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REWORKED DOLOMITE CRUSTS IN THE WETTERSTEINKALK (LADINIAN, ALPINE TRIASSIC) AS INDICATORS OF EARLY SUPRATIDAL DOLOMITIZATION AND LITHIFICATION

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SUMMARY

Dolomitic intraclastic sediments intercalated in a cyclic limestone–dolostone sequence of the Wettersteinkalk represent a rock type with reworking fabrics demonstrating early lithification and dolomitization. The extreme flatness and the angularity of the pebble-sized doloclasts, the lack in plastically deformed dolomitic fragments, and clasts of previously cementated arenites and oncolites testify to a pre-reworking consolidation which, besides biogenic stabilization and dehydration, requires an early cementation. In the different types of doloclasts cementation both by dolomite and by calcite has been confirmed by stained peels and thin-sections, electron-microphotographs, and electron-microprobe analysis.

The prevailing rock type, a very poorly sorted mixture of doloclasts and minor amounts of rounded limeclasts with a pelletal calcite mud matrix is interpreted as storm sediment formed by the introduction of subtidal lime muds to dolomite incrusted supratidal flats.

INTRODUCTION

Studies of lithification in carbonate sediments are normally dealing with diagenetic changes in porosity, permeability and mineralogy. Also time and degree of lithification are recognizable in the reactions of the sediments on compaction, and in the erosion products of penecontemporaneously reworked sediments.

Without regard to exceptions demonstrated by FISCHER and GARRISON (1967), and THOMPSON et al. (1968), early diagenetic consolidation of carbonate sediments seems to be favoured by subaerial conditions (FRIEDMAN, 1964). Carbonate rocks with evidence of early diagenetic subaerial exposure, as indicated for instance by prevailing penecontemporary dolomites, therefore should reveal the best examples of early lithification.

As SANDER (1936) has already demonstrated in his still unequalled studies, penecontemporary dolomites and their reworking products are characteristic features of the Dachstein Formation (FISCHER, 1964), the Hauptdolomit and the Wettersteinkalk (SCHNEIDER, 1964; SARNTHEIN 1965, 1966; GERMANN, 1968) of the Alpine Triassic. The present investigation is part of a study on the syngenetic lead–zinc deposits of the Wettersteinkalk (Ladinian, Middle Triassic), in which contemporaneous reworking of different rock and ore types is a common process (SCHNEIDER, 1964; MAUCHER and SCHNEIDER, 1967). Samples are derived from the author's own work in the Mieminger mountains, Tyrol, and an extensive collection of Wettersteinkalk Pb–Zn ores and rock types of Schneider and coworkers. Stained peels were prepared by a technique described in GERMANN (1965).

EVIDENCE OF DOLOMITIC REWORKING FABRICS IN THE UPPER WETTERSTEINKALK

Nomenclature

Carbonate rocks with arenaceous and rudaceous non-skeletal rock fragments derived from a penecontemporaneous source, are well known from the Paleozoic to the Recent. They have been described by a broad variety of terms, e.g., intraformational breccia or conglomerate, desiccation conglomerate, mudstone conglomerate, edgewise conglomerate, flat-pebble conglomerate, lithoclastic sediment. Limestone and dolostone rock fragments in these sediments purely descriptively may be termed "limeclasts" (K. H. Wolf in: WOLF, 1965, p.35) and "doloclasts". The genetic term "intraclast" was proposed by FOLK (1959, p.4) to describe "fragments of penecontemporaneous, usually weakly consolidated carbonate sediment that have been eroded from adjoining parts of the sea bottom and redeposited to form a new sediment". Intraclasts as particles reworked from within the basin of deposition and within the same formation are a "resediment" in the view of SANDER (1936, p.77).

Intraclasts may show a complete range of degrees of consolidation and lithification (FOLK, 1962, p.63), depending from the environmental position of the sediment layers from which they are derived. Thus they may have a marked textural contrast with their host rock. Specifically excluded are only fragments of consolidated limestone eroded from ancient limestone outcrops in an emergent land area (FOLK, 1962, p.63). According to that wide scope of the intraclasts of Folk it appears unneccessary to extend the meaning of the intraclast definition as proposed by WOLF (1965) and CHANDA (1967).

Following Folk, rocks of the Wettersteinkalk containing more than 10% of pebble-sized dolostone rock fragments derived from a penecontemporaneous intraformational source in either a sparry calcite cement or lime mud matrix are classified as "dolointrasparrudites" and "dolointramicrudites".

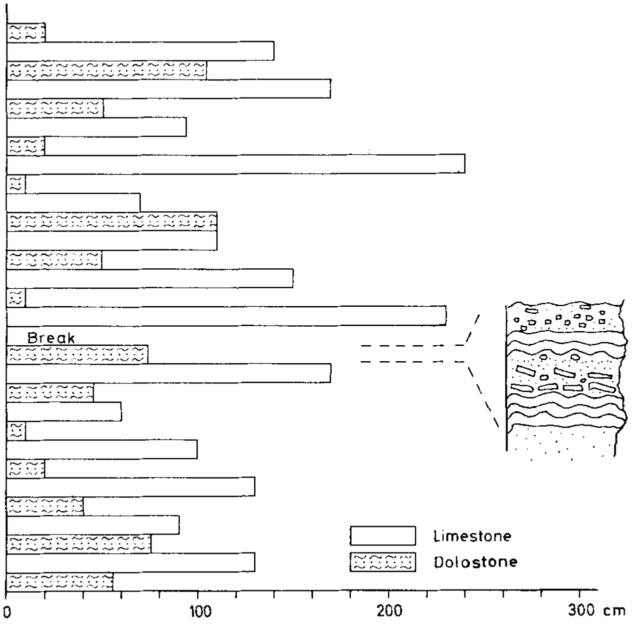

Fig.1. Schematized cyclic limestone–dolostone sequence in the Upper Wettersteinkalk of the Mieminger mountains (Tyrol). Dolomitic intraclastic sediments represented by a typical sequence are restricted to the dolostone intercalations.

Geological setting

Non-skeletal intraformational reworking fabrics are abundant in the Upper Wettersteinkalk of the southern parts of the northern Limestone Alps (Mieminger, Wetterstein, and Karwendel mountains), where a cyclic limestone–dolostone sequence (Fig. 1) of back reef or lagoonal origin is developed. In the northern parts (e.g., Ammer mountains), however, sediments of the same stratigraphic and environmental position do not show any indications to cyclicity. The cyclic series, for the first time described by SANDER (1936), recently was analyzed and interpreted from the Wettersteinkalk around Innsbruck (Tyrol) in SARNTHEIN (1965, 1966).

A normal cycle starts with a thick limestone layer composed of prevailing bio- and pelmicrites. A low dolomite content usually is restricted to the basis and the top of the series. In these more dolomitic parts small slit-like openings may occur which Sarnthein interpreted as crystal molds of gypsum. On the top of the limestone layers the dolomite content of the sediments rapidly increases and thin dolomitic stromatolite and dolomicrite layers appear, alternating with doloarenites and coarse-grained intraclastic sediments. The mode of formation of these reworking fabrics will be discussed in this paper.

Bird's-eye structures and mud-cracks in these dolomitic sediments provide evidence of an inter- to supratidal environment of deposition, whereas the underlying bio- and pelmicrites of the weakly dolomitic limestone layers should have been laid down in a subtidal area. Compared with the Upper Triassic Lofer cyclothems (FISCHER, 1964), the Wettersteinkalk cycles show some marked differences. A basal disconformity with accompanying conglomerate and insoluble-rich red limestones, interpreted by Fischer as reworked residue of soil material, is not developed in the Wettersteinkalk. Layers of red limestones and dolostones with a minor content of insolubles, and greenish argillaceous micrites with brown to black limestone or dolostone fragments, however, in the Wettersteinkalk are conformal constituents of the dolomite-rich intercalations. In contrast to the subtidal member of the Lofer cycle, the limestones of the Upper Wettersteinkalk almost without exception reveal a more or less distinct dolomite content, and the supratidal member contains appreciable amounts of calcite. Therefore, the boundary between the subtidal limestone member and the inter- to supratidal dolostone sequence is not as sharp as in the Lofer cycle.

Thus the limestone–dolostone cycles of the Upper Wettersteinkalk appear to be deposited within a very shallow lagoon with very gentle depositional slope in which even minor oscillations of sea-level or sea-bottom could lead to emergence of extensive tidal flats and supratidal areas, on which dolomitization could occur.

Texture of the intraclastic sediment

In the Upper Wettersteinkalk the majority of coarse-grained intraclastic sediments is composed of loosely packed dolostone and limestone fragments with sizes up to 10 cm embedded in a calcite mud matrix (grain size less than 0.063 mm) with various amounts of densely packed pellets, and small portions of pore-filling cement. Accordingly, these sediments with a grain/matrix ratio about 3/1 rather belong to the intramicrudites than to the intrasparrudites which represent the great majority of intraclastic rocks (FOLK, 1959, p.20). They are mud-supported wackestones, and only in parts grain-supported muddy packstones according to the classification of DUNHAM (1962). Inasmuch as the grain/matrix ratio is controlled by the degree of wave or current action, an association of such large carbonate rock fragments, and a mud matrix must be considered as a textural inversion (FOLK, 1962) the hydraulic significance of which requires an explanation.

Grain-size distribution was determined from peels by counting the apparent longest diameters of grains on the screen of a microfilm reader. Irrespective of the mean grain size which varies between 1.4–2.3ϕ, the intramicrudites reveal a sorting (inclusive graphic standard deviation of FOLK and WARD, 1957) about 3 which means that the sediment is very poorly sorted. Grain-size distribution curves are bi- to polymodal indicating the mixing of two or more populations derived from different sources. A vertical grading of grain sizes in the individual

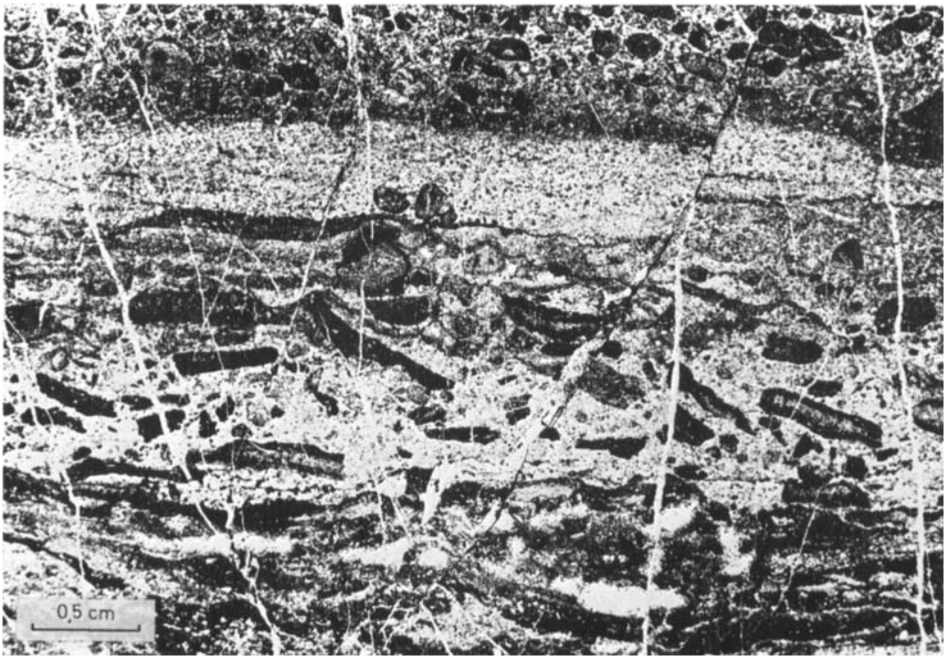

Fig.2. Dolointramicrudite with angular dolostone fragments (black) and doloarenite layer above a dolomite crust with calcite-cemented horizontal sheet cracks (white). Positive print of a dolomite-stained acetate peel.

layers of 3–30 cm thickness is not common even if well-sorted doloarenite layers may be intercalated (Fig.2).

The arrangement of clasts within the sediment allows to distinguish two types reflecting different distances of transport and a variable energy of reworking. A very short transport is demonstrated by angular doloclasts in close contact to their mud cracked dolomitic substratum from which they were eroded and torn up (Fig.2). Mixtures of subangular to subrounded limeclasts and doloclasts above dolomite crusts lacking obvious desiccation features (Fig.3) correspond to longer distance of transport, and to an erosion energy able to remove a mud cracked surface of the underlying crust.

In summary, on the base of an intraclast layer normally a dolomite crust is preserved from which the doloclasts have been eroded as to be deduced from their lithologic analogy with the crust. Also a dolomite crust may be developed on the top of the intraclastic sediment.

The flat doloclasts are incorporated into the intramicrudite layers with more or less steep inclination, thus possibly reflecting current directions as in the case of edgewise conglomerates. As proved by geopetal structures some clasts are even in an inverted position. There are, however, no indications as to the activity of

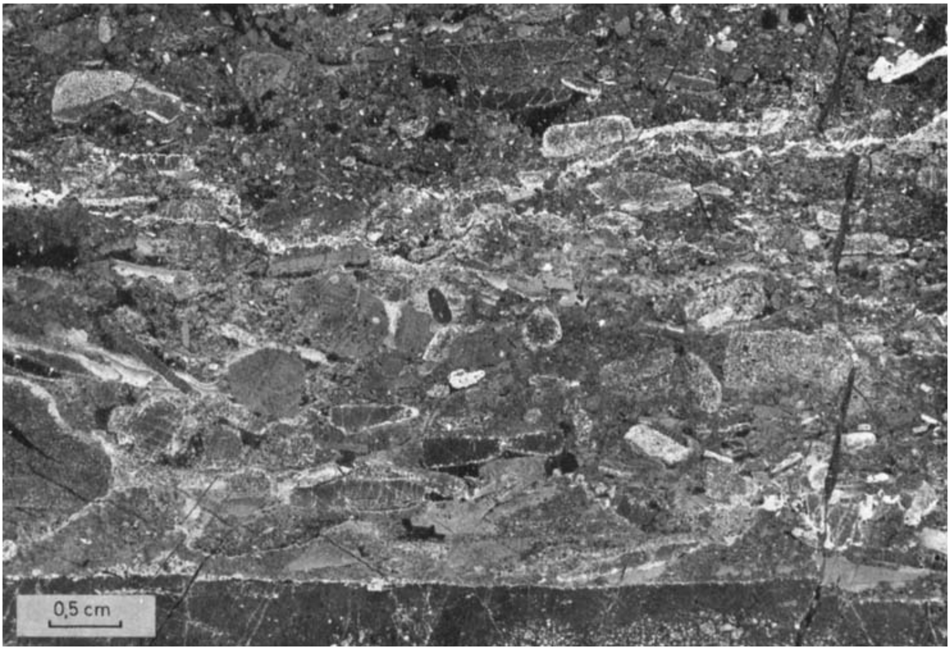

Fig.3. Mixture of dolomitic flat pebbles and well-rounded limeclasts in a calcite matrix. The dolomite crust on the base consists of micrite and arenite. The calcite-filled voids (black) in the matrix below some clasts in the lower part of the specimen where grain-support predominates, may be due to a sheltering effect. In the upper parts shrinkage pores occur below and at the side of the clasts. The small joints in the doloclasts are filled with calcite. Negative print of an acetate peel.

burrowing organisms or roots responsible for the mixing of crust fragments and mud by tilting the crust at angles (SHINN et al., 1965, p.112).

Calcite-cemented voids open underneath some clasts (Fig.3, 7, 8). In places where grain-support is existent these pores may be due to a shelter effect (DUNHAM, 1962, plate III) of the clasts having prevented an original mud-free grain-supported sediment from subsequent infiltering of mud. These structures occurring below floating clasts must be attributed, however, to the desiccation shrinkage of the matrix. In these cases they belong to the shrinkage type of bird's eyes (SHINN, 1968a, p.218) which is well-developed in the mud off the clasts.

Texture and composition of the clasts

The intraclastic sediments of the Wettersteinkalk are composed of pebble-sized dololutite and calcilutite fragments as well as doloarenite clasts, and a pelleted calcite or dolomite mud matrix. The amount of limeclasts may vary from 0–60%. The most frequent doloclasts (more than 50%) consist of a nearly structureless, sometimes pelleted mud made up (see Fig.11, 12) from a mosaic of microcrystalline subhedral dolomite (1–10 μ). Another type of dolomitic fragments shows crusty algal growth in the form of stromatolitic layers and oncolites reflecting the organosedimentary facies of inter- to supratidal flats. Fragments of dolomite-cemented doloarenites and calcite-cemented oncolitic rocks (see Fig.7) prove previous reworking and cementation processes.

Crystal sizes in the broken dolomite mud crusts and stromatolitic layers normally are below 10 μ which means absence of a marked crystal-enlargement effected by dolomitization, and a good preservation of crystal sizes of early diagenetic dolomites in the micrite and microspar range.

Size analysis of 500 dolomite crystals of dolomicrites on electron microphotographs resulted in a mean crystal size of 3 μ, and a sorting (standard deviation) of 0.94; the distribution curve is moderately positive skewed ($Sk = +0.22$) and leptocurtic ($k = 1.16$); ϕ-data distribution is perfectly normal between 6.25 ϕ (0.013 mm) and 8.45 ϕ (0.0029 mm), whereas from 8.45 ϕ the curve is slightly bent towards the smaller crystals. Thus, a bimodality of the crystal-size distribution is indicated which, however, must be verified by additional measurements. Tentatively, this bimodality can be attributed to a diagenetic enlargement of dolomicrite to 60% of a dolomicrospar larger than 3 μ.

Limeclasts in parts reveal the same textural properties as doloclasts: micrites and dismicrites are the main components, and aggregates of grapestone type are locally abundant, whereas the stromatolitic types are lacking.

In the case of the micrite clasts there are a lot of transitional products ranging from the prevailing pure doloclasts to pure limeclasts, thus reflecting different stages of dolomitization attained before reworking.

Coarse crystalline sparry calcite as a constituent of the clasts or as single fragment with thin dolomitic rims seems to be a relic of pre-erosion cements. The coarse infilling of bird's eye vugs or shells, for instance, may have been more resistant during the reworking process than the surrounding dolomite mud.

Morphometric properties

Shape and roundness of the clasts should render possible an evaluation of their degree of consolidation. By measuring the apparent long diameters and the apparent thickness of the clasts in peels, flatness ratios were determined (Fig.4). Flatness ratios of doloclasts are distributed in a field of the diagram which differs markedly from that of limeclasts: the doloclasts are highly elongated flat pebbles mainly, whereas the limeclasts are more spherical and smaller on the average. Doloclasts increase in sphericity with decreasing grain size due to a shortening of the long diameter only, whereas the thickness of the clasts remains similar. Limeclasts, however, at least in parts maintain an original sphericity while being reduced to smaller grains.

Measurements of the roundness index (CAILLEUX, 1952) testify to the better rounding of limeclasts in contrast to the angularity of the dolomite fragments

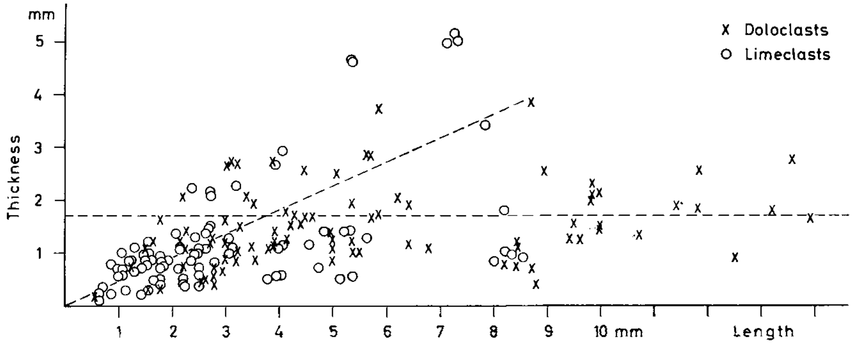

Fig.4. Flatness ratios of doloclasts and limeclasts (four specimens). Apparent length and thickness were measured from peels on the screen of a microfilm reader.

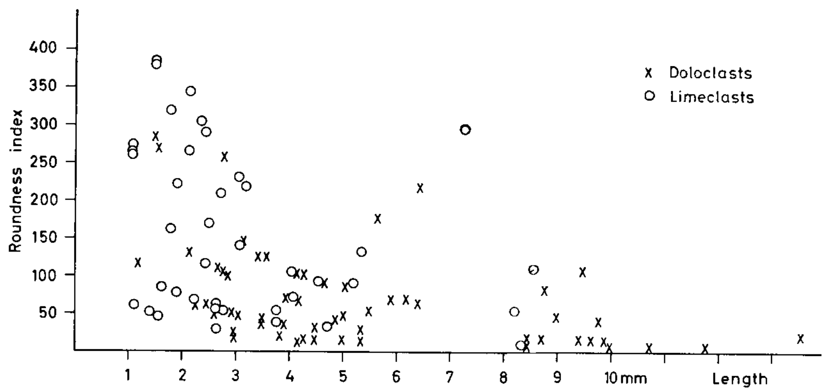

Fig.5. CAILLEUX' (1952) roundness indexes ($2r/L \cdot 10^3$) of doloclasts and limeclasts versus apparent longest diameters L (three specimens). L and smallest radius of curvature r were measured from peels on the screen of a microfilm reader.

(Fig.5). For the most part this may be due to prevalence of normally better rounded small grains (1–3 mm) in the limeclast fraction, but generally even the large limeclasts exhibit well-rounded outlines.

Highly elongated and angular doloclasts indicate conditions of lithification which prevented them from being reduced to smaller pieces of lower flatness ratios and better rounding. Limeclasts, more spherical, better rounded and smaller than the doloclasts demonstrate an initially lower degree of consolidation.

The outlines of the angular clasts are fairly sharp and definite. Normally the margins of the clasts cut across pre-existing organic and inorganic structures, an effect which only can be produced by fracturing or abrading highly consolidated materials. A subsequent alteration of the grain outlines is effected by pressure solution which preferably in the case of local grain support has produced stylolitic contacts and embayed grains (see Fig.8).

In contrast to the limeclasts and the lime matrix, the dolomitic fragments often are intensively cracked by narrow-spaced microfractures healed by calcite (Fig.3, 8). These small fractures are parallel to a system of larger ones which transect both fragments and matrix. According to their directions, both micro-joints and large fractures belong to a conjugate set of faults produced by vertical pressure. This type of deformation with fractured blocks of dolostone in less fractured limestone appears to be due to a brittle (competent) reaction of dolomite in a relatively ductile (incompetent) calcite matrix during tectonic stress produced by the overburden. GRIGGS and HANDIN (1960, p.356–357, plate 7, 8) succeeded in simulating experimentally this typical deformation pattern in dolomite cores sheathed in marble.

Pre-tectonic fractures, indicating brittle reaction of the dolostone during the reworking process and transport are clearly preserved in some fragments (see Fig.8). These fractures do not follow the directions of the tectonic system, and they are crossed by the micro-joints.

Mineralogical types of intraclastic sediments

Two main mineralogical types, reflecting different time relations of intraclast formation and dolomitization, can be distinguished on the basis of intraclast and matrix mineralogy. The most frequent type with doloclasts and minor amounts of limeclasts in a calcite matrix with low dolomite content (Fig.2, 3) indicates a dolomitization prior to the reworking process. Controlling factors of a subsequent selective dolomitization could have been differences in either effective porosity or primary mineralogy of clasts and matrix. Differences in porosity and permeability should have rather led to dolomitization in the more porous matrix than in the dense mud clasts (BEALES, 1953; SHINN, 1968b). A selective dolomitization of aragonite or magnesian calcite clasts, both more susceptible to replacement than a pure calcite matrix, seems quite unlikely. In this case, dolomitization should be expected to have affected unanimously the whole number of clasts of a certain rock type which is characterized by a specific mineralogy and texture. On the one hand, however, a broad variety of different rock types was dolomitized, and on the other hand the most frequent textural type is preserved in dolomite as well as in calcite. Beyond this, a late diagenetic replacement of lithified clasts should have produced much coarser grain sizes than really present.

In the case of doloclasts in a dolomitic matrix, which is a locally abundant type, a subsequent dolomitization of the matrix at least should be supposed. Partly the dolomite content of the matrix may have been produced by the erosion of the doloclasts. Similar dolomite-in-dolomite intraformational breccias, resulting from "primary" dolomite clasts and a secondary dolomitization of the matrix were reported by FÜCHTBAUER (1964, p.514) from the Zechstein of northern

Fig.6. Typical dolomitization–lithification–reworking sequence: biodismicrite with dolomite-lined shrinkage pores at the base covered by a faintly laminar dolomite crust (white) and its reworking products in a calcite matrix (gray). The top of the specimen is a dolomitic stromatolite layer with calcite-filled shrinkage voids (black). Negative print of an acetate peel.

Germany. Calcite intraclasts in a dolomite matrix and calcite-in-calcite fabrics known from both Recent (SHINN, 1968b, p.612; LUCIA, 1968, p.845) and ancient (MATTER, 1967, p.605; SCHÜLLER, 1967, p.358) carbonate rocks, are rarely found in the Wettersteinkalk. Thus, the prevailing dolomite-in-calcite type indicates a close connection between contemporaneous dolomitization, hardening and reworking. This interpretation is supported by the observation that normally reworking fabrics only occur on the top of dolomite crusts, the clasts having close textural similarity with the crusts.

DOLOMITIZATION–LITHIFICATION–REWORKING SEQUENCE

A sequence of events can be deduced from the intraclastic sediments, comprising sedimentation, dolomitization, lithification, and reworking. Original material of such sequences is either a true subtidal or intertidal sediment which got to its subaerial environment by regression and emergence. Or it is subtidal material which was transported mechanically to a supratidal site by spring tides and storms. Typical accumulations of subtidal sediments as for instance biomicrites with abundant debris of dasyclad algae (Fig.6) in these cases could be subject to subaerial desiccation and the related shrinkage, dolomitization, and reworking processes. A drying of these sediments in a supratidal environment has produced by shrinkage (Fig.6, 9, 10) the well known vugs of bird's eye type (SHINN, 1968a), the "shrinkage pores" in the "loferites" of FISCHER (1964, p.116). Vertical prism cracks and horizontal sheet cracks (FISCHER, 1964, p.114) are developed in dolomite crusts mainly, and are filled by sparry calcite. Generally, typical mud cracks are rarer than in the comparable sediments of the Lofer facies. This phenomenon in parts may be due to the intensive reworking processes in the Wettersteinkalk series which destroyed mud-cracked surfaces.

Dolomitization

With the development of desiccation, superficial layers of the supratidal sediment started to become dolomitized by brines which were produced by capillary concentration and evaporation (ILLING et al., 1965; SHINN et al., 1965; FRIEDMAN and SANDERS, 1967; SHINN, 1968b). The high Mg ratio of the brines being an indispensable condition to dolomitization could be explained by a pre-dolomitization precipitation of calcium carbonates in pore space. Evidently cementation of pores with calcium carbonates is a process closely related to dolomitization as demonstrated by Recent carbonate sediments (DEFFEYES et al., 1965; LUCIA, 1968), and is the chief cause of lithification (SHINN et al., 1965, p.117). Generally, dolomitization in modern sediments seems to be accompanied by an increase in consolidation. From Recent dolomitic sediments, SHINN (1968b, p.612) has described selective dolomitization and related cementation of sedimentary structures. In contrast to the intraclastic sediments of the Wettersteinkalk, in the Recent Florida Bay sediments compacted but not cemented lime mud nodules are floating in a cemented dolomite matrix. No information is given, however, on the nature of the cement in the dolomite matrix. In the Wettersteinkalk dolomite crusts early cementation by calcite and dolomite can be detected.

Conditions and degree of lithification

Intraclasts, reworked from a wet carbonate mud, generally should round immediately during transport, and deform plastically on deposition. A reaction like this is unknown in the case of Wetterstein doloclasts and only was realized in

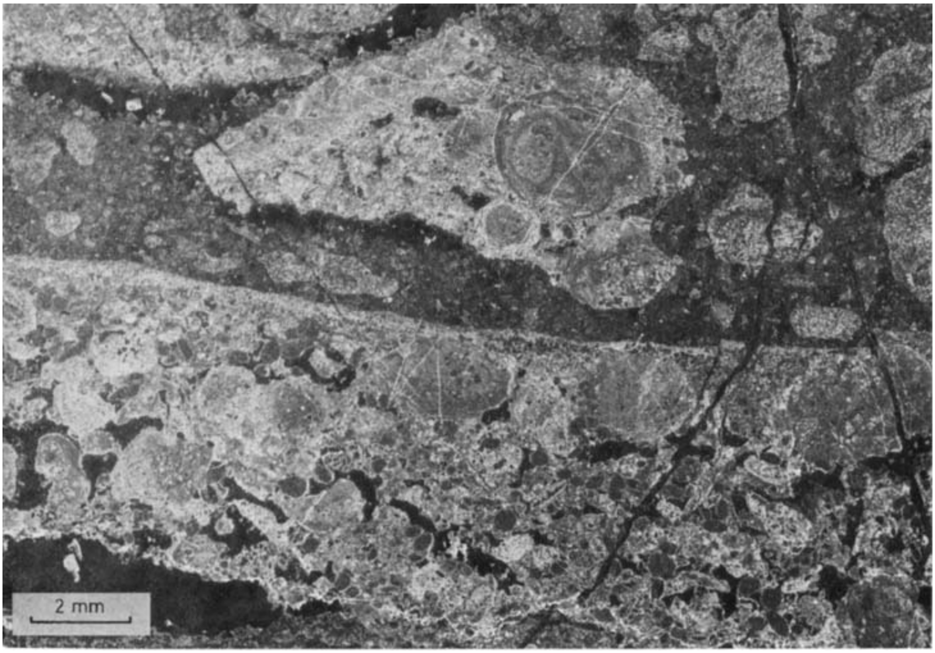

Fig.7. Fragments of calcite-cemented doloarenites and oncolites in a calcite mud matrix (calcite dark gray to black). Negative print of a dolomite-stained acetate peel.

limeclasts. A provisional early diagenetic consolidation of these dolomite layers could have been produced by biogenic stabilization as in the case of stromatolites, or by increased cohesion caused by the loss of water during desiccation. The mere loss of water during desiccation is supposed to produce a cohesion which is so firm that the semilithified products are sufficiently resistant to wave action and can be rounded (GINSBURG, 1957, p.91). A similar interpretation as desiccation conglomerates is appreciated for many fossil intraclastic sediments of ancient near mean sea-level environments (e.g., DAVIS, 1966; LAPORTE, 1967; MATTER, 1967; SCHENK, 1967; BRAUN and FRIEDMAN, 1969).

If a stronger cohesion of particles derived from dehydration were the only reason for the early diagenetic consolidation of the dolomite muds, a rewetting caused by reworking and transport in marine waters should remove this effect. Laboratory experiments were carried out with artificially dried mud crusts prepared from ground dolostones. After rewetting in gently agitated waters, the mud clasts with their typical shrinkage structures were rounded and disintegrated after minutes.

The doloclasts of the Wettersteinkalk, however, to which an interpretation as normal mud-cracked polygons would especially fit, do not show indications of blurred boundaries or plastic deformation as a consequence of rewetting. On the contrary, even the extremely flat clasts turn out to be of an unusual stability and

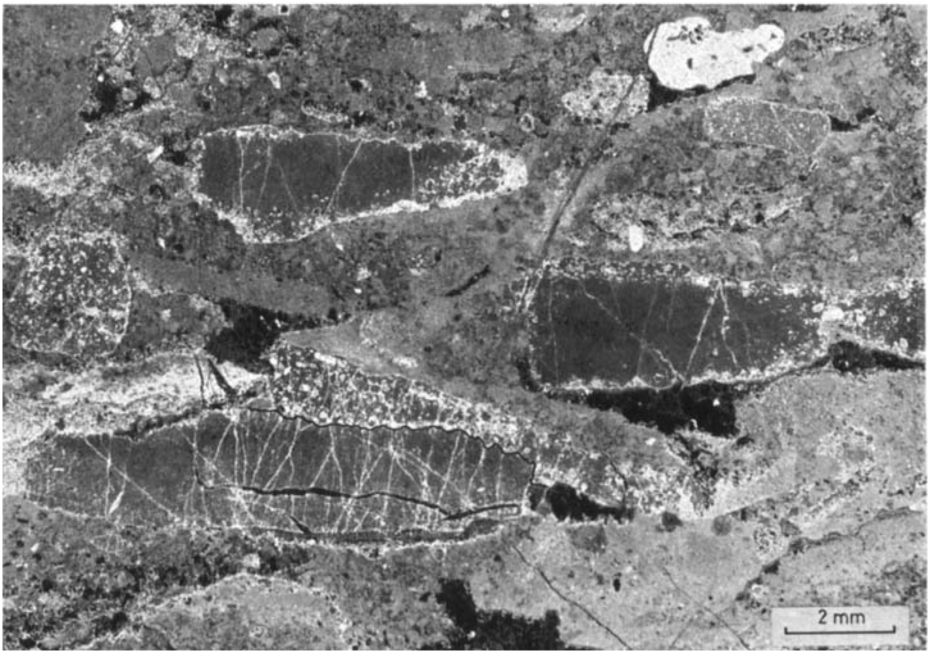

Fig.8. Embayed stylolitic contact between doloclasts (lower center), and calcite-filled tectonic micro-joints (white) in the doloclasts. Pre-tectonic fracturing is shown in the lowest fragment. Negative print of an acetate peel.

rigidity which allows them to react upon erosion and transportation stress by fracturing only. The trapping and binding action of blue-green algal filaments may supplement the desiccation cohesion of the muds. After rewetting the algal threads, indeed, can preserve the integrity of mud crusts (FAGERSTROM, 1967, p.77), but it seems unlikely that they can prevent soft muds from being plastically deformed.

Other indications to a high degree of lithification in the doloclasts are given by fragments of previously reworked, sparcemented sediments (Fig.7) which prove a cementation preceding their rearrangement. Fracture surfaces irrespective of pre-existing structures testify to a lithification which was almost completed before the reworking process began (Fig.8).

Accordingly the effects of biogenic stabilization and desiccation-cohesion must have been increased by a cementation of pores with calcium carbonates and dolomite.

Pre-reworking cementation of dolomitic rocks with calcite is clearly visible in the clasts of doloarenites and oncolites. In the abundant bird's eye dolostones of the Wettersteinkalk the cavities normally are cemented by calcite. The occurrence of dolomite rhombs radially lining the walls of bird's eye pores (Fig.9) and fossil molds or being a geopetal drusy infilling of cavities (Fig.10) suggests that

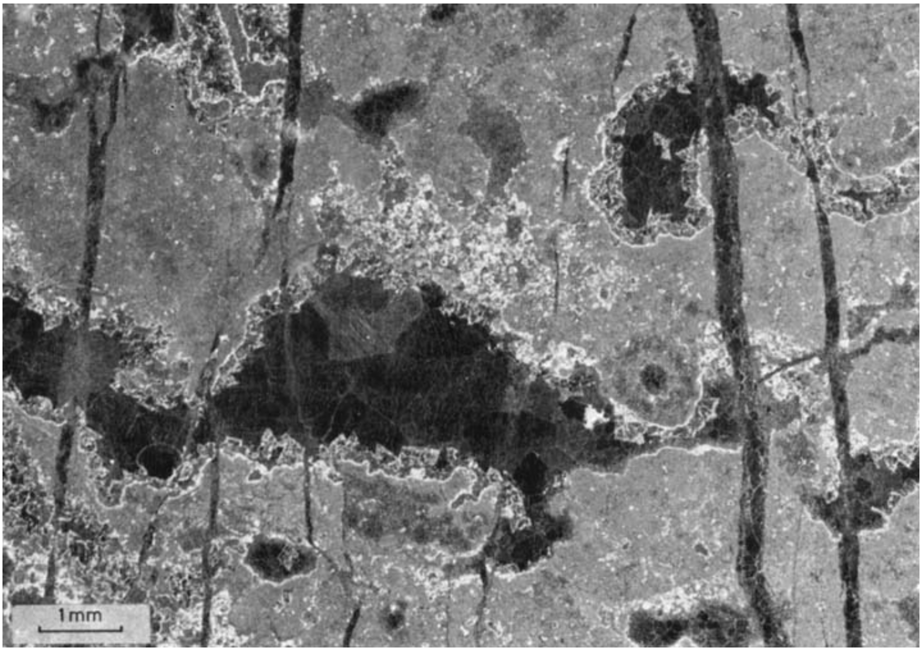

Fig.9. Dolomite crystals (white) radially lining the walls of calcite-cemented bird's eyes in a biodismicrite. Negative print of an acetate peel.

dolomite, too, is able to fill pre-existing pore space. The early diagenetic origin of these dolomite cements in many cases is proved by a replacement of the rhombs by the calcite cement filling the remainder of the pores.

It is very difficult, however, to detect primary cements in the dense dolomicrites. The dolomicrites studied by electron microscopy (Fig.11, 12) are composed of hypidiotopic to xenotopic mosaics resembling the pavement type of calcimicrites demonstrated in FISCHER et al. (1967, p.17). The characteristic euhedral rhombs, representing the initial stage of replacement in the Recent Persian Gulf dolomites (ILLING et al., 1965, p.99), are comparatively rare. As to the sizes, in the dolostones the original 1–3 μ micrite is only partly preserved. Dolomicrospar with crystals up to 10 μ occurs which appears to have been produced by syntaxial overgrowths (rim cement) growing in optical continuity from the original euhedral crystals, thus being true primary precipitates (FRIEDMAN and SANDERS, 1967, p.279). These primary dolomite cements which besides calcite may have been the main agents of early lithification are faintly indicated in the center of some dolomite crystals which on electron microphotographs show nuclei of higher relief (Fig.11).

It cannot be decided, however, if the dolomicrospar is the product of a solution–reprecipitation process within the sediment, or if the dolomite rims were precipitated from solutions coming from outside the porous sediment.

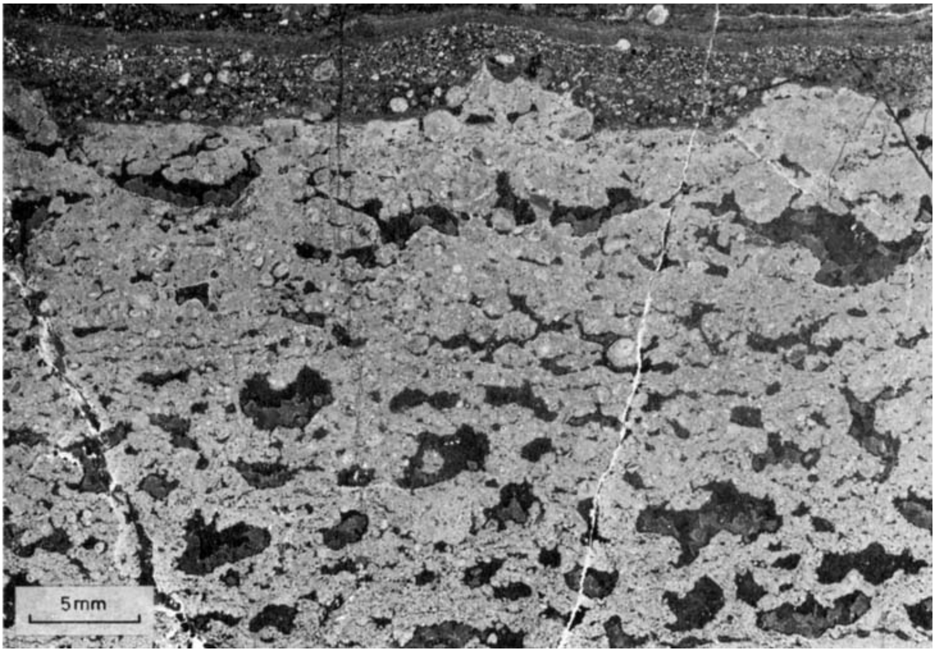

Fig.10. Bird's eye dolostone (white) with dolomite rhombs (medium gray) occupying the floors of calcite-cemented cavities (dark gray). An erosional surface is covered with a thin layer of doloarenite. Negative print of an acetate peel.

In other cases individual dolomite crystals are separated by narrow areas of low relief (Fig.12) which may be attributed to a more soluble carbonate mineral, presumably calcite. To verify the existence of calcite cements in the μ-range, electron-microprobe analysis was chosen, because X-ray diffraction at any case would have yielded calcite reflexes arising from calcite inclusions in the mm-range, and from the calcite-filled micro-joints. The analysis was performed on polished and carbon-coated sections of dolomicrite with an ARL microanalyser. Step scanning profiles with 1-μ and 5-μ intervals were measured to determine the Ca/Mg ratios in the sample recorded in the form of Ca and Mg intensities (counts/sec).

Both from the 1-μ and the 5-μ profiles the presence of calcite is clearly visible in 10–15 μ broad fields only (Fig.13). Minor fluctuations in the Ca/Mg intensity ratios of the dolomite beyond the normal standard deviation tentatively could be attributed to inclusions of calcite in the 0.1–1 μ range being smaller than the electron beam. Measurements near boundaries between small calcite and dolomite crystals, and fluorescence excitation from calcite below the visible surface, too, may produce a similar pattern. Finally, the low fluctuations in Ca/Mg intensities may originate from variations in the chemical composition of the dolomites. These variations can not occur within single crystals as their range (3–15 μ) is

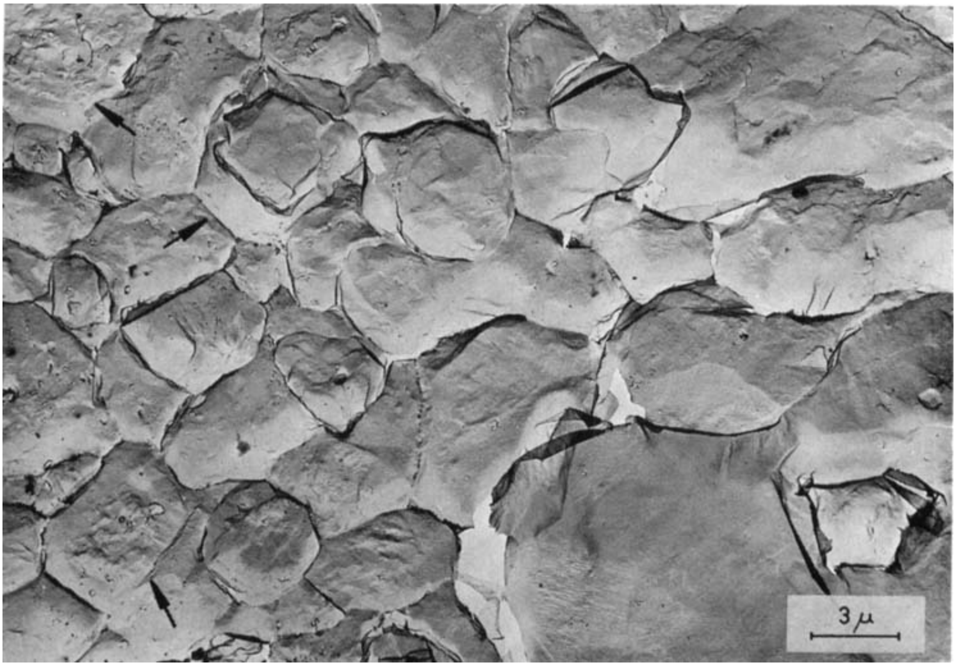

Fig.11. Electron-micrograph of a Pt–Ir-shadowed, carbon-coated replica of a doloclast. The polished specimen was etched in 5 *N* HCl to overcome the etch resistance of dolomite. Dolomite grains are anhedral to subhedral with rounded outlines due to slightly embayed boundaries. The small grains are rich in inclusions. In some grains (arrows) "primary nuclei" are faintly indicated. The large grain at the base with the distinct cleavage pattern presumably is calcite. Clear white areas following grain boundaries are due to tears in the carbon replica.

beyond the mean crystal size of the micrites. Thus, only the existence of single non-stoichiometric dolomite crystals with different Ca/Mg ratios could be supposed. As proved by X-ray diffraction, however, the early diagenetic dolostones of the Wettersteinkalk without exceptions are very close to the ideal $Ca_{50}Mg_{50}$ type.

Reworking

The lithified superficial crusts subsequently could be separated by erosion only to act along incompletely cemented horizontal shrinkage pores and vertical cracks or poorly lithified non-dolomitic layers. In a following phase the supratidal area occupied by the dolomite crust must have been invaded by high-energy waves able to erode the crust and to transport the clasts.

In Recent supratidal environments spring and storm tide-induced waves are the most effective agents in sedimentation and reworking. Exceptionally, tsunamis may flood supratidal areas. As shown on Recent supratidal mud flats

Fig.12. Electron-micrograph of a doloclast showing a hypidiotopic and partly idiotopic mosaic of dolomite grains rich in inclusions. Some of the high-relief dolomite grains appear to be embedded in a lower relief matrix which may be calcite (arrows). Dark membranes (upper left, center) are due to the doubling of the carbon coating induced by the deeply etched relief.

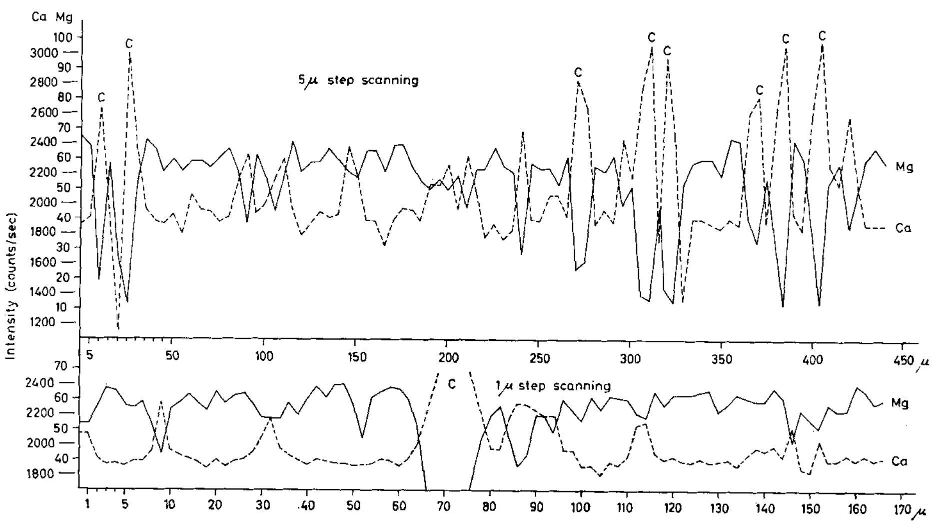

Fig.13. 5-μ and 1-μ step scanning profiles of Ca and Mg on dolomicrite fragments measured by microprobe analysis. Calcite peaks are marked *C*.

in the Florida Keys (SHINN, 1968b, p.613), the water coming in from the sea during spring tide flooding is relatively clear, and little sediment is deposited. During storms, however, subtidal sediments can be stirred into suspension to form a milky soup of lime mud (BALL et al., 1967, p.585) which is transported shoreward. It seems reasonable to adopt a similar mechanism to explain sedimentation on supratidal flats of the Wettersteinkalk. Highly agitated mud suspensions while passing over the cemented supratidal dolomite crusts were able to erode the mud-cracked upper surface, and to keep clasts of the crust floating. Locally, the dolomite crust may have been removed entirely, and the underlying less consolidated lime mud material could have been incorporated into the sediment. The dispersed phase of very fine–grained particles retarded the settling of the coarse clasts. Thus a non-graded mixture of rudaceous and arenaceous dolomite and lime mud particles and a lime mud matrix of some centimeters in thickness could be deposited in the supratidal areas. During transport the lithified dolomitic flat pebbles mainly were broken to smaller pieces and only partially rounded, whereas the soft lime pebbles could be rounded immediately. The weakly dolomitic lime mud matrix at least in parts may be composed of completely disintegrated limeclasts and doloclasts.

After deposition the process of drying, shrinkage, cementation, and dolomitization started again, sometimes leading to an entirely dolomitized intraclastic sediment.

As shown in Fig.6 some storm sediments may have been overgrown shortly after deposition with laminated algal mats which in their turn were subject to desiccation, cementation, dolomitization and reworking, thus creating sediments with dolomitic intraclasts of stromatolitic origin.

In the Pb–Zn-bearing units of the Wettersteinkalk ("special facies" of SCHNEIDER (1964) some typical intramicrites with ore fragments have a close similarity to turbidites (SCHNEIDER, 1964, p.38). They may be attributed tentatively to reworking of supratidal or intertidal sediments. Clasts of colloform sphalerite (Schalenblende) in a lime mud matrix (SCHNEIDER, 1964, fig.7) appear to be of syngenetic near mean sea-level origin. In these environments the conditions of sulphide deposition should have been at an optimum: hydrogen-sulphide could be produced by bacterial decomposition of gypsum, and warm hypersaline solutions carrying zinc and lead as chloride complexes were formed by filtration through adjacent sediments, capillary concentration and evaporation; an additional volcanic source for Pb and Zn may be supposed (SCHNEIDER, 1964). From the Recent sabkha dolomites of the Persian Gulf subsurface reducing conditions in supratidal sediments have been reported (ILLING et al., 1965, p.107).

CONCLUSIONS

Dolomitic intraclastic sediments may serve as key rocks in the recognition of both an early diagenetic subaerial lithification and a supratidal dolomitization. The high degree of lithification of the doloclasts cannot be explained as a mere desiccation phenomenon. Cementation by calcite and dolomite must have contributed to the pre-reworking consolidation process which is closely related to early diagenetic dolomitization. Beyond this, dolointramicrudites set an example of the origin of a textural inversion (FOLK, 1962, p.82), a mixture from coarse grains and mud matrix.

In contrast to a common interpretation of intramicrites given by some authors (e.g., FOLK, 1962, p.83) who recognize a production of the clasts in high-energy environments and a transport to low-energy areas, the clasts of the Wettersteinkalk seem to be more or less in their original position. The calcite mud matrix was introduced from a subtidal site by storm-induced suspensions.

In this type of sediment, which is interpreted as storm layers, only the very short period of time is recorded during which sedimentation occurred on supratidal flats after a period of drying. Supratidal storm sediments are recognizable in ancient carbonate rocks only if a sediment sufficiently lithified in supratidal areas has been eroded.

Thus, the dolostone conglomerates and breccias of the Wettersteinkalk as typical representatives of supratidal sedimentation do not imply any fundamental change in environmental conditions. The cyclic alternation of sub- and supratidal sediments cannot be explained by the storm-sedimentation theory alone. Additional influences ("dictator" of SANDER, 1936, p.37) superimposed on the episodic changes in sea level induced by storms must be supposed. Eustatic oscillations of sea level (FISCHER, 1964, p.146), and tectonic movements (SARIN, 1962, p.470) have been supposed to be the cause of comparable cyclic limestone–dolostone sequences.

Eustatic control of cyclicity in the case of the Wettersteinkalk can be excluded because of the lack of widespread persistence of the cyclic sequence. A local source influencing the vertical movement of sea bottom must be responsible for the repeated change from subtidal to supratidal conditions. Intermittent subsidence characterized by periods of standstill or short uplifts may explain the near mean sea-level facies pattern in the Upper Wettersteinkalk. Presumably the coincidence of supratidal dolostone facies and syngenetic Pb–Zn-deposits which require a volcanic source (SCHNEIDER, 1964; MAUCHER and SCHNEIDER, 1967) indicates that sea-bottom movements could have been effected by submarine volcanism.

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