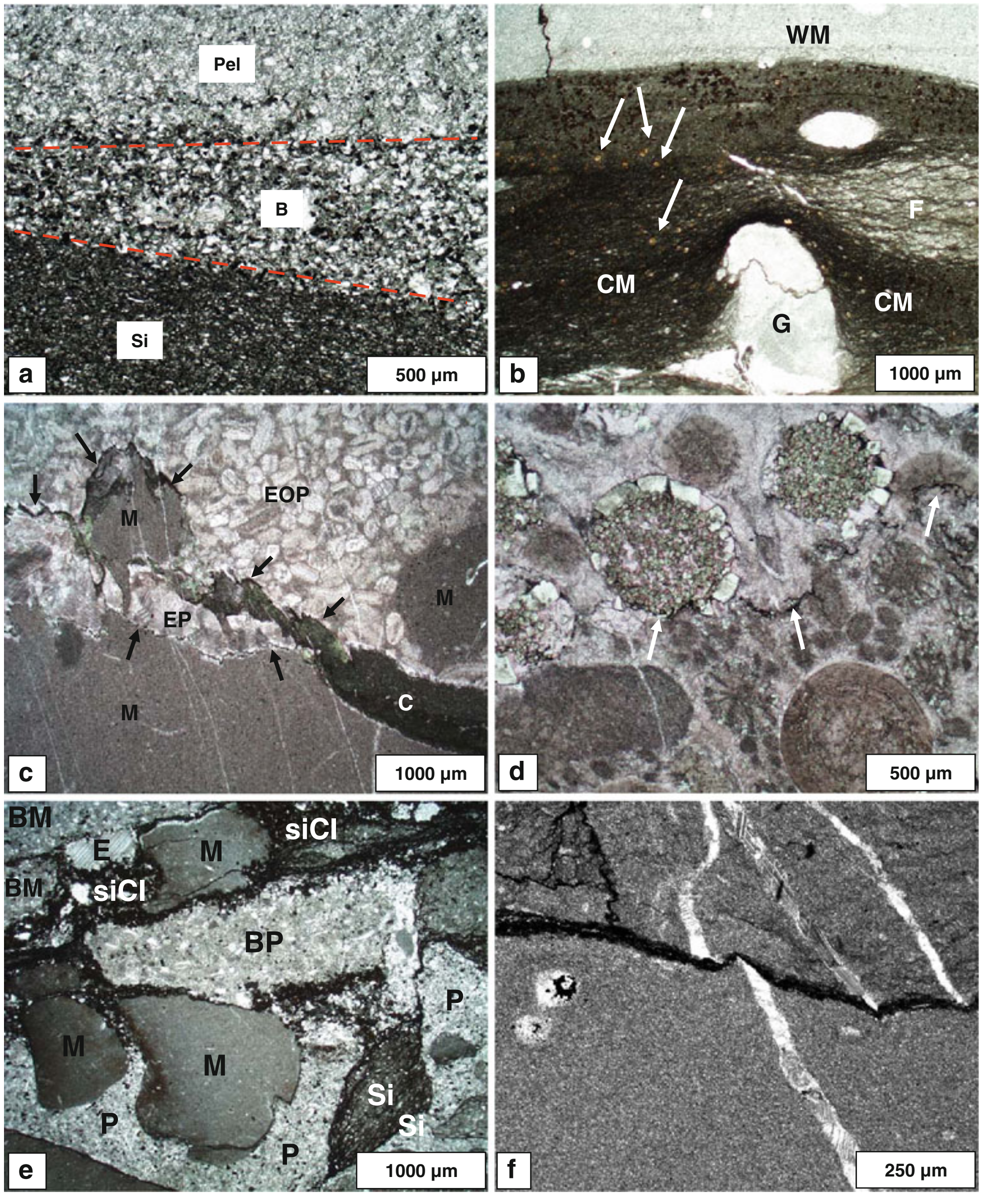

Fig. 6 Boundaries of sedimentation units and stylolitic contacts between varying facies types. **a** Alternation of silty, clayey micrite (Si) with fine-grained bioclastic packstone (B), and recrystallized pelsparite (Pel). The form of the sedimentation units depicted, indicates lateral pinch out within a low energy environment. **b** In a clay-rich mudstone-wackestone (CM) with minor amounts of small gastropods (G; up to 3 mm in size) marked differential compaction occurs. Around the gastropod (dissolved and cemented by granular calcite) the clay-rich sediment was compacted within a lateral distance of about 2 cm to half of the original thickness, which corresponds to the height of the gastropod. Within the compacted mudstone tiny, brownish dedolomite rhombohedra occur (*arrows*). A peloidal lens is characterized by clay flasers (F). The uppermost whitish micrite (WM) reveals just traces of completely recrystallized microfossils. **c** Different facies types can be separated by marked stylolitic boundaries even within one limestone bed. Locally relics of mudstone (M), calcareous claystone (C), and relics of echinoid-packstones (EP) can be recognized. They are overlain by echinoid-ooid-packstone (EOP). **d** Ooid bearing lithoclast peloid packstone overlain by an oolitic grainstone. The boundary is marked by an undulating stylolitic contact (*arrows*). Particles, which are relatively more stable against pressure solution act as spikes invading the over- or underlying rock. Ooids with well-preserved tangential textures are interpreted as primary Mg-calcite ooids. Ooids in the overlying grainstone were bimineralic ooids with Mg-calcite cores and aragonitic outer cortices. **e** Different limestone types (*M* mudstone, *BM* biogenic bearing mudstone, *BP* biogenic packstones, *Si* silty marls, *SiC* silty claystone, *E* echinoid fragment) are separated by stylolitic clay-rich accumulations of 0.01–1 mm thickness. The matrix rock is a slightly silty wackestone–packstone (P) nearly completely composed of very fine debris of fossils and carbonate crystals (10–100 µm). **f** At least two different generations of fractures occur, interrupted by marked stylolites. The first generation of fractures (depicted here), which is dislocated by stylolites, was formed before stylolitization. The fractures are up to 50 µm wide and are filled by coarse granular calcite

Eogenetic stage				Telogenetic stage	Dolomitization	Dedolomitization	Mesogenetic stage shallow and deep burial		Mesogen. Shallow burial
Recrystallization 1.st ooid generation									
	2nd generation ooid cortices								
		Compaction; split-off							
			Iso-pacheous cements						
				Internal Sediment; microspar					
				Dissolution of aragonite grains	Dolomite in matrix				
				Fitting of grains	Dolomitization Mg-Peloids				
				Granular cements	Dolomite in molds				
				Sytaxial overgrowth on echinoids					
				1st. gen. authigenic silica		Partly dedolomitization			
							Stylolites; pressure solution		
								Fractures along stylolites	
				2nd. gen. authigenic silica				Syntectonic fibrous calcite	
									Late fractures ganular calcite

Fig. 7 The relative timing of diagenetic events in the Middle Cambrian limestone analyzed. Subsequently to eogenetic marine and telogenetic freshwater stages, local dolomitization, and dedolomitization occurred before pressure-solution diagenesis markedly altered the rock

centimetres. The relative density of stylolites decreases to the top of the profile. Their style, spatial distribution and the thickness of clay enrichments allow the differentiation in several types.

The stylolite type (thickness 0.5–5 mm) which predominantly is responsible for the formation of diagenetic bedding (Fig. 6f) is nearly parallel to the original bedding plane (Wanless 1979) and is smooth with slightly weavy appearance (Logan and Semeniuk 1976). Locally iron minerals and silica neoformations are associated with clay residues.

A second type of stylolites penetrates limestone beds and commonly forms irregular anastomosing sets (Fig. 6c, e). These stylolites have no influence on the macroscopic bedding features of the carbonate rocks. Their amplitude is low and they form a dense network of interconnected stylolites. The thickness of the clay enrichments on single stylolites is <0.3 mm. They are often associated with sutured multi-grain seams (Fig. 5d) as classified by Wanless (1979).

A third type of stylolites is characterized by stylolaminated sets often developing laterally in small swarms around components and in clay rich carbonates (Fig. 6b). They have amplitudes of a few millimetres and form dense swarms with a lateral extension of a few centimetres. This type also contributes significantly to the formation of diagenetic bedding.

Furthermore, horizontal stylolites as defined by Turnit (1967), Turnit and Amstutz (1979) with marked small amplitudes occur (Fig. 6f) documenting lateral compaction stress.

Compaction, pressure solution, and stylolitization have been described by many authors (e.g. Bathurst 1975, 1995; Füchtbauer and Müller 1977; Tucker and Wright 1990; Railsback 1993; Flügel 2004). A general subdivision in mechanical compaction (loss of pore water, dislocation and rotation of allochems) and in chemical compaction (pressure solution, stylolitization) has to be made (Brown 1959; Barrett 1964; Fruth et al. 1966; Logan and Semeniuk 1976; Wanless 1979; Buxton and Sibley 1981; Pratt 1982; Shinn and Robbin 1983; Simpson 1985; Ricken 1987; Bathurst 1987, 1995).

Nevertheless, the question at which overburden pressure and temperature the boundary between mechanical and chemical compaction should be drawn is still open to debate as discussed by Heidug and Leroy (1994), Zhang and Spiers (2005), Lehner (2009) and also earlier documented by Park and Schot (1968), Rezak and Lavoie (1993) and underlined by the introduction of the term "chemomechanical process" (Lehner 2009). Many calculations and modelings were carried out to elucidate the loss of porosity and fluid during compaction (Meyers a Hill 1983; Ortovela et al. 1993; Broichhausen et al. 2005), and the time and depth of formation of stylolites (Audet 1995). Even self-organization (Railsback 1998) and the fractal structure of stylolites was analyzed (Drummond and Sexton 1998).

The formation of limestone-marl couplets is of great interest and explained by varying models due to compaction and/or due to variation in primary mineralogical composition of the carbonate material (Ricken 1987; Thunell et al. 1991; Westphal and Munnecke 1997; Westphal et al. 2000; Munnecke et al. 2001).

What is preserved of the primary facies and microfacies types?

The Zhangxia Formation (about 160 m thick in the Beijing area) is characterized by oolitic limestone, storm deposits, calcirudites, skeletal peloidal limestone, micritic limestone and dolomite. It can be subdivided in a lower, marlier unit and an upper unit dominated by oolites. Locally also stromatolitic–thrombolitic bioherms occur intercalated in shallow marine facies types and often laterally pinching out within some meters. All different facies types and their lateral and vertical interfingering observed, reflect low to moderate energy sedimentary environments influenced by various admixtures of silt-sized siliciclastic detrital material derived from a hinterland.

On the first glance thin-bedded, nodular, platy limestone are interbedded between oolitic packstones and grainstones and all other facies types of the 1st and the 2nd cycle of the Zhangxia Formation, as mentioned above.

Our studies indicate that on the one hand different facies microfacies types occur within the same thin section in their original spatial distribution (Fig. 6a, b). Silty, clayey micrite, fine-grained bioclastic packstone and recrystallized pelsparite occur in close association reflecting a low to moderate energy environment with high siliciclastic detrital input and lateral pinch out of sedimentation units.

Clay-rich mudstones and wackestones containing some gastropods reveal just slight changes in composition indicating a very low energy environment (Fig. 6b). Furthermore, pronounced differential compaction is documented by clay seams and flasers running around biomolds of former gastropods, which were early cemented by granular calcite. Primary clay rich sediment was compacted within a lateral distance of about 2 cm to half of the original thickness, which corresponds to the height of the gastropod nearby. Furthermore, a peloidal lens revealing much less clay flasers indicates the primary presence of slightly different clay-rich sediments.

On the other hand most commonly marked compaction-dissolution features can be recognized in the scale of the same thin section (Fig. 6c, d, e, f).

Locally, relics of mudstone, calcareous claystone, and relics of echinoid-packstone are closely associated and indented. Overlying echinoid-ooid-packstones reveal vertically indented boundaries indicating the disappearance of probably large but unknown amounts of different microfacies types (Fig. 6c).

In oolitic limestone marked dissolution can be recognized too (Fig. 6d). Ooid bearing lithoclast peloid packstones are overlain by oolitic grainstones. The boundary is marked by an undulating stylolitic contact. Particles relatively more stable against pressure solution act as spikes invading the over- and underlying rock. Both rocks indicate different primary facies conditions which are reflected by different ooids in the overlying microfacies types separated by the stylolite. Ooids with well-preserved tangential textures in the lower microfacies type are interpreted as primary Mg-calcite ooids. Ooids in the overlying grainstone are interpreted as bimineralic ooids with Mg-calcite cores and aragonitic outer cortices.

In other samples a complex mixture of different microfacies types is preserved (Fig. 6e). Mudstone, biogenic bearing mudstone, biogenic packstone, silty marl, silty claystone, and echinoid packstone are separated by stylolitic clay-rich accumulations of 0.01–1 mm thickness. A slightly silty wackestone–packstone, nearly completely composed of very fine debris of fossils and carbonate crystals (10–100 μm) is considered as background sediment.

The insoluble residue varies in the different microfacies types and is enriched in stylolites containing different amounts of silty quartz derived from silty claystones and marls.

All these sediments were primarily deposited besides and above each other according to "Walther's Law" reflecting primary low energy environments with the contemporary intercalation of high-energy oolitic facies. It cannot be excluded that different microfacies types were completely dissolved and consequently are missing in the sediment record now. Furthermore, there occur at least two generations of fractures interrupted by marked stylolites (Fig. 6f), which resulted in a more intensive dislocation of the isolated relics of different facies types.

The microfacies types in close association and indented fabrics reflect areas of small low-relief sedimentary bodies deposited by low to moderate water energy strongly influenced by tides. Packstone and grainstone layers were deposited by higher water energy whereas micrite/clay/marl deposits were formed in low relief areas by low water energy.

Consequently, the bedding of Middle Cambrian platy limestone of the Zhangxia Formation reflects primary different facies types deposited in a shallow sea. On the one hand, primary sedimentary features were subsequently enhanced by intense early and late diagenetic compaction, which was initiated at primary microfacies boundaries characterized just by very small differences (e.g. non carbonates, silt content, microfossils, different ooids). On the other hand, primary sedimentary features disappeared due to intense compaction, which resulted in clay seams (enrichments) of various thicknesses depending on the primary amount of insoluble residue in different microfacies types. Therefore, no statement can be made about the original thicknesses of the single beds and whether complete parts disappeared due to intense chemical compaction.

Discussion and concluding remarks

Plattenkalk, Lithographic Limestone, platy limestone—Where do the Cambrian limestones belong to?

In the context of the International Symposium on Lithographic Limestone and Plattenkalk it seems to be the right place for a discussion about the definition of Lithographic Limestone, Plattenkalk, and platy limestone. This was already discussed by Swinburne and Hemleben (1994), who subdivided the depositional environments of these sediments in (1) lake, (2) lagoon/tidal flat, (3) inner shelf, and (4) outer shelf. This also has to be seen under the view of the Fossil Lagerstätten concept (Sailacher 1970) and the varying quality of preservation of fossils in such sediments. The basic question is, how the wide variation of carbonate rocks containing a well-preserved fossil record can be classified into groups, which reflect the depositional environment as well as the conditions for fossil preservation. This might also enable us to get an idea of the conditions through time, responsible for the elimination of parts of the primary fossil content to varying degrees.

In general, single beds of Lithographic Limestone, Plattenkalk, and platy limestone are commonly homogeneous and reveal no or only weak internal bedding features or laminations. For their differentiation the field, classification of stratified sediments as presented by Flügel (2004, Fig. 3.2 on p. 55) can therefore be used.

Stratification types and their occurrence in varying depositional environments as illustrated by Flügel (2004; Fig. 3.2 on p. 57) can also be helpful for further characterization. Planar lamination, planar thin-bedding and graded bedding are features most common in slope and basin sediments. These characteristics correspond to the facies subdivision of Plattenkalk as documented by Swinburne and Hemleben (1994).

Furthermore, limestone beds appearing homogeneous at the first glance in the field might exhibit textural and structural inhomogeneity when analyzed in greater detail and reveal internal differentiation in fine laminae representing different small-scale sedimentation units.

Flügel (2004) postulates that field studies of bedding and stratification must consider (1) boundary planes and bedding surfaces, (2) bed thickness, (3) composition and internal structure of beds, and (4) vertical bed sequences. Bedding and lamination are caused by changes in depositional, biological and diagenetic factors. Furthermore the following parameters should be regarded when analyzing stratified sediments:

(1) Depositional factors primarily include changes in sedimentation rates, and in the composition of the sediment, and alternations of sedimentation and non-sedimentation phases.
(2) Biological controls are predominantly a result of the interaction of microbes and microbial mats with their physical and chemical environment and their influence on binding and trapping of the sediment (Noffke et al. 2001). Bioturbation commonly alters or destroys bedding and lamination structures and contributes to a homogenization of the sediment.

It is obvious that even small changes in sediment composition (primary and/or diagenetic) lead to different conditions resulting in the conservation of fossils to varying degrees. Therefore, primary facies and early diagenesis are most responsible for the conservation potential in such limestone.

This is also valid for the Upper Jurassic Plattenkalk of Southern Germany (Solnhofen Limestone) deposited in different basins with varying conditions over a period of about 5 Mio years (Schweigert 2007). Most prominent models for their formation are published by Barthel (1972), Keupp (1977), Viohl (1998), Keupp et al. (2007). The fine alternation of pure limestone and thin/or thick marl intercalations either reflect primary sedimentary processes or were formed by diagenetic alterations (Ricken 1987; Westphal and Munnecke 1997; Munnecke et al. 2001) enhancing primary sedimentological signals. Furthermore, Viohl and Zappa (2007) document silicified Plattenkalk from the Schamhaupten location (Kimmeridgian–Tithonian, S-Germany; "Kieselplattenkalk"). Dolomitic Plattenkalk is described by Fürsich et al. (2007) from the Upper Kimmeridgian of the Northern Franconian Alb. Lanza and Zeiss (2007) document “Lithographic Limestone” from the Upper Jurassic (Tithonian) of Argentinia. Dietl et al. (1998), Bantel et al. (1999) describe sections of the Nusplingen Lithographic Limestone (Nusplinger Plattenkalk; Upper Kimmeridgian of SW-Germany). Jurkovsek and Kolar-Jurkovsek (2007) describe a variety of platy limestone and laminated limestone rich in fossils (especially fishes) from various horizons within the Cretaceous platform carbonates from the Upper Cretaceous Komen–Triest Plateau in Slovenia. Plattenkalk with primary millimetrical lamination from the Upper Cretaceous of NE Mexico are described by Ifrim et al. (2007). The Fossil Lagerstätte of Monte Bolca (Eocene, Northern Italy) is described by Viohl (2008) and famous for its fish findings.

It can be stated that stagnant bottom water conditions and micritic matrix are most characteristic for Plattenkalk and Lithographic Limestone as described above. Combined with dark colours, which are indicative for a certain content of fine-dispersed organic matter, these parameters are the prerequisite for good fossil preservation. As already discussed by Füchtbauer and Goldschmidt (1964), Hall and Kennedy (1967), Scherer (1977), Kemper and Koch (1982), Seuß et al. (2009) organic matter in the matrix and in fossils hinders the water access, oxidation and recrystallisation. A very fine crystal size of micrite is responsible for very low flow rates forming a closed diagenetic system. Both are favoured by fine dispersed organic matter (stagnant bottom water) and by homogeneous very fine particle size of micrite (0.5–3 μm) as discussed by Koch (2007) for the Solnhofen Limestone. If the system is opened (enlarged permeability) by silty, sandy admixtures or by aggrading neomorphism of the micrite (recrystallisation) the fossils within the limestone bed will be altered (oxidation) within time spans of some years to tens of years.

Therefore, conditions of the depositional environment are most important for the later quality of bedded limestone as Fossil Lagerstätten. Consequently, a sound facies analysis based on sedimentological, faunal, and diagenetic parameters should be established. These parameters should also be added to the names of the bedded limestones (Plattenkalk, Lithographic Limestone, platy limestone) giving informations of the environmental conditions.

In all these models of Plattenkalk, Lithographic Limestone and platy limestone diagenetic parameters (diagenetic bedding, stylolitization, clay-marl alternations, dissolution, cementation) commonly influence and alter the primary sedimentary record of the fine-grained sediments. But these parameters, which are most characteristic for the platy limestone analyzed, were neglected until now in all discussions about Plattenkalk and platy limestone and attempts to their classification.

How to classify Plattenkalk, Lithographic Limestone and platy limestone?

Following the proposal of McKee and Weir (1953) the term “bed” should be limited to strata thicker than 1 cm. Very thin strata (thickness <1 cm) are called laminae (Campbell 1967). Laminae are the result of changing depositional conditions causing variations in grain size, texture, mineral composition, and content of clay and organic matter.

Bedded limestone of the type documented here, generally belong to the limestone “families” named Plattenkalk, Lithographic Limestone or platy limestone. In general, a rough idea of the depositional environment and genesis is also combined with these names. However, these limestones can form in many environments as summarized by Swinburne and Hemleben (1994). Consequently, using these names without detailed knowledge about some characteristic parameters (e.g. thickness, surface morphology, composition of allochems, particle and crystal size) results in more confusion and hinders the comparison of Plattenkalk, Lithographic Limestone, and platy limestone from different locations throughout the earth history.

Therefore, we propose to strictly separate the different terms as follows:

The descriptive term Plattenkalk refers to sequences composed of fine-grained, laminated limestone, which are bedded in flat centimetre-decimetre thick, parallel-sided units (Swinburne and Hemleben 1994).

The term Lithographic Limestone (“Lithographenschiefer”) according to Hohl (1981) refers to an Upper Jurassic platy limestone, which can be used for lithography (see Portenlänger 1998; Keupp 1999; Derra 2002) because of its homogeneous texture and very fine particle size. Bernier (1994) underlines the use of the word lithographic in order to have a precise word to define a precise limestone. It is predominantly quarried in the area of Solnhofen and specific technical data are required (homogeneous, very tight, no visible porosity, intercrystalline microporosity of up to 8% between tiny crystals of 0.5–2.5 μm in size, high pressure stability (yellowish Solnhofen = 1,600 kg/cm^2; grey–bluish Solnhofen = 2,600 kg/cm^2). Therefore, the term Lithographic Limestone is well defined and excludes all other limestones, which do not fit into this precisely described group.

Platy limestone can be characterized in a very broad sense as limestone, which separates in plates of different thicknesses when quarried (Röper 2005; Munnecke et al. 2008). Platy limestone can have irregular and inclined bed surfaces, which also can pinch out laterally. Commonly, an analysis of the morphology of the plates (thickness, bed surface, horizontal bedding, etc.) is missing.

The single beds in both Plattenkalk and platy limestone can have different thicknesses, internal structure (e.g.

micritic, microsparitic) and fabric (e.g. homogeneous, nodular), fossil content, abiogenic particles, micro-morphology of bed surfaces and other variations (e.g. chemical, mineralogical). All these detailed parameters should be added to the basic name of the Plattenkalk and platy limestone and used in a system similar to Folk's limestone classification.

We propose a classification, which is based on these macroscopic, microscopic and sub-microscopic parameters. In general, the term "stratified sediments" can be used. These can be subdivided into Plattenkalk or platy limestone even by field analysis.

Further analyses reveal if Lithographic Limestone occur as a subgroup of Plattenkalk with well-defined parameters, which allow using this limestone for lithography. Therefore this name should only be used when this data are available. Characteristic primary and secondary (later non synsedimentary diagenetic features) should be added to each name according to a logic system as in Folk's classification for limestones (Folk 1959, 1962). The thickness of beds as well as textural characteristics (homogeneity, lamination) should be used as prefix in a similar way.

Accordingly, names like "homogeneous, thin-bedded Lithographic Limestone", or "siliceous, slightly laminated Plattenkalk", or "undulatory, compactional, nodular limestone" may be used. All these names reflect the depositional environments to a certain degree as well as diagenetic parameters. They also give hints to the quality of a limestone, which might be used in building stone industry. A consequent use of this classification with all the detailed parameters will help to understand fossil preservation and/or non-preservation in different types of Plattenkalk, Lithographic Limestone, and platy limestone. According to this classification the thin-bedded limestones of the Zhangxia Formation are classified as "compaction-formed, platy limestone with parallel, lenticular, and weavy textures". This name clearly reflects the macroscopic appearance as well as important aspects of the diagenetic history of these bedded limestones.

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