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POTENTIAL SIGNIFICANCE OF SYNDEPOSITIONAL CARBONATE DISSOLUTION FOR PLATFORM BANKTOP AGGRADATION AND SEDIMENT TEXTURE: A GRAPHIC MODELING APPROACH.

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ABSTRACT

In shallow-water carbonate environments, within the unlithified sediment, a substantial portion of calcium carbonate may be dissolved and recycled to the sea, resulting in a lowering of the net sediment budget. The potential implications of dissolution loss to the stratigraphic development of carbonate platforms to date were unexplored. An estimate of the stratigraphic consequences of dissolution on banktop aggradation by means of comparison with recent carbonate environments is set back by the facts that both dissolution and biogenic plus "inorganic" precipitation of calcium carbonate proceed simultaneously, that long-term off-site/to-site sediment transport is difficult to quantify, and that each of these processes varies in space and time. Herein, the possible geological significance of dissolution loss on sediment texture and banktop aggradation is evaluated by graphic models. The models include individual, idealized sediment particles as basic "building blocks" of idealized sediments, and serve to illustrate possible consequences of dissolution each on individual particles, on sediment texture, and on the thickness of both unlithified sediment layers and lithified carbonate intervals.

Model results indicate that depending on (a) composition of the idealized sediment (including primary pore space), and (b) precipitation of calcium carbonate subsequent to dissolution, a marked reduction of stratigraphic thickness of the lithified rock column will occur only at net losses (dissolution recycling minus total precipitation) exceeding about 50 - 70% calcium carbonate. For lower net losses, in most cases, the detraction from banktop aggradation is relatively low and overlaps with the range of potential thickness reduction imposed by other processes. On its own merit, dissolution loss of up to about 50% the annual budget of calcium carbonate probably can hardly drown a productive, ecologically intact tropical-subtropical carbonate platform. Dissolution loss will significantly lower the aggradation potential only upon a sustained lowering of carbonate production, and/or upon persistently lowered carbonate accumulation at site. Because mud-sized particles in general are more susceptible to dissolution than larger grains, it seems plausible that the major portion of dissolved calcium carbonate is derived from lime mud. Dissolution may influence the long-term development of carbonate shelf geometry, by reducing the amount of lime mud available for off-bank transport, and by lowering the net sediment budget on platform flanks of intrinsically lower sediment production. In shallow-water carbonate sediments, because of rapid sediment turnover, micritization, boring, abrasion and fragmentation, features indicative of dissolution tend to be erased. Common textures and compositions of shallow-water carbonate rocks may conceal substantial dissolution.

1. INTRODUCTION

For shallow neritic carbonate environments, actuogeological field studies and sediment incubation experiments demonstrated that a substantial proportion of calcium carbonate is dissolved in the unlithified sediment (Morse et al., 1985; Moulin et al., 1985; Walter and Burton, 1990). Syndepositional dissolution results from the interaction of the carbonate system with chemical compounds released during the remineralization of organic matter, and is greatly enhanced by bioturbation and bioirrigation (Walter and Burton, 1990; Ku et al., 1999). The dissolved calcium carbonate in part may reprecipitate as a cement within the sediment (for instance, in intraskeletal pores or between sediment grains), i. e. it is redistributed, but another part is recycled to the sea by the bioirrigative water flux. Although the relative amounts of redistribution versus recycling are still poorly constrained, estimates of the reflux of dissolved calcium carbonate suggest that up to 50% of the annual calcium carbonate budget may be recycled (Walter and Burton, 1990).

The results of these observations and experiments may appear paradox in view of the geological record containing thick successions of shallow-water platform carbonates. Yet the actuogeological studies documenting dissolution include carbonate environments that persisted for millions of years and are underlain by thick carbonate piles. Deep-tiered, intense bioturbation and bioirrigation pertained at least over Meso-Cainozoic time, and substantial dissolution of aragonitic and, locally, of calcitic fossils has been documented for Palaeozoic and Mesozoic neritic successions (Sanders, 1999, 2001, 2003; Cherns and Wright, 2000; Wright et al., 2003). Because syndepositional dissolution obviously is not a geologically young phenomenon, the questions arise what are potential implications of syndepositional dissolution for the stratigraphic development of carbonate platforms? And why are features of dissolution not commonplace in shallow-water carbonate rocks, or why has syndepositional dissolution been recognized much earlier in deep-water limestones? To evaluate possible consequences of syndepositional dissolution on banktop aggradation, a one-to-one comparison with recent carbonate environments is severely complicated by the facts that both dissolution and carbonate production proceed simultaneously and vary in space and time, that long-term off-site/off-bank sediment transport is difficult to quantify, and that the stratigraphic thickness of the final, lithified carbonate rocks is also reduced by meteoric dissolution during subaerial exposure and by pressure solution. In the present paper, following a summary account on processes and

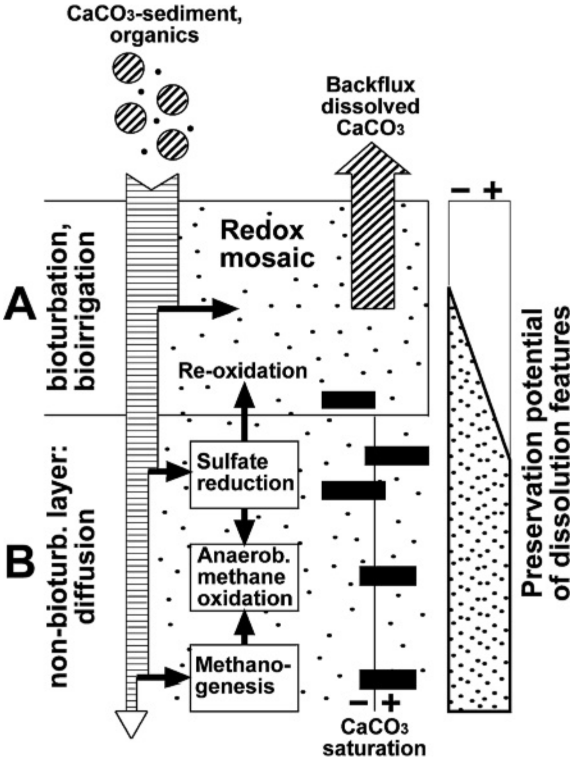

Figure 1: Processes of syndepositional dissolution and typical saturation states of calcium carbonate in unlithified sediment. A (active layer): In the upper part of the sediment column, bioturbation and bioirrigation produce a redox mosaic, and propel a backflux of dissolved calcium carbonate to the sea. Frequent reoxidation of reduced chemical species results in prevalent undersaturation for calcium carbonate. Preservation potential of textural features produced by dissolution is low. B: In the non-bioturbated layer below, sulfate reduction (including anaerobic methane oxidation) and methanogenesis, and the related typical saturation states of calcium carbonate are mainly controlled by diffusion. Preservation potential of dissolution-related textures is high. Because of absence of burrowing, potential for dissolution tends to be lower than in the active layer.

geological features of syndepositional dissolution, the above questions are explored by geometrical considerations and by graphic modeling of sediments and sediment columns. Results suggest that, except major dissolution losses and/or lowered carbonate production, dissolution exerts comparatively little effect on the stratigraphic development of platform banktops, and a significant amount of calcium carbonate may be dissolved without leaving a clear-cut record thereof. Widespread neritic processes such as rapid sediment turnover, micritization, abrasion and fragmentation all act to erase potential indications of solution.

1	$CH_2O + O_2 = H_2O + CO_2$
2	$HS^- + 2\ O_2 = SO_4^{2-} + H^+$; $H_2S + 2\ O_2 = SO_4^{2-} + 2\ H^+$
3A	$2\ CH_2O + SO_4^{2-} = HS^- + HCO_3^- + H_2O + CO_2$
3B	$CH_4 + SO_4^{2-} = H_2S + H_2O + CO_3^{2-}$
4	(4.1) $2\ CH_2O + 2\ H_2O = 2\ CO_2 + 4\ H_2$ (4.2) $4\ H_2 + CO_2 = CH_4 + 2\ H_2O$
5	$CaCO_3 + CO_2 + H_2O + = Ca^{2+} + 2\ HCO_3^-$
6	$CaCO_3 + H^+ = Ca^{2+} + HCO_3^-$
7	$2\ CaCO_3 + 2\ CH_2O + 2\ O_2 = 2\ Ca^{2+} + 4\ HCO_3^-$

Table 1: Net reactions of organic matter oxidation relevant to calcium carbonate saturation, in pore waters of pure carbonate sediment (compiled from several authors). Vertical arrangement of reactions (1) to (4) reflects prevalent redox reaction down-section, or from a burrow wall or a sea grass/algal rhizome into the adjacent sediment. (1): Aerobic oxidation; (2) Aerobic oxidation of hydrogen sulfide species produced by sulfate reduction; (3A) Sulfate reduction; (3B) Sulfate reduction by methane oxidation (anaerobic methane oxidation); (4) Methanogenesis (two-step process). In bioturbated-bioirrigated shallow-water sediments, reactions (1) to (4) may proceed adjacent to each other, in a patchy "redox mosaic". (5), (6): Dissolution of calcium carbonate due to production of Co^2 and H+ in reactions (1) to (3A). (7) Net equation of stoichiometric coupling of carbonate dissolution to organic matter oxidation (Ku et al., 1999, their eqn. 7).

2. Process of syndepositional dissolution

Unlithified, pure shallow-water carbonates essentially consist of aragonite, magnesian calcite, calcite, organic matter and pore fluid. In the pore fluid, by controlling pH and alkalinity, both organic matter remineralization and re-oxidation of reaction by-products influence the saturation state of calcium carbonate. Organic matter is remineralized by several redox reactions (Tab. 1). In neritic carbonate sediments, the bioturbated-bioirrigated active layer (Fig. 1) is down to more than a metre in depth (e. g. Walter and Burton, 1990; Tedesco and Aller, 1997). Per square metre sediment, crustacean burrows add about 1-9 m^2 of diagenetically reactive surface (Griffis and Suchanek, 1991, Tab. 5). In recent burrowed carbonate sediments of the Bahamas and South Florida, the upper 50-350 cm are completely turned over within 100-600 years at most (Tedesco and Aller, 1997), but rates of bioturbative, combined sediment turnover and sediment dislodgement in the subsurface are higher still (Griffis and Suchanek, 1991, p. 177). Because of intense bioturbation and bioirrigation a low, continuously replenished stock of labile organic matter fuels a high rate of redox reactions (Walter and Burton, 1990). In the active layer, the same unit volume typically is driven hundreds to thousands of times through a cycle of aerobic oxidation to methanogenesis (cf. Tab. 1) (Aller and Aller, 1998). Because of effective production of CO_2 and H_2S, and because of re-oxidation of H_2S (producing H^+ ions; equation 2 in Tab. 1), the pore water in the resulting redox mosaic (Fig. 1) of the active layer tends to be undersaturated for calcium carbonate, and dissolution prevails (Morse et al., 1985; Walter and Burton, 1990). As a net effect of redox cycling, dissolution is stoichiometrically coupled to organic matter oxidation (equation 7 in Tab. 1) (Ku et al., 1999). Based on alkalinity flux, for sites in South Florida, for the top 25 cm of the sediment, Walter and Burton (1990, p. 630) estimated that up to 50% of the annual calcium carbonate production may be recycled, in dissolved form, to the sea by bioirrigation. Although part of the alkalinity flux may result from solution of very early $CaCO_3$ precipitates (cf. Broecker and Clark, 2003; Morse et al., 2003), significant reflux is supported by coupling of dissolution to organic matter remineralization (Ku et al., 1999; Andersson et al., 2003), and by the high bioirrigative pore water flux in tropical to temperate neritic environments (cf. Griffis and Suchanek, 1991; Bromley, 1996). In the active layer, because of rapid sediment turnover by bioturbation and during high-energy events, the preservation potential of textural features produced by dissolution is low.

In the non-bioturbated layer (B in Fig. 1), below the active layer, organic matter is oxidized by sulfate reduction and methanogenesis. Methanogenesis and high rates of sulfate reduction tend to result in oversaturation for calcium carbonate, whereas low rates of sulfate reduction tend to produce undersaturation (Fig. 1) (Walter and Burton, 1990). In the non-bioturbated layer, dissolved calcium carbonate produced by local undersaturation can migrate by diffusion to sites of local precipitation, i. e. it is redistributed. Because the sediment is undisturbed or disturbed only by a few, deep-tiered burrows, loci of early cementation such as burrow tracts, and features of dissolution such as "ghosts" of dissolved shells or tests (see below) are of high preservation potential.

3. GEOLOGICAL INDICATIONS

In carbonate rocks, syndepositional dissolution is recognized by textural features, by taphonomy, and by sediment composition (see Sanders, 2003, for detailed descriptions). For shells of calcite and/or aragonite, such as in molluscs, aragonite dissolution is indicated by replacement of the aragonitic shell layer by matrix (Fig. 2 A, Fig. 3 B). Similar features of dissolution are long-known for deep-water limestones (Fig. 3 A). For bioclasts with constructional cavities, such as the central channel in dasyclads, widening of such cavities indicates dissolution (Fig. 2 B, Fig. 3 C). Partial to wholesale dissolution of shells or tests may be recorded by "hair-lines" of dark organic material or of iron sulfide (Fig. 2 C, Fig. 3 D). Gradients of shell preservation from internal moulds with totally dissolved shells at the base to well-preserved shells at the top of beds (Fig. 2 D) or, in bioturbated limestones, patches with internal moulds adjacent to patches with partially dissolved shells (Sanders, 2003, Fig. 14) also indicate dissolution. Former presence of bioclasts that were dissolved while resting in unbioturbated sediment is recorded by lateral gradients of fossil assemblage, preservation and host lithology (Fig. 2 E) (El Albani et al., 2001). If shells or skeletons were dissolved in bioturbated sediment, their former presence may yet be indicated by a larger-scale, lateral contrast in fossil assemblage and preservation, without a marked change in palaeobathymetry and substrate indicated (Cherns and Wright, 2001; Wright et al., 2003). In lime mudstones to wackestones to floatstones, pores are locally common that show highly irregular margins (Fig. 2 F, Fig. 3 E). Fossils projecting into these pores are corroded or truncated. Although the development of such pores may have started by burrowing and/or during dewatering, this indicates that they were at least overprinted by dissolution (see Sanders, 2003, p. 100 ff.). Hardgrounds along drowning unconformities may consist of an irregular, pitted solution surface coated by iron sulfide. In dissolution pores below the hardground, pore-linings of iron sulfide and truncated fossils may also record dissolution (Fig. 2 G) (Read, 1982). In pores containing several generations of marine cement, cement generations may be separated by dissolution surfaces (Fig. 2 H) (Tobin and Bergstrom, 2002). The described pore types all were documented from limestones not subject to early subaerial exposure. In poorly sorted bioclastic sediments derived from organisms secreting both calcite and aragonite, such as many molluscs, a composition largely or exclusively of calcitic shell fragments ("calcite-biased" bioclastic sediment fraction) hints on dissolution of the aragonitic fragments (Sanders, 2003, p. 102 f.).

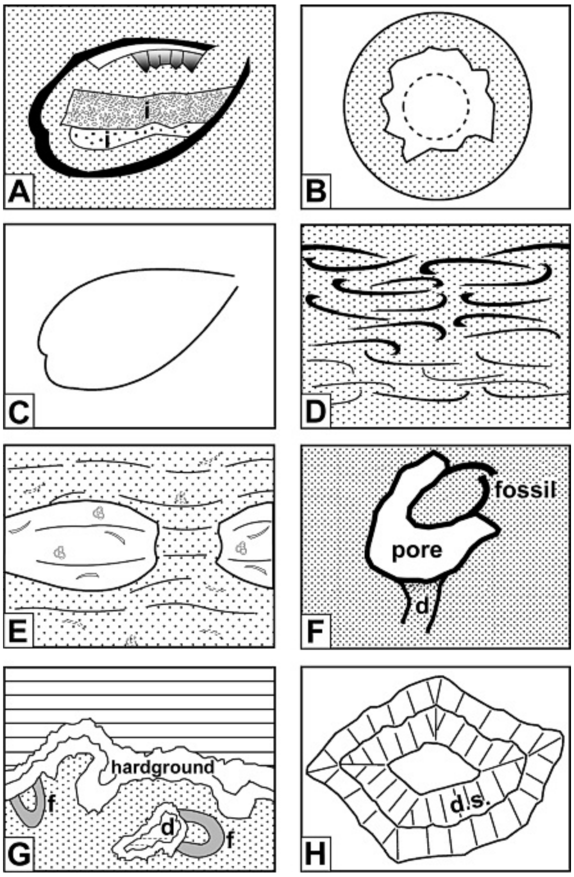

FIGURE 2: Geological indicators of syndepositional dissolution (see Sanders, 2003, for full descriptions and discussion). A: Mollusc. Calcitic shell layer (black) is preserved. Aragonitic shell layer (white) is partly or totally dissolved and replaced by matrix (stippled) that is of identical nature and in physical continuity with the matrix the fossil is embedded within. Deposition of internal sediments (i) may have occurred before aragonite dissolution, or after dissolution (in contact with the calcitic shell layer). Dissolution is also recorded by corroded and truncated crystals of intraskeletal cement (grey) in contact to matrix. B: Bioclast (e. g. a dasyclad alga) with primary internal cavity (dashed circle) that has been widened by dissolution. C: Wholesale dissolution of mollusc, with relict of periostracum (black line) remained. D: Shell storm bed, with vertical gradient in shell preservation (no inverse grading; see Sanders, 2003). E: Limestone nodules with fossils, in a matrix of marl with fossil ghosts. F: Spar-filled pore that originated or was widened by dissolution, with corroded fossil projecting into. Pore generation or pore widening was associated with dewatering along discrete pathways (d). G: Marine, encrusted hardground with fossils (f) truncated along the hardground and at the contact to dissolution pores (d). H: Pore-lining marine cement, with dissolution surface (d. s.) between cement generations.

4. SIGNIFICANCE OF DISSOLUTION FOR CARBONATE TEXTURES: A GRAPHIC TEST

Walter (1985) showed that depending on the degree of undersaturation for calcium carbonate, dissolution is controlled by bioclast microstructure, both bioclast mineralogy and microstructure, or only by mineralogy. In general, magnesian-calcitic bioclasts (coralline algae, benthic foraminifera) and aragonitic bioclasts with finely crystalline microstructure (*Halimeda*) dissolve more readily than bioclasts of dense aragonite (corals, molluscs), dense magnesian calcite (echinoderms), and calcite (some larger benthic foraminifera) (Moulin et al., 1985; Walter and Morse, 1985). In recent carbonate sediments, the different vulnerability of bioclasts to dissolution leads to taphonomic shift that can be quantified by comparing the life assemblage to the composition of the sediment (e. g. Murray and Alve, 1999; Powell et al., 2002). In carbonate rocks, taphonomic shift is difficult to quantify since the original proportions of bioclasts are unknown, at least in most cases (see Cherns and Wright, 2000; Wright et al., 2003, for exceptions). Many bioclasts contain constructional cavities typically ranging in width from centimeters to microns, resulting in a large total surface (Walter and

Morse, 1984). Although only a fraction of the total surface is available (Walter and Morse, 1985), dissolution does proceed in inner cavities of bioclasts (Fig. 3 C) (e. g. Henrich and Wefer, 1986; Sanders, 1999).

To estimate the potential impact of syndepositional dissolution on texture, graphic images of sediment grains have been produced and quantitatively checked. Figure 4A shows a simplified image of bioclasts as seen in thin section, such as a bivalve shell, a crinoid stem fragment, and a calcareous alga or a foraminifer. In figure 4A, no dissolution is inferred. In a next step, calcium carbonate (=black area in graphic image) was removed from each of the bioclasts. For the bivalve shell, calcium carbonate was removed only from the outer surface; for the crinoid fragment, most material removed was from the outer surface and a small part from the surface of the central channel; for the alga/foraminifer, about the same amount of material was removed both from the outer and inner surface. Removal of calcium carbonate (=black area) simulates dissolution, and was done with the eraser function of the program Adobe Photoshop 6. After removal, the remaining black area (=calcium carbonate preserved) was quantified by the pixel count ("magic stick") function of Adobe Photoshop 6. Figure 4B shows the same bioclast ensemble than figure 4A, but with 30% calcium carbonate removed by simulated dissolution; figure 4C shows 57% calcium carbonate removed.

Next, patches of "artificial grainstone" were built (Fig. 4D-4F). Each patch was produced by random arrangement of eight "sediment building blocks" as shown in figure 4A to 4C. To achieve different amounts of simulated total dissolution, a different number of sediment building blocks 4A to 4C was used to construct each of the grainstone patches in figure 4D to 4F. The sediment patch of figure 4D shows a grainstone with 18% total dissolution; figure 4E shows a total loss of 40%; in figure 4F, total dissolution loss is 50%. This approach implies that loss of calcium carbonate may result in comparatively little obvious change of bioclast shape/size and of grain fabric, and that apparently "normal" shallow-water carbonate sediments may conceal significant amounts of total dissolution.

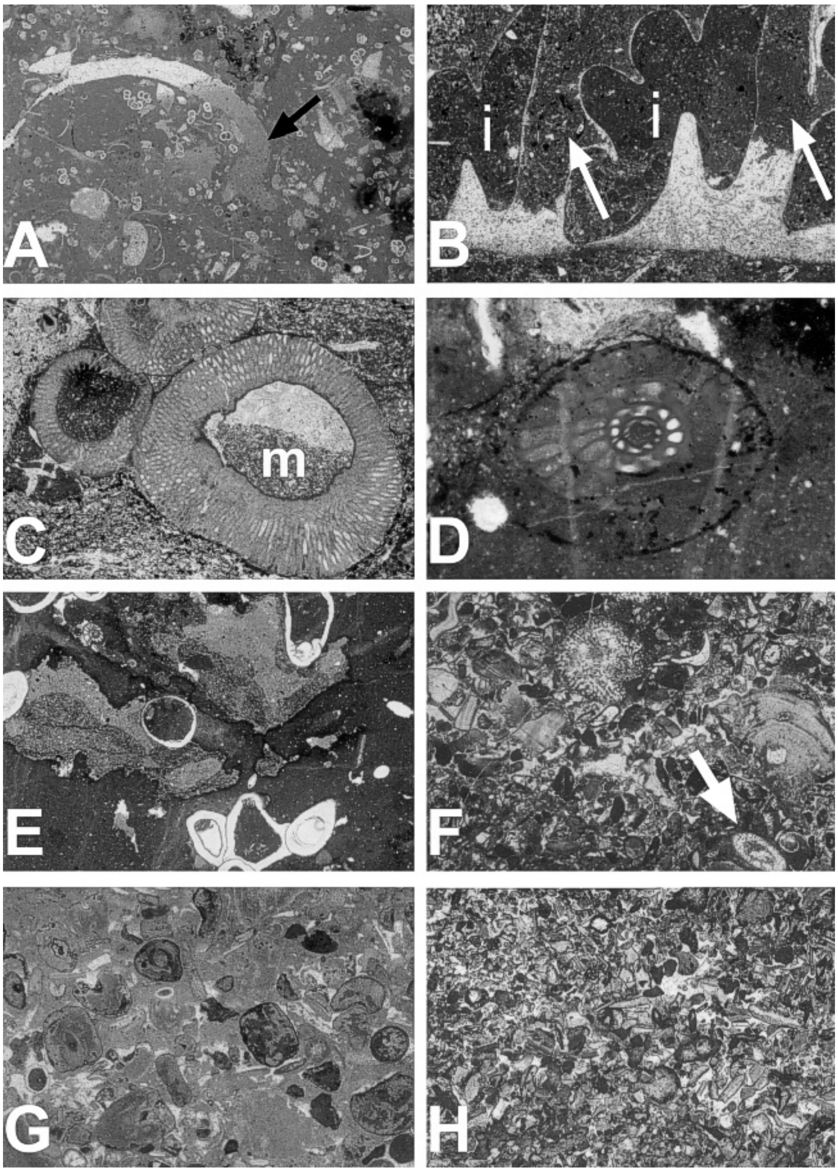

Figure 3: Thin section photomicrographs of features of syndepositional dissolution. A: Dissolved bivalve shell, geopetally infilled by lime mud (arrow). Deep-water limestone with planktonic foraminifera, mollusc debris, and echinoderm fragments. Upper Tithonian, Austria. B-H: Shallow-water limestones. B: Section through nerineid gastropod shell, with whorls filled by internal sediment (i). Syndepositional dissolution removed most of the shell (arrows); the resulting pore space became filled by matrix identical to and in physical continuity with the matrix embedding the fossil. Coniacian, Austria. C: Section through calcareous algae with geopetal sediment fill (m). The central cavity of the algae was widened by syndepositional dissolution. Asselian, Austria. D: Fusulinacean foraminifer, partly removed by dissolution in the firm sediment, and partly pyritized (black line). Gzhelian, Austria. E: Pores in lime-muddy mound with auloporid corals (light cross-sections). The pores show an highly irregular, "ragged" outline, are widened by early dissolution, and are thinly fringed by pyrite (blackened pore margins). Gzhelian, Austria. F: Bioturbated shallow-water bioclastic packstone to grainstone composed of formerly aragonitic fragments (rudists, corals, dasycladaleans) and calcitic fragments (rudists). Arrow shows dasycladalean fragment with widened central channel. Campanian, Austria. G: Neritic limestone composed mainly of crinoid fragments of highly different taphonomic state (light grey: well-preserved; grey to dark grey: more-or-less micritized, stained, and marginally corroded). H: Bioturbated bioclastic packstone to grainstone rich in micrite-rimmed bioclasts of calcitic and formerly aragonitic mineralogy. Santonian, Pyrenees.

For deep-water limestones, taphonomic shift by dissolution has long been recognized (e. g. Schlager, 1974, and many others). The diagenesis of deep-water limestones is mainly controlled by diffusion, i. e. fabrics indicative of dissolution, such as partly to completely dissolved ammonite shells, commonly stay preserved. Conversely, shallow-water platform sediments are subject to intense physical and biological processing down to a depth of a few decimeters at least (e. g. Tedesco and Wanless, 1991; Tedesco and Aller, 1997; Ku et al., 1999). Reworking and mixing of sediment during high-energy events and by burrowing, and fragmentation, grain abrasion and destructive

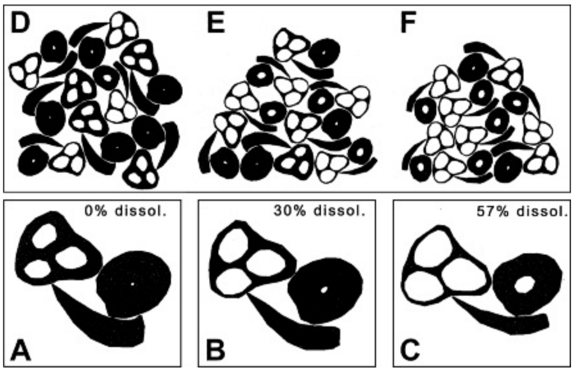

Figure 4: A-C: Three idealized bioclasts, with different amounts of dissolution (see Fig. 3B, 3C, 3D, for dissolution proceeding from the outer surface and/or the inner surface of bioclasts). D-F: Artificial grainstone each composed of a random arrangement of eight building blocks as shown in A to C. D: 18% of sediment dissolved. E: 40% of sediment dissolved. F: 50% of sediment dissolved. See text for discussion.

micritization all act to remove, or to strongly overprint at least, the record of syndepositional dissolution. In limestones that, during deposition of the sediment, were subject to bioturbation, dissolution is scarcely recorded directly, and in a non-quantitative way, such as by widened inner cavities in some fossils (Fig. 3 C, 3 F). Locally, distinct differences in preservation may hint on dissolution (Fig. 3 G), whereas in many other cases, no obvious textural or compositional record of dissolution is preserved (Fig. 3 H). Thus, in shallow-water sediments, just the processes that propel extensive dissolution (mainly bioturbation and bioirrigation, see above) at the same time erase the textural and compositional record thereof. In other words, mere presence of a "normal" carbonate rock composed of a shallow-water mixture of formerly aragonitic bioclasts and calcitic bioclasts does not imply that syndepositional dissolution was inactive.

5. SIGNIFICANCE OF DISSOLUTION FOR BANKTOP AGGRADATION: GRAPHIC MODELING APPROACH

Provided that a reflux, from the sediment to the sea, of dissolved calcium carbonate of up to 50% of the annual $CaCO_3$ site budget is widespread (see chapter "Process of syndepositional dissolution"), the question arises what this may imply for the stratigraphic development of carbonate shelves. At face value, one might expect a 50% reduction of the rate of banktop aggradation. Because sediments consist of particles, however, such intuitive reasoning is incorrect. To approach that question, consider an idealized sediment of equal-sized spheres of calcium carbonate. For a sphere, the volume is $v = r^3\pi$ (r: radius), hence the diameter is $d = 2r = 2(v/\pi)^{1/3}$. In other words, upon a linear change of volume, the corresponding change of diameter is much lower. Thus, if a sphere of calcium carbonate is subject to 50% dissolution, its diameter decreases only by 21% (Fig. 5). Because for an idealized sediment of equal-sized spheres, the diameter of spheres can be taken for stratigraphic thickness (for any type of sphere packing), this implies that if such a sediment were subject to 50% dissolution loss, stratigraphic thickness were reduced for only 21% (Fig. 5). For losses smaller than 50%, the reduction of stratigraphic thickness would be quite small (Fig. 5). For instance, for 30% loss, the reduction of thickness were about 11%.

In a next step, the effect of dissolution loss versus processes of lithification (including cementation and pressure solution) on the final thickness of a fully lithified sediment layer was tested by graphic modeling (Fig. 6). Idealized sediments include "ooids" (full black circles in Fig. 6A, 6D), "hollow bioclasts" with a single larger constructional cavity (black rings in Fig. 6B, 6E), and "complex grains" (white-hatched circles in Fig. 6C, 6F) simulating bioclasts with more complicated cavities. Construction and arrangement of each sediment column was done in Freehand 10. Each of these sediments was then subjected to 30% and 60% dissolution. Again, dissolution was simulated by removal of black area (=calcium carbonate) from the constituent grains, and was quantified by pixel counting in Adobe Photoshop 6. Under the simplifying approximation that carbonate lithification can be modelled as the reduction of primary or intrinsic porosity down to zero percent, two diagenetic pathways were tested, case (1), syndepositional dissolution followed by lithification exclusively by pressure solution (Fig. 6A-C), and case (2), dissolution followed by lithification by both cementation and pressure solution (Fig. 6D-F).

Case 1: In this case, for grains such as ooids, the relations outlined in figure 5 pertain (see Fig. 6A). Assuming that dissolution leads to an equal reduction of ooid diameter, *within* each of the columns A1 to A3, the relative reduction of lithified layer thickness (LLT) is the same. Note, however, that even with 60% dissolution loss and complete occlusion of the pore space by pressure solution (A3), the LLT is 64% of that with zero percent syndepositional dissolution (A1). This is still within the typical range of reduction of layer thickness by pressure solution deduced for real carbonate successions (see below). For sediments composed of grains with a constructional cavity, because both primary and intrinsic pore spaces are larger due to the cavities, lithification only by pressure solution leads to a comparatively larger

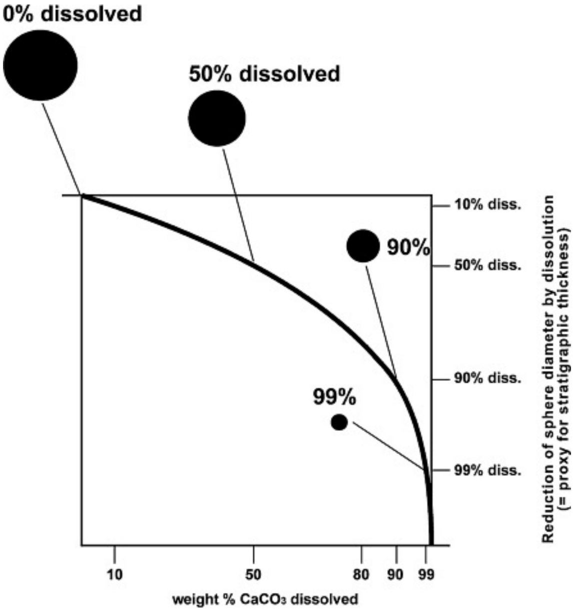

Figure 5: Curve to show reduction of the diameter of a sphere (black circles) as a function of the reduction of its weight. Black circles represent idealized spherical particles of calcium carbonate; weight reduction represents dissolution. Reduction of sphere diameter (Y-axis) is a proxy for stratigraphic thickness (for any type of sphere packing). On the right-hand Y-axis, the reduction of sphere diameter (stratigraphic thickness) is indicated for 10%, 50%, 90% and 99% dissolution. See text for discussion.

reduction of LLT (Fig. 6B1, 6C1) than for "ooids". As a result, the impact of dissolution loss is larger, too. Whereas a loss of 30% yields reductions of LLT within the range observed for many natural carbonates (see B2, C2), for 60% loss, values of LLT of 48% and 41% the thickness without dissolution result (B3, C3). Note, however, that case 1 is extreme in that it assumes that all dissolved $CaCO_3$ is lost from site, and that lithification is exclusively by pressure solution.

Case 2: Before syndepositional dissolution was discovered, tropical shallow subtidal carbonate environments became prominent for the widespread precipitation of early marine cement both in inter- and intragrain pores. Carbonate environments are compartmentalized with respect to the ratio of carbonate production (biogenic production plus precipitation) versus destruction (destructive micritization, "chemical" dissolution) (Sanders, 2003). At least in most tropical, shallow neritic carbonate environments, thus, loss of calcium carbonate by dissolution will be partly compensated by precipitation of cement and/or by epitaxial overgrowth of calcium carbonate before or after dissolution (see e. g. Perry, 2000; Morse et al., 2003) and, perhaps, by precipitation at the sediment-water interface (cf. Jahnke and Jahnke, 2004). In case 2, to account for cementation, a diagenetic pathway was checked including dissolution, followed by 50% reduction of the resulting pore space by cementation, followed by pressure solution occluding the remaining porosity to zero. For sake of visual clarity, in figure 6 D to F, the cement has not been shown separately. The results indicate that relative to dissolution followed by lithification only by pressure solution (Fig. 6D1, E1, F1), adding 50% cementation after dissolution markedly dampens the substractive effect on LLT (Fig. 6D-F). Also in the case of 60% dissolution loss before cementation and pressure solution, reduced LLTs result that are well-within the range of reduction of final layer thickness in natural carbonate rocks (see 6D3, E3, F3).

At least over large areas of platform banktops, both dissolution (Morse et al., 1985; Walter and Burton, 1990; Ku et al., 1999) and early cement precipitation proceed simultaneously (compare e. g. Perry, 2000; Morse et al., 2003). The final effect of total dissolution loss on LLT thus will depend on site-specific conditions. The investigated case 1 and case 2, however, suggest that in real carbonate environments with both dissolution and precipitation, except total dissolution *loss* (not just redistributon within the sediment) of more than about 50-70% of calcium carbonate, the impact of dissolution on LLT will be comparatively low. On platform banktops, the "potential" stratigraphic interval thickness (i. e. thickness only due to carbonate production) is reduced not only by syndepositional dissolution, but also by other processes such as off-site/off-bank sediment transport, dissolution during subaerial exposure, and pressure solution. In carbonate successions, a 5-40% reduction of thickness by pressure solution is common (Ricken and Eder, 1991). Similarly, off-site/off-bank sediment transport is nearly ubiquitous, but can be of highly variable rate even during aggradation of a single upward-shoaling platform cycle (cf. Hine, 1983). In lithified banktop successions, thus, a

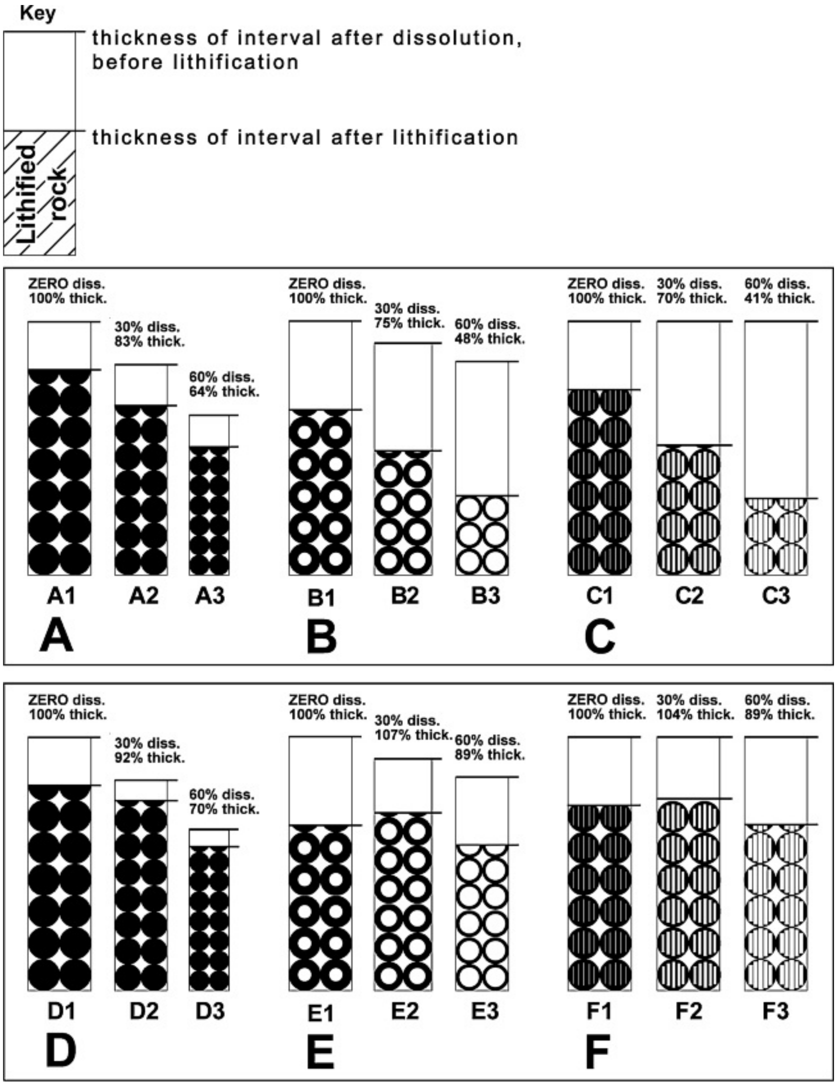

Figure 6: Columns of idealized sediments to indicate effect of dissolution loss, cementation and pressure solution on final, lithified layer thickness (LLT). In each column, the upper black line indicates "unlithified" layer thickness after dissolution, the lower black line indicates LLT (zero porosity). Above each column, "diss." indicates percentage dissolution loss, "thick." the percentage of final thickness after full lithification. Each percentage is relative to the column with ZERO dissolution. Case 1 (columns A, B, C): Effect on LLT of dissolution followed by lithification only by pressure solution. A: "Ooids". Dissolution proceeds from the outer grain surface. B: "Dasyclad stems". Dissolution proceeds from both the outer and inner grain surface. C: "Complex bioclasts" with constructional inner cavities. Dissolution proceeds only from the inner cavities. Case 2 (columns D, E, F): Effect on LLT of dissolution followed by cementation of 50% of the pore space, followed by pressure solution (cement is not shown graphically). For comparison, columns D1, E1 and F1 are the same than above, i. e. lithified by pressure solution only. If 50% of the pore space after dissolution is filled by cement, the substractive effect on LLT is much less. In case of 30% dissolution and 50% reduction of intrinsic pore space by cementation, LLT may exceed that of zero dissolution and lithification only by pressure solution (columns E2, F2). In case of 60% dissolution followed by 50% cementation of the intrinsic pore space, reduction of LLT is comparatively low (columns E3, F3), in particular as compared to lithification only by pressure solution.

reduction of 10-30% of the original, potential sediment thickness by syndepositional dissolution probably is difficult to demonstrate as yet, due to the influence of other variables that each is difficult to quantify, but that acted towards the same end.

In both case 1 and case 2, the potential presence of interstitial lime mud was neglected. Mud to silt-sized carbonate particles dissolve more rapidly than sand-sized grains (Walter and Morse, 1984). In "lime-muddy" fabrics supported by carbonate sand, thus, dissolution of interstitial mud may readily buffer pore water undersaturation (cf. Munnecke et al., 1997). Although this case was not tested, it is obvious that in grain-supported fabrics (packstone, rudstone), dissolution of interstitial mud instead of sand-sized sediment grains would, if at all, result in only a very small reduction of unlithified LLT. Aragonite needles are compact sediment particles without inner cavities. Thus, for aragonite muds, basically a similar reasoning than for ooids (Fig. 6A, 6D) may apply. Relative to ooid sands, the larger primary pore space of uncompacted aragonite muds can be considered to apply for each aragonite mud in each case, without and with dissolution/cementation, i. e. within the category of aragonite muds, the relative effects on LLT probably were similar. Preferred dissolution of carbonate mud is a major obstacle to a quantitative reconstruction of solution loss in carbonate rocks. At present, only minimum amounts of dissolution can be quantified by comparative taphonomy (cf. Cherns and Wright, 2000; Wright et al., 2003).

6. Discussion

On ecologically intact, "healthy" platforms, prolific calcium carbonate production P compensates carbonates destruction D by both bioerosion and "chemical" dissolution within the sediment. On fully productive platforms, the P/D ratio tends to be well-above unity (cf. Sanders, 2003, Fig. 23). The banktop of healthy platforms thus can stay close to sea-level over long intervals of time, also at relatively high rates of subsidence, giving rise to cyclic peritidal successions up to thousands of meters thick (cf. Bosscher and Schlager, 1993). This is supported by the graphic modeling presented herein: although dissolution loss of up to a few tens of percent potentially is widespread, because of geometrical constraints and because of early calcium carbonate precipitaton concomitant to dissolution, the subtractive effect of dissolution on banktop aggradation and final thickness of the lithified rock probably is low. By itself, dissolution recycling does not have the capacity to drown a productive, healthy platform. If, however, carbonate production decreased by ecological disturbance (cf. Hallock and Schlager, 1986), because dissolution persists (cf. Andersson et al., 2003), the loss will come to bear as a significant long-term reduction of sediment budget. Along marine hardgrounds and firmgrounds, a common association of burrows and features of dissolution (e. g. Palmer et al., 1988; Sanders, 2001) probably is not coincidental, but causal. During hardground formation, dissolution may proceed within the sediment during a long phase (cf. Mallarino et al., 2002) of lowered carbonate production during platform foundering and drowning. Similarly, along the flanks of carbonate shelves, in deeper-water areas with lower production of calcium carbonate, dissolution loss may result in a significant reduction of sediment budget. Syndepositional dissolution thus may exert an influence on the long-term development of carbonate platform to slope geometry (Wright and Cherns, in press). In particular a commonly observed, gradual steepening with time from a ramp-like shelf profile into a flat-topped platform with steep flanks may, in part, be produced by a systematic difference in long-term net sediment budget and preservation between banktop and slope. Because the effect of dissolution loss on final thickness also depends on sediment type and primary pore space (Fig. 6), dissolution may serve to enhance thickness differences between lithified carbonate lithosomes of different composition.

The physico-chemical system underlying dissolution is mainly controlled by site-related factors, such as depth and rate of bioturbation-bioirrigation, permeability, bioclast mineralogy and microstructure, and input of labile organic matter (see chapter "Process of syndepositional dissolution", and discussion in Sanders, 2003). Secular changes in oceanic Mg/Ca ratio, and long-term changes in atmospheric pCO_2 and terrigenous input of organic matter probably exerted a background influence on patterns of syndepositional dissolution that is unquantified as yet. Although syndepositional dissolution may locally produce marked taphonomic shift (Sanders, 1999; Cherns and Wright, 2000; Wright et al., 2003) the apparent prevalence of cements and ooids of calcitic or formerly aragonitic mineralogy during interpreted intervals of calcite or aragonite seas (cf. Stanley and Hardie, 1998) seems to preclude that secular calcite-aragonite changes are mere taphonomic artefacts (Sanders, 2003). Deep-tiered burrowing appeared during the Late Ordovician and increased in intensity since (see Bromley, 1996, for summary), whereas macroboring became widespread from the Middle Devonian (Perry and Bertling, 2000). An overall, Phanerozoic speeding of "chemical" and biological dissolution and reflux thus seems probable.

In neritic carbonate environments, rapid precipitation of marine cement is favoured by high-permeability diagenetic systems (reefs, sand bodies, beaches) allowing for effective replenishment of oversaturated sea water. By contrast, in the active layer of bioturbated carbonate sand to lime ooze, dissolution may prevail (cf. Ku et al., 1999). Carbonate environments thus appear compartmentalized with respect to the rates of precipitation and of syndepositional dissolution of calcium carbonate. Scaled sediment accumulation rates of platform successions imply that the rate of carbonate production decreases with increasing time interval of consideration. Precise reasons for this relation are unknown yet, but it is almost certain that environmental factors control the lowering of production rate with time (Schlager, 1999). Such factors include ecological disturbances that lower biogenic carbonate production (Hallock and Schlager, 1986; Leclerq et al., 2002). Syndepositional dissolution of calcium carbonate is one of the factors that steer the budget of carbonate available for preservation in the rock record (Sanders, 2001, 2003). As suggested by the present paper, however, except for significant solution loss combined with sustained lowering of shallow-water carbonate production, syndepositional dissolution should not exert a major influence on banktop aggradation and thickness of the lithified succession.

As mentioned, mud-sized carbonate particles tend to be more vulnerable to dissolution than larger grains, and it seems plausible that the major portion of dissolved calcium carbonate is derived from the fine-grained sediment fraction (Walter et al., 1993; compare Munnecke et al., 1997). On platform banktops, however, mud-sized particles are not only subject to dissolution, but also are the locus of epitaxial carbonate precipitation (Morse et al., 2003); this counterbalances, to an amount unknown as yet, the reduction of carbonate budget by dissolution. The effect of syndepositional dissolution on platform geometry thus potentially is twofold, i. e. lowering the amount of exported carbonate mud and reducing the net sediment budget on platform flanks of intrinsically lower sediment production.

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