RELATIVE AGES OF VISIBLY CRYSTALLINE CALCITE IN LATE PALEOZOIC LIMESTONES

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ABSTRACT

Four types of visibly crystalline calcite occur in late Paleozoic limestones examined in this study. (A) Grain-growth calcite, characterized principally by irregular size and shape and random orientation of crystal grains, probably formed by solid-state recrystallization of microcrystalline calcite sediment. (B) Blade calcite, characterized by tapered, blade-shaped crystals bunched in flowerlike aggregates, probably formed by recrystallization under mild shearing stresses. (C) Encrusting calcite, characterized by aggregates of fibrous to irregular crystals, probably formed by precipitation around algal tissues that subsequently decayed. (D) Void-filling calcite, characterized by orientation of crystals perpendicular to walls of filled voids and by general increase in crystal size toward center of filled voids, formed through inorganic precipitation.

Encrusting calcite probably formed during deposition of surrounding sediment and seems to be the earliest of the calcite types to form. Most void-filling calcite probably formed early in the limestone's history, during or soon after partial consolidation of fine sediment. Early filling of voids, reducing the porosity, probably inhibited compaction. Although its age relations are poorly known, grain-growth calcite is probably not older than most of the adjacent void-filling calcite. Blade calcite and void-filling calcite that occupies post-lithification fractures and other openings seem to be the latest to form.

Visibly crystalline calcite may be defined simply as calcite consisting of crystals that are large enough to be seen readily as individuals in thin section at low magnification. In this respect, visibly crystalline calcite contrasts with microcrystalline calcite, which consists of crystals either too small or too poorly defined to permit individual crystals to be distinguished. The distinction between visibly crystalline calcite and microcrystalline calcite is a semi-quantitative one. Limits between the two types, in terms of dimensions of individual crystals, cannot be precise, however, because size of crystals intergrades continuously.

This paper is based principally on the study of Pennsylvanian limestones, particularly those of the Upper Pennsylvanian Lansing Group in southeast Kansas and parts of the Magdalena Limestone (Pennsylvanian) in the Caballo Mountains of southwest-central New Mexico and the Hueco Mountains of West Texas. In addition, several hundred specimens from various Pennsylvanian and Permian limestone units in Kansas and the McCloud Limestone (Permian) of northern California have been examined for comparison. Conclusions drawn in this study are probable applicable to many late Paleozoic limestones, and perhaps to limestones of other ages as well.

Both thin sections and acetate peels have been examined in studying the limestones described here. Peels are superior in some respects because of the great fidelity with which they reproduce the microscopic details of the limestone. Methods of preparing and photographing peels have been described previously (Harbaugh, 1959, p. 295).

INTRODUCTION

Many geologists who have examined limestones under the microscope are aware that coarsely crystalline or visibly crystalline calcite poses problems. For example, several generations of calcite formed by different processes may be present in a single specimen. It is the purpose of this paper to consider the classification, origin, and age relations of different types of calcite that have been observed in late Paleozoic limestones. Improved understanding of the different types of visibly crystalline calcite should help in interpreting conditions of sedimentation and diagenesis of limestone. Furthermore, the microscopic characteristics have relevance to porosity and entrapment of oil and gas. This report, like two previous papers published by the Survey (Harbaugh, 1959, 1960), reports progress in the study of limestone fabrics.

Acknowledgments.—I am indebted to my associates of the State Geological Survey and colleagues at Stanford University for review of the manuscript. William Taft, of Stanford University, assisted in collecting some of the specimens illustrated here that were obtained in Texas and New Mexico. Herbert Mendoza, formerly of the University of Kansas, made the acetate peels used in the study. Ruperto Laniz, of Stanford, made the thin sections used in the study, and photographs of the thin sections were prepared by Perfecto Mary, of Stanford. Mrs. Jeannette Rust, of Stanford, typed the manuscript. Expenses for field work in Texas and New Mexico and for preparation of thin sections and photographs were borne by National Science Foundation Grant G6597.

CLASSIFICATION AND CHARACTERISTICS OF TYPES OF VISIBLY CRYSTALLINE CALCITE

In this paper four specific types (Fig. 1) of visibly crystalline calcite are considered: (A) grain-growth calcite, (B) blade calcite, (C) encrusting calcite, and (D) void-filling calcite. Types A and B probably are formed through recrystallization in the solid state, whereas types C and D are formed through precipitation. A genetic classification is presented in Table 1, and criteria useful in distinguishing the types are summarized in Table 2. It should be noted that criteria for dis-

TABLE 1.—*Genetic classification of types of visibly crystalline calcite.*

Broad classification and origin.	**RECRYSTALLIZED CALCITE** Calcite formed through recrystallization of carbonate sediment.		**PRECIPITATED CALCITE** Calcite formed as a result of precipitation of calcium carbonate from solution.	
Specific classification and origin.	GRAIN-GROWTH CALCITE Calcite in which larger grains have been formed through migration of crystal boundaries, accompanied by obliteration of most small crystals.	**BLADE CALCITE** Calcite in which large bladelike crystals replace pre-existing calcium carbonate.	**ENCRUSTING CALCITE** Calcite formed as a result of successive encrustations on surfaces, particularly at sediment—sea water surface.	**VOID-FILLING CALCITE** Calcite formed as a result of precipitation of calcium carbonate in water-filled, enclosed voids.
Conditions surrounding origin.	Poorly known.	Probably mild shearing stresses prevailed.	Some, perhaps most, of this type formed as calcareous "tufa". Thus, precipitation may be organically induced.	Presence of water-filled voids.

TABLE 2.—*Criteria for distinguishing types of visibly crystalline calcite.*

	GRAIN-GROWTH CALCITE	BLADE CALCITE	ENCRUSTING CALCITE	VOID-FILLING CALCITE
Crystal shape.	Very irregular.	Smoothly curved and much elongated. Many crystals have rounded ends.	Irregular and slightly to notably elongate.	Elongate near margins of mass; irregular toward center.
Relative size of crystals.	Irregular; large and small crystals randomly mixed.	Fairly uniform.	Roughly uniform.	Small near margins of mass; progressively larger toward interior.
Crystal orientation.	Random.	Roughly radial to dendritic.	Perpendicular to surfaces of crusts; radial in some examples	Perpendicular to margins; random orientation toward interior.
Boundaries between crystals.	Intricate and irregular.	Smoothly curved.	Irregular.	Plane; where boundaries seem irregular they are generally composed of short segments of plane surfaces.
Boundaries between crystal masses and surrounding sediment.	Diffuse and patchy.	Very sharp.	Some boundaries sharp, but others diffuse and vague.	Mostly sharp.
Presence of inclusions of unrecrystallized sediment within crystal masses.	Very common; contribute to patchy appearance.	Absent.	Very common.	Locally present, but not as common as in other types.

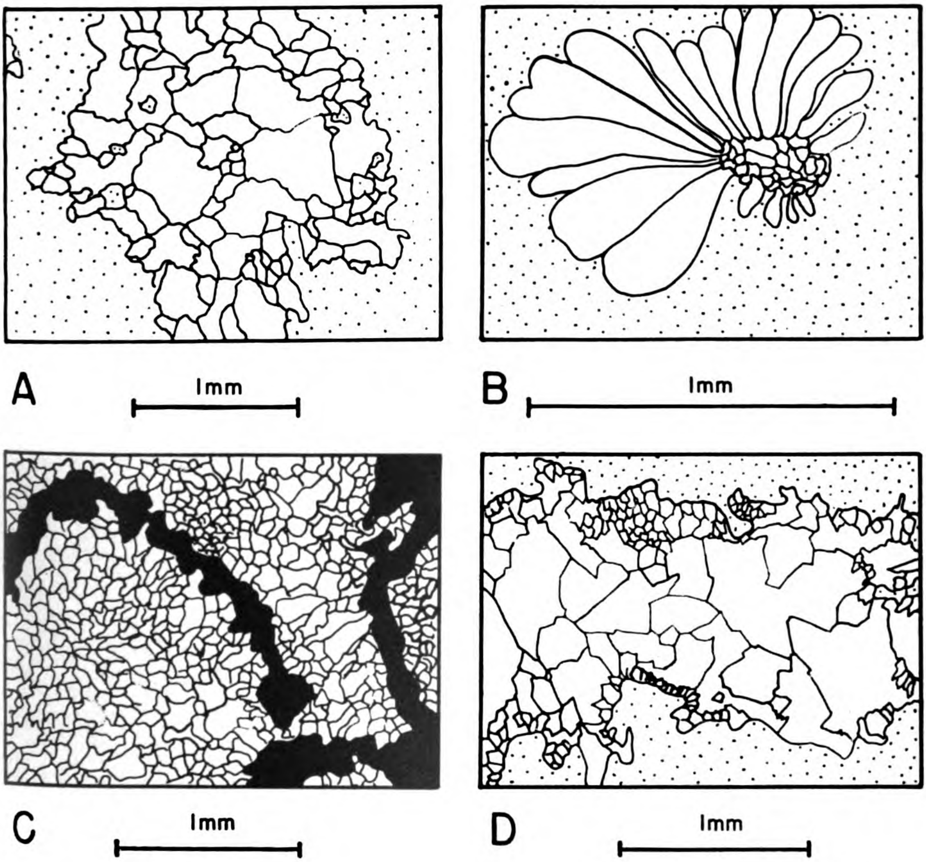


FIG. 1.—Characteristic appearance of four principal types of visibly crystalline calcite: (A) grain-growth calcite; (B) blade calcite; (C) encrusting calcite; (D) void-filling calcite. Drawings correspond to photomicrographs shown in Plates 1, 3A, and 8A. Boundaries of individual crystals are shown by lines; stippling indicates fine sediment. Thick lines in C represent dark matter that is presumably organic material.

tinguishing grain-growth calcite and void-filling calcite have been adapted from the work of Bathurst (1958, 1959a, 1959b). Detailed considerations of origin, age relations, and environmental and depositional significance of each type are presented in subsequent sections of this paper. Calcite produced through replacement of dolomite, quartz, anhydrite, or other minerals is not considered here, although such calcite may be of considerable significance locally (Lucia, 1961).

Grain-Growth Calcite

Grain-growth calcite is one of two types of visibly crystalline calcite formed through recrystallization. Grain-growth calcite is characterized by irregular size and shape and random orientation of crystal grains (Fig. 1A, Pl. 1A, and Table 2). Bathurst (1959a, p. 375) pointed out that in the process of grain growth, boundaries between initially small crystal grains migrate so that a large crystal takes the place of many small crystals. Grain growth probably takes places in the solid state and probably involves transfer of material over only very small distances. Prior to grain growth, however, transfer of material by solution probably was effective in bringing about the intimate contact of crystal grains necessary for subsequent migration of their boundaries. Grain growth seemingly is similar in some respects to the processes by which marble is produced, but the results are different. Marble is of more nearly uniform grain size and it forms at elevated temperatures or under shearing stresses, conditions that were probably unnecessary in the formation of grain-growth calcite.

The factors that govern grain growth are poorly understood. Typically, patches of grain-growth calcite are irregularly distributed within fine-grained parts of limestone. It may be speculated that certain crystals served as "seed" nuclei, which stimulated recrystallization of surrounding microcrystalline calcite. In many examples no explanation can be offered for factors that governed localization of patches of grain-growth calcite. In other examples, however, the presence of adjacent void-filling calcite seems to have localized grain-growth calcite. In some specimens from the Lansing Group in Kansas, grain-growth calcite is markedly localized adjacent to void-filling calcite (Pl. 2 and Fig. 2).

The age relations of grain-growth calcite are not well known, but the following conclusions may be drawn: (1) Grain-growth calcite necessarily formed later than the sediments in which it occurs. (2) As far as most available evidence indicates, grain-growth calcite seemingly could have formed at any time after deposition of the sediments

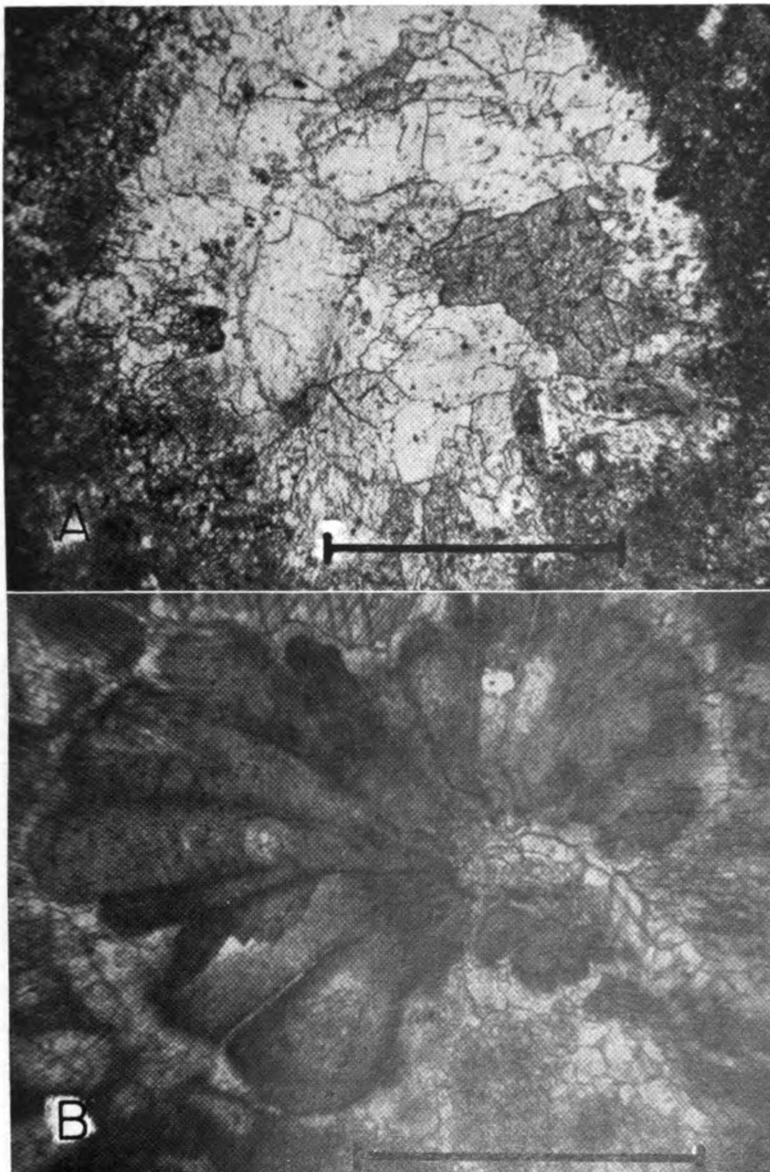


PLATE 1.—A. Grain-growth calcite forming "burst" of coarsely crystalline calcite **surrounded by carbonate** siltstone (dark). Specimen from Spring Hill Limestone **Member of Plattsburg** Limestone of Lansing Group. See Figure 1A for **clarification of details. Positive** photograph of acetate peel, ×40. Length of line **showing scale is 1 mm. B.** Blade calcite. Specimen from McCloud Limestone **(Permian) of northern California.** Positive photograph of thin section, ×90. See **Figure 1B for clarification of details.** Length of line is 0.5 mm.

PLATE 2.—Localization of grain-growth calcite adjacent to void-filling calcite. Grain-growth calcite presumably is not older than void-filling calcite. See Figure 2 for clarification of details. Specimen from Spring Hill Limestone Member of Plattsburg Limestone of Lansing Group. Negative peel print made by direct projection of acetate peel, ×4. Surface of peel is parallel to bedding.

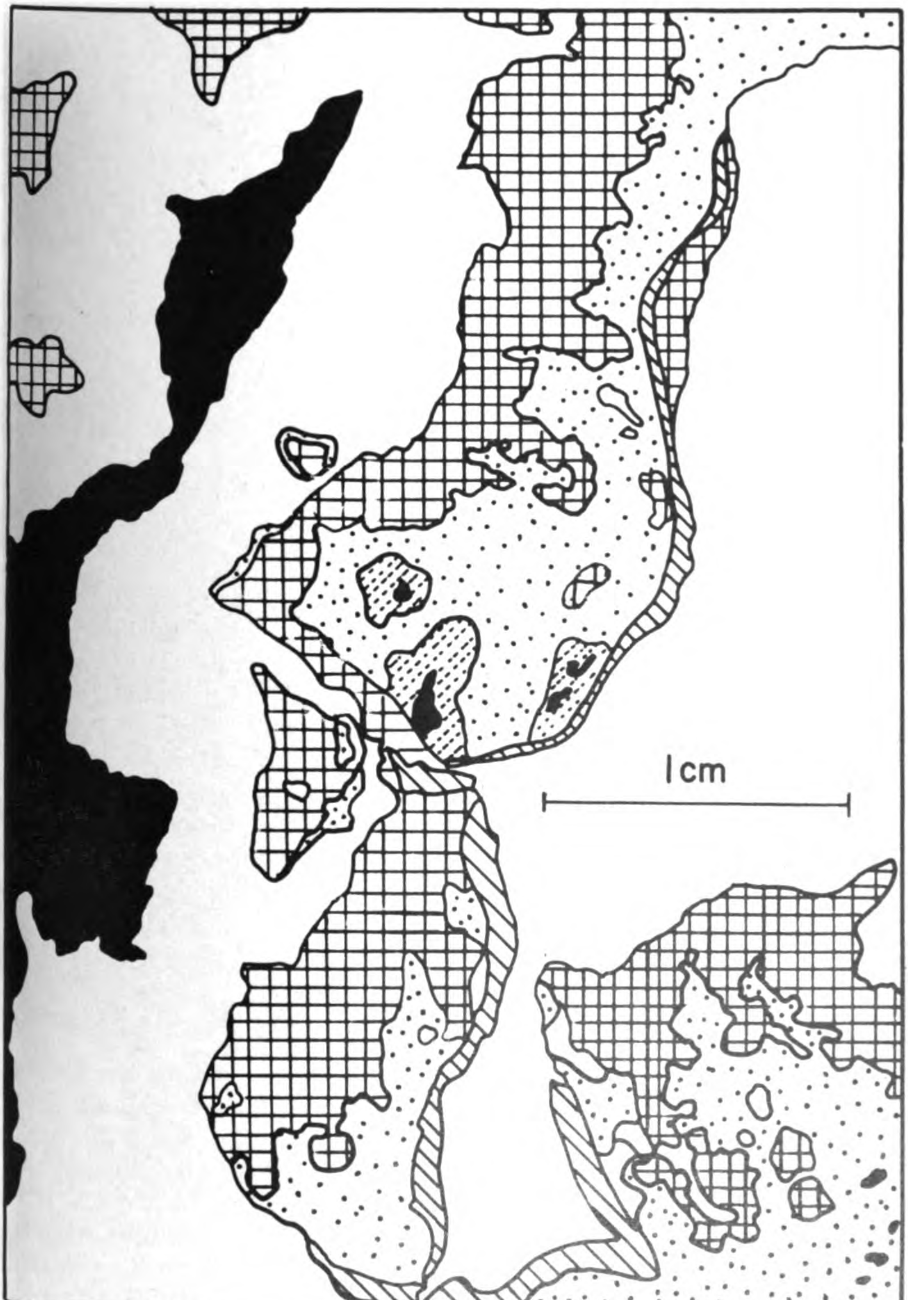


Fig. 2.—Drawing to accompany Plate 2 showing localization of grain-growth calcite **adjacent to void-filling calcite.** Grain-growth calcite is cross hatched, void-filling calcite **is clear, fine carbonate sediment** is stippled, vugs and pores are black, leaflike algae are **diagonally ruled, and dolomitized** zones are indicated by short diagonal dashes.

in which it occurs. (3) Where grain-growth calcite is localized adjacent to voil-filling calcite, however, it may not be much older than the void-filling calcite.

Blade Calcite

Blade calcite consists of relatively large blade-shaped crystals that occur in sheaflike bunches of radiating, flowerlike aggregates (Pl. 1B and Fig. 1B) on the order of 1 to 3 mm in diameter. The blades commonly cut across fossils and other fragmental material in the rock, indicating that blade calcite formed after the rock formed. Blade calcite is readily distinguished by the shape of the crystals, which are elongate, tapered, smoothly curved, and generally rounded on the ends. In addition, the blades, each of which is a single crystal, show undulatory extinction when viewed under the crossed nicols of a petrographic microscope when the stage is rotated. Undulatory extinction is probably due to strain, the crystals having been slightly warped by stresses.

The origin of blade calcite is poorly understood. The example shown in Plate 1B is from the McCloud Limestone (Permian) of northern California. In places the McCloud Limestone has been subjected to a very mild degree of thermal and dynamic metamorphism, and it seems possible that blade calcite may have formed as an initial response to metamorphosing conditions. It should be pointed out, however, that blade calcite bears little resemblance to coarsely crystalline calcite so common in marble, the usual product of metamorphism of limestone. It seems probable that blade calcite is a product of recrystallization in the solid state. The relative age of recrystallization to blades is poorly known, but seemingly calcium carbonate could recrystallize at any time after consolidation of the sediment, even long afterward.

Encrusting Calcite

Encrusting calcite consists of calcite that forms distinctive crusts on or around skeletal fragments and intraclasts. Two interrelated subtypes of encrusting calcite can be recognized: (1) relatively thick and irregularly lumpy crusts composed of irregular or slightly elongate crystals that may show a crude radial orientation (Pl. 3A and Fig. 1C) and (2) thin crusts of one or more laminae composed of fibrous crystals that are oriented perpendicular to the surfaces of the crusts (Pl. 3B, 4, and 5; Fig. 3, 4, and 5). The thick crusts (first subtype) commonly occur as (a) lumpy encrustrations as much as several inches thick and (b) as intraclasts (Pl. 6 and Fig. 6). The thinner crusts (second sub-

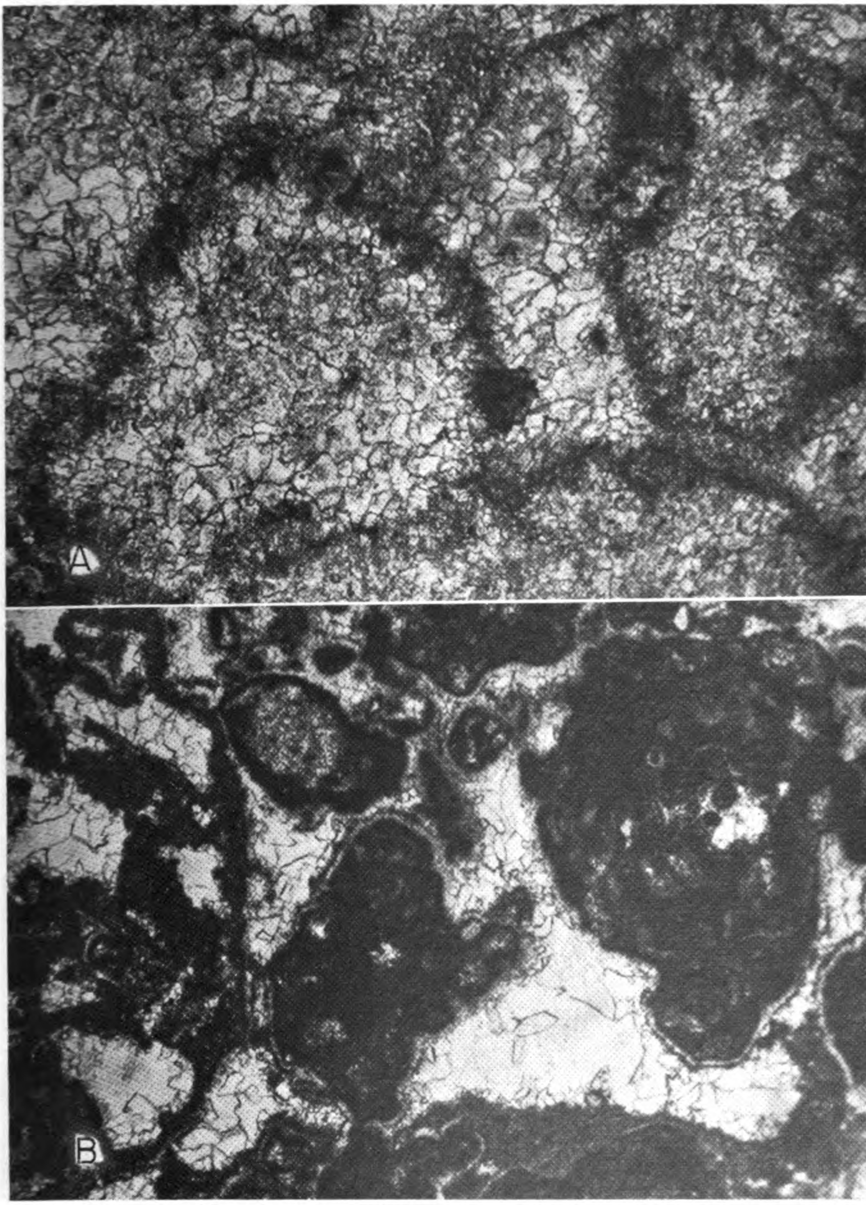


Plate 3.—Contrast between subtypes of encrusting calcite. Specimens from Magdalena Limestone of Hueco Mountains, Texas. Positive photographs of thin **sections, ×25. A. Encrusting** calcite of subtype consisting of relatively thick and **irregularly lumpy crystalline** masses. Dark bands are fine material that may **contain carbonaceous residue.** See Figure 1C for clarification of details in central **part of photograph. B. Encrusting** calcite of subtype consisting of fibrous, relatively **thin laminae. Laminae** surround intraclasts (dark) that are in turn **cemented by void-filling calcite** (light). See Figure 3 for clarification of details.

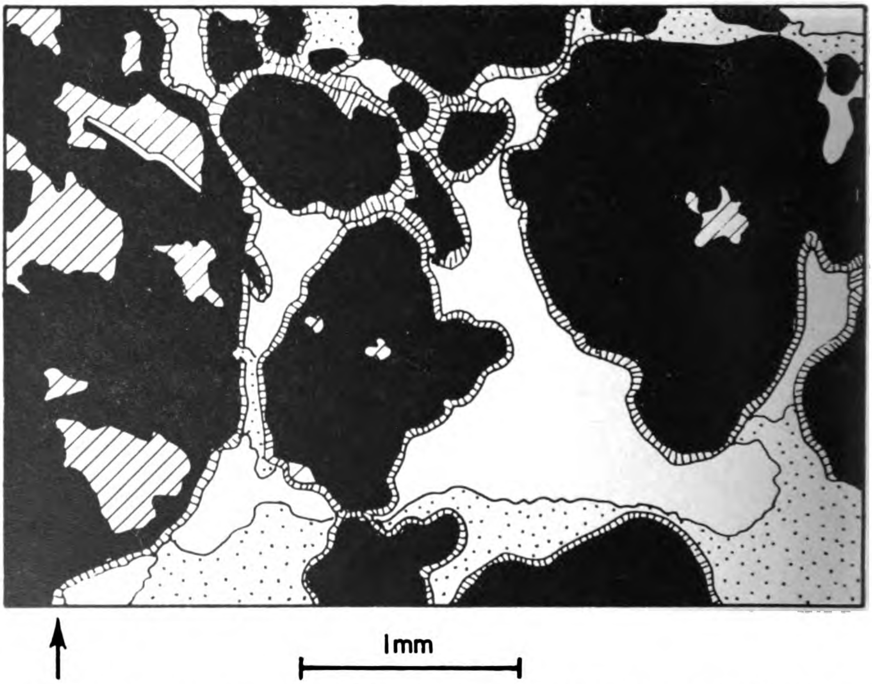


FIG. 3.—Drawing to accompany Plate 3B showing relations of intraclasts, encrusting calcite, void-filling calcite, and fine sediment. Note following features: Encrusting calcite (hachured), consisting of fibrous thin laminae, surrounds intraclasts (black) but does not surround fine sediment (stippled) outside intraclasts. Encrusting calcite is interpreted as younger than intraclasts and older than fine sediment. Void-filling calcite is of two generations. Older void-filling calcite (diagonally ruled) occurs within intraclasts, and younger void-filling calcite (clear) forms cement between intraclasts. Complete sequence of relative ages, oldest to youngest, is interpreted as follows: (a) fine material of intraclasts, (b) void-filling calcite in intraclasts, (c) encrusting calcite, (d) fine sediment, and (e) void-filling calcite between intraclasts. Arrow points to top of bed.

type) occur (c) surrounding intraclasts (Pl. 3B and Fig. 3), (d) as distinct thin crusts that have broken loose and are now surrounded by other types of calcite (Pl. 4A), (e) as crusts that serve to separate other types of calcite, such as fine carbonate sediment from void-filling calcite (Pl. 4B and Fig. 4), and (f) as encrustations formed on the upper surfaces of skeletal fragments, such as leaflike algal fragments (Pl. 5 and Fig. 5).

The origin of encrusting calcite is not well known. Two possible modes of origin have been suggested: (1) The crusts may have been formed by recrystallization of aragonite or calcite that was initially

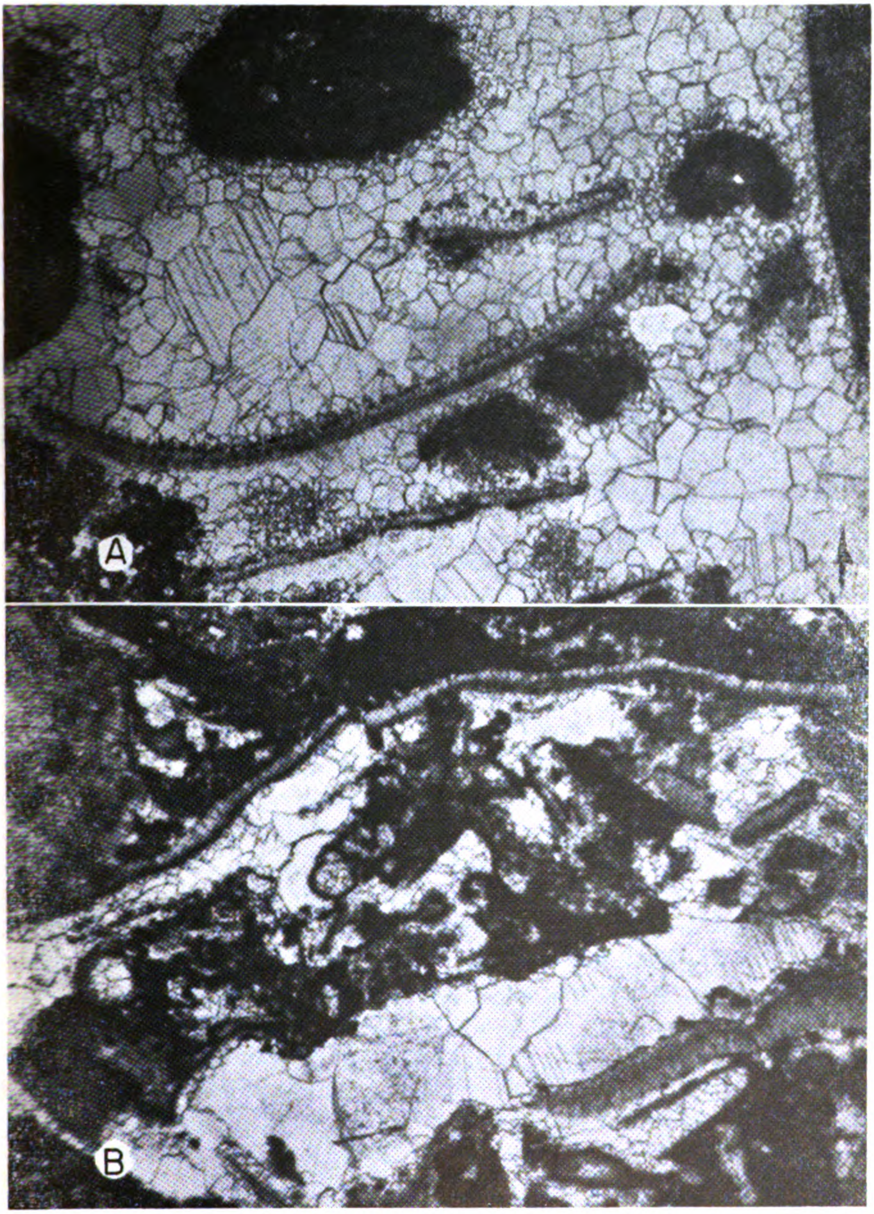


PLATE 4.—Specimens containing encrusting calcite that is necessarily older than adjacent void-filling calcite. Specimens from Magdalena Limestone of Hueco Mountains. Positive photographs of thin sections. **A.** Curving fragments of encrusting calcite are surrounded by void-filling calcite cement (light). Dark objects are intraclasts. ×26. **B.** Encrusting calcite fragments separate fine sediment (dark) in upper part of photograph from void-filling calcite (light) beneath. See Figure 4 for clarification of details. ×20.

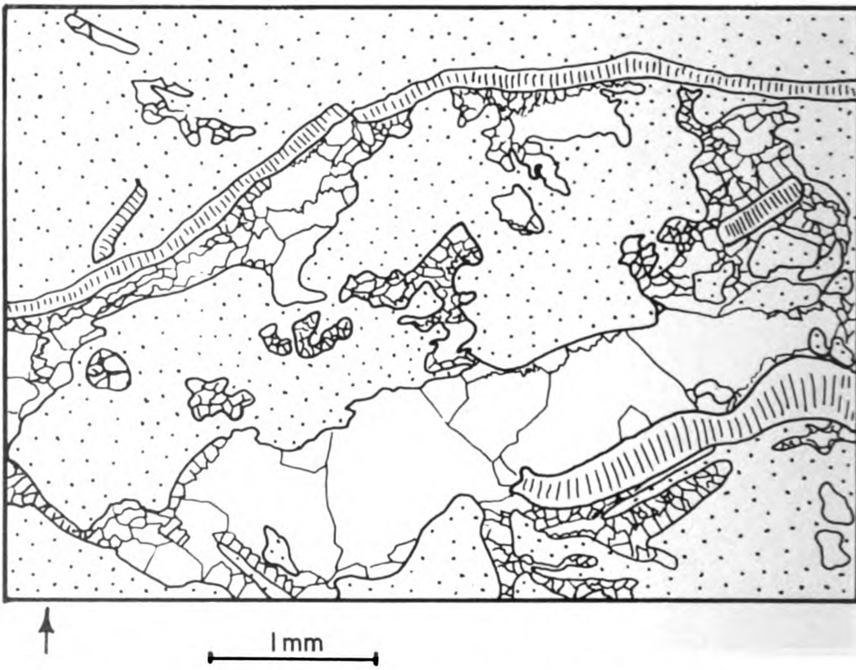


FIG. 4.—Drawing to accompany Plate 4B. Encrusting calcite is hachured, fine sediment is stippled, and boundaries of individual crystals in void-filling calcite are shown by lines. Arrow points to top of bed.

precipitated inorganically around intraclasts and on the upper surfaces of skeletal fragments. (2) It is also possible that the crusts were formed by calcareous algae. Of these two possibilities, an algal origin seems more likely. Some examples of the thicker crusts (Pl. 3A) bear at least a close superficial resemblance to masses of calcite that are presumed to be of algal origin, such as those in the tufaceous deposits described by Scholl (1960). Furthermore, the tendency for some of the calcite crusts to form on the upper surface of skeletal fragments (Pl. 5 and Fig. 5) also suggests an algal origin. The algae presumably responsible for them would seemingly have rested on the upper surface of fragments while exposed at the sea floor.

The occurrence of encrusting calcite on the upper surface of leaf-like algal fragments is of particular interest. The algal fragments served as "umbrellas" and sediment "catchers", as indicated by the fact that sediment has commonly been trapped on the upper surfaces, whereas void-filling calcite occurs adjacent to the sheltered undersides

(Pl. 5 and Fig. 5). Most of the algal fragments have evidently been preserved in the position in which they came to rest upon the sea floor. Localization of encrusting calcite on the upper surface of algal fragments or sediment-filled, cup-shaped algal fragments is significant because it suggests that the encrusting calcite probably formed at the surface of the sea floor. Furthermore, the sea floor would seem to be the most likely site for incorporation of the small pelletlike aggregates of fine sediment observed within some encrusting calcite (Pl. 5 and Fig. 5).

The role of algae in the formation of encrusting calcite is poorly understood. The development of encrusting calcite seems to be neither a result of simple precipitation in water-filled voids nor is it necessarily a recrystallization process analogous to grain growth. Instead, it is suspected that encrusting calcite was formed by a process in which original organic structures were replaced by precipitated calcium carbonate. The dark matter present in some examples (Pl. 3A) may be carbonaceous residue derived from the algae. The algal structures probably influenced crystal orientation, imparting a crude radial arrangement to the crystals in some examples. Admittedly, however, no cellular structures that would verify an algal origin have been observed in my samples.

The age relations of encrusting calcite seem generally to be simple. (1) Where preserved in position of "growth" (Pl. 5), encrusting calcite probably formed almost simultaneously with surrounding sediment. (2) Where present as transported intraclasts (Pl. 4A and 6), encrusting calcite is necessarily older than the surrounding sediment and void-filling calcite. (3) Where present as a thin coating that merely surrounds intraclasts (Pl. 3B), encrusting calcite is younger than the intraclasts themselves, but is probably older than sediment between the intraclasts. The coatings probably formed while the intraclasts were being transported and before they finally came to rest.

Void-Filling Calcite

Void-filling calcite (also termed open-space calcite) is exceedingly common in limestone. Most specimens of unmetamorphosed limestone upon close scrutiny will be found to contain some void-filling calcite. Recognition of void-filling calcite is valuable because of the light thrown on conditions of deposition and subsequent diagenesis and on alteration of limestone, including development of porosity. Bathurst (1958, 1959a, 1959b) has discussed at length criteria for recognition of void-filling calcite, of which the three principal ones are: (1) crystals

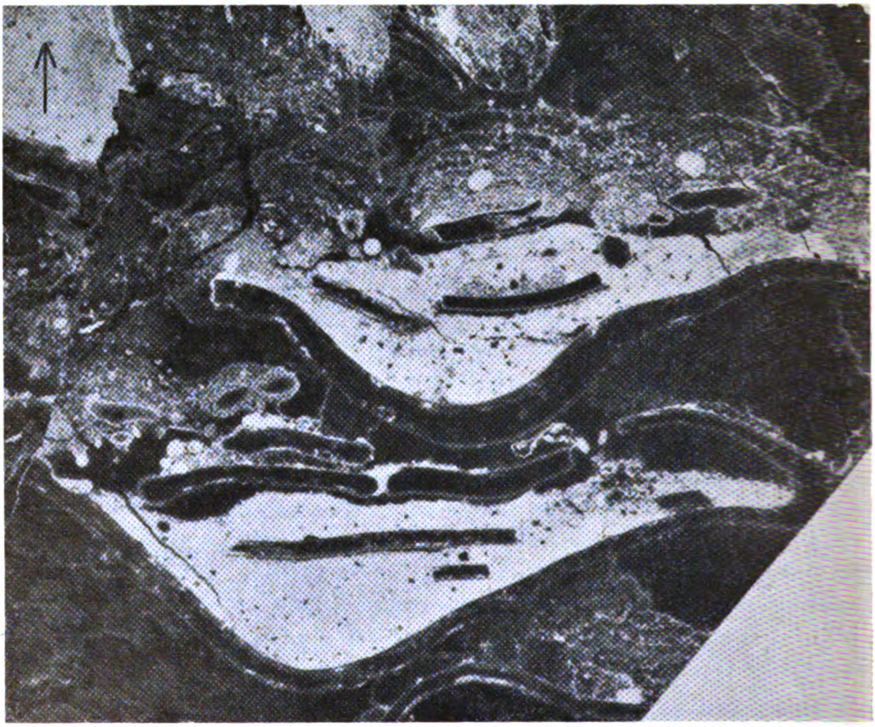


PLATE 5.—Encrusting calcite in position of "growth". Encrusting calcite consists of curved laminae that rest on sediment-filled cups formed by fragments of leaf-like algae. Encrusting calcite is necessarily younger than sediment-filled cups. Specimen from Magdalena Limestone of Hueco Mountains. See Figure 5 for clarification of details. Negative print made by direct projection of thin section, ×6. Arrow points to top of bed.

near the walls of filled voids are oriented more or less perpendicular to the walls; (2) boundaries between individual crystals are plane surfaces; and (3) there is an increase in size of crystals from the walls toward the center of filled voids. Additional characteristics are listed in Table 2.

As its name implies, void-filling calcite has been formed through precipitation in water-filled voids. Under exceptional conditions void-filling calcite may have been deposited in voids only intermittently flooded and normally occupied by air. Presumably precipitation is directly controlled by inorganic factors, for there is little evidence that organisms have directly influenced precipitation. The solubility relations of calcium carbonate are exceedingly complex, however, and

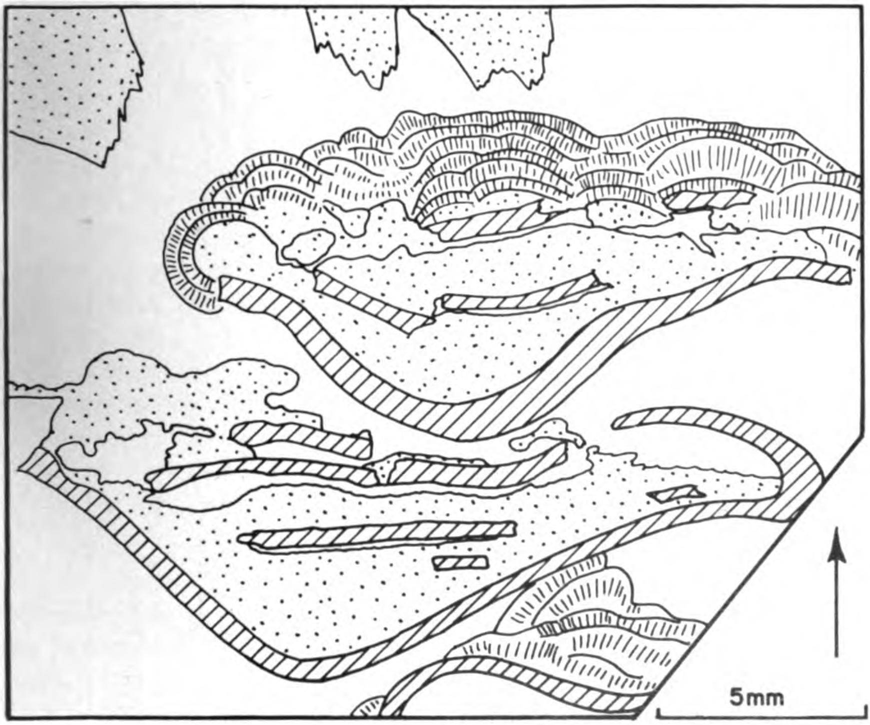


FIG. 5.—Drawing to accompany Plate 5. Encrusting calcite is hachured, fine sediment is stippled, leaflike algae are diagonally ruled, and void-filling calcite is clear. Jagged boundaries between fine sediment and void-filling calcite in upper part of illustration are stylolites. Arrow points to top of bed.

in environments where limestone forms, these relations are intimately connected with organic processes, such as photosynthesis of algae and other green plants. Therefore, in many limestones, organic processes probably had an important but indirect influence on precipitation of calcium carbonate in water-filled voids.

Voids in sediments are produced in many ways. In the late Paleozoic limestones examined in this study seven principal modes of occurrence of filled voids have been recognized, as follows: (1) beneath "umbrellas" provided by leaflike algae and other skeletal material, (2) as cement in sorted calcarenites and oolites, (3) between breccia fragments, (4) filling irregular openings (sometimes termed Stromatactis), many of which seem to have been produced by contraction of the sediment, (5) in formerly hollow interiors of shells and leaflike algae, (6) as transported intraclasts, and (7) in post-lithification fractures.

TABLE 3.—*Summary of relations of various modes of void-filling calcite in respect to degree of consolidation of sediment and to time of filling.*

Mode of occurrence of void-filling calcite.	Minimum degree of consolidation of fine sediment needed for voids to form.	Earliest possible time of void filling.	Latest possible time of void filling.
1. Beneath umbrellas.	None.	As soon as umbrellas were deposited.	No limit.
2. Cement.	None.	Immediately after deposition of sediment.	No limit.
3. Between breccia fragments formed prior to complete consolidation. 4. Filling irregular openings (Stromatactis) and pre-lithification cracks.	Partial consolidation.	After contraction and partial collapse of sediment.	No limit.
5. Filled interiors.	None.	After death of organism and decay of soft tissues.	No limit.
6. As transported intraclasts.	Partial consolidation.	After contraction and partial collapse of sediment surrounding fillings when formed.	Before complete consolidation of sediment surrounding fillings and before transportation.
7. In post-lithification fractures.	Complete consolidation.	After fracturing.	No limit.

Each of the seven principal modes is described and interpreted on succeeding pages, and summarized in Table 3.

Void-Filling Calcite Beneath "Umbrellas"

The presence of void-filling calcite beneath miniature "umbrellas" in sediments is exceedingly common (Harbaugh, 1960, p. 204, 228). The umbrellas consist of skeletal fragments that have appreciable lateral extent. Fragments of leaflike algae (Pl. 5 and Fig. 5) have provided excellent opportunities for void filling; but shells, bryozoan fronds, and fragments of encrusting calcite (Pl. 4B and Fig. 4) are also notable in this respect. These fragments provide voids adjacent to their sheltered undersides by preventing sediment from completely filling the space. Much of the sediment seems to have been caught on the upper surfaces of the umbrellas, and the voids thus formed were available for subsequent filling by precipitated calcium carbonate.

Several conclusions may be drawn concerning age of void-filling calcite beneath umbrellas relative to surrounding sediment. Consider the following points: (1) The voids were available for filling as soon as the umbrellas were laid down; at the earliest, filling could have begun almost simultaneously with deposition of surrounding sediment. (2) The surrounding sediment need not have undergone any degree of consolidation to permit the voids to exist; the rigid skeletal fragments forming the umbrellas were sufficient to maintain the voids. (3) There is no evidence that fine sediment was squeezed into the voids. Thus, even if consolidation of the sediment was delayed, the voids were filled before the weight of overlying material became great enough to cause compaction. Otherwise, the fine sediment seemingly would have been squeezed into the voids. (4) Filling of voids may have taken place over an extended period of time, and some voids may never have been completely filled (Murray, 1960, p. 66). Evidence in support of this conclusion is found in the tendency for solution pores in some limestones to be localized in places formerly occupied by void-filling calcite. It has been suggested that pores remaining as a result of incomplete filling of voids were later enlarged through solution by ground water (Harbaugh, 1960, p. 206).

In summarizing the age relations of void-filling calcite beneath umbrellas, it seems probable that most of the filling occurred early in the sediment's history—before, during, or shortly after the time when partial consolidation took place. Filling could have continued long after the sediment had been well consolidated, however.

Calcite Cement

Void-filling calcite occurring as cement is widespread in limestone, although most noticeable in sorted calcarenite, oolite, and coarse-

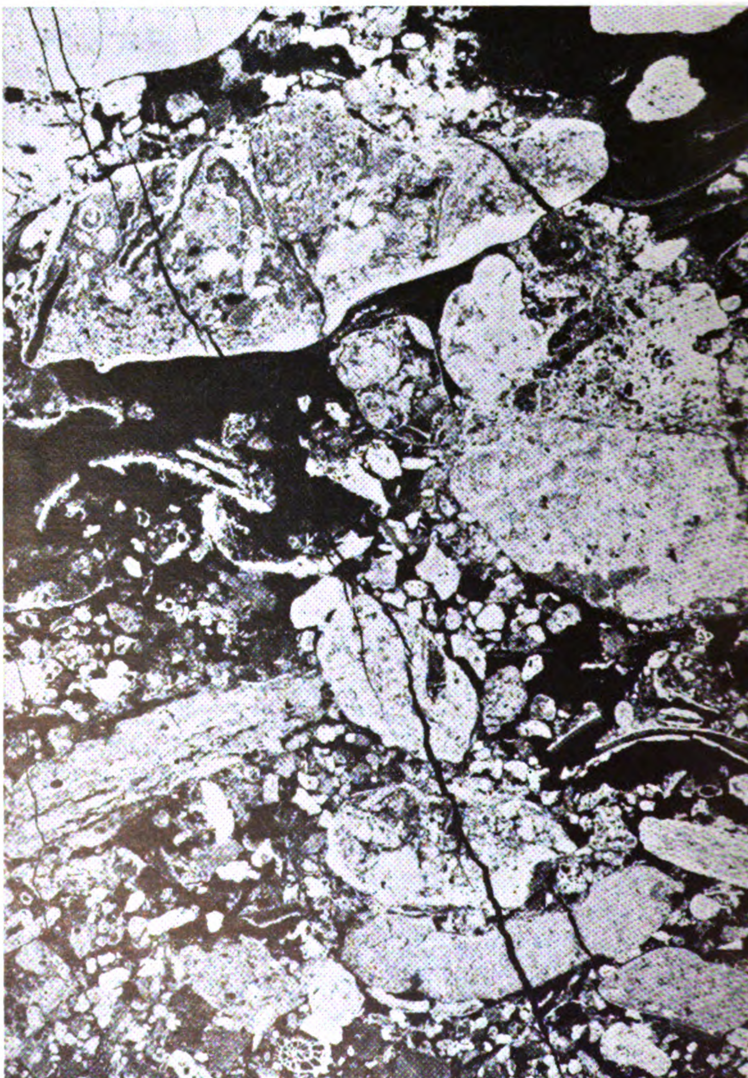


PLATE 6.—Limestone conglomerate composed of intraclasts in which are included fragments of encrusting calcite. Negative print made by direct projection of thin section, ×7. Intraclasts appear light; cement consisting of void-filling calcite appears dark. Specimen from Magdalena Limestone of Hueco Mountains. See Figure 6 for clarification of details.

grained fragmental limestone. The cement is necessarily younger than the surrounding sediment, but in many examples most of the cement seemingly is not much younger. Evidence is the large proportion of

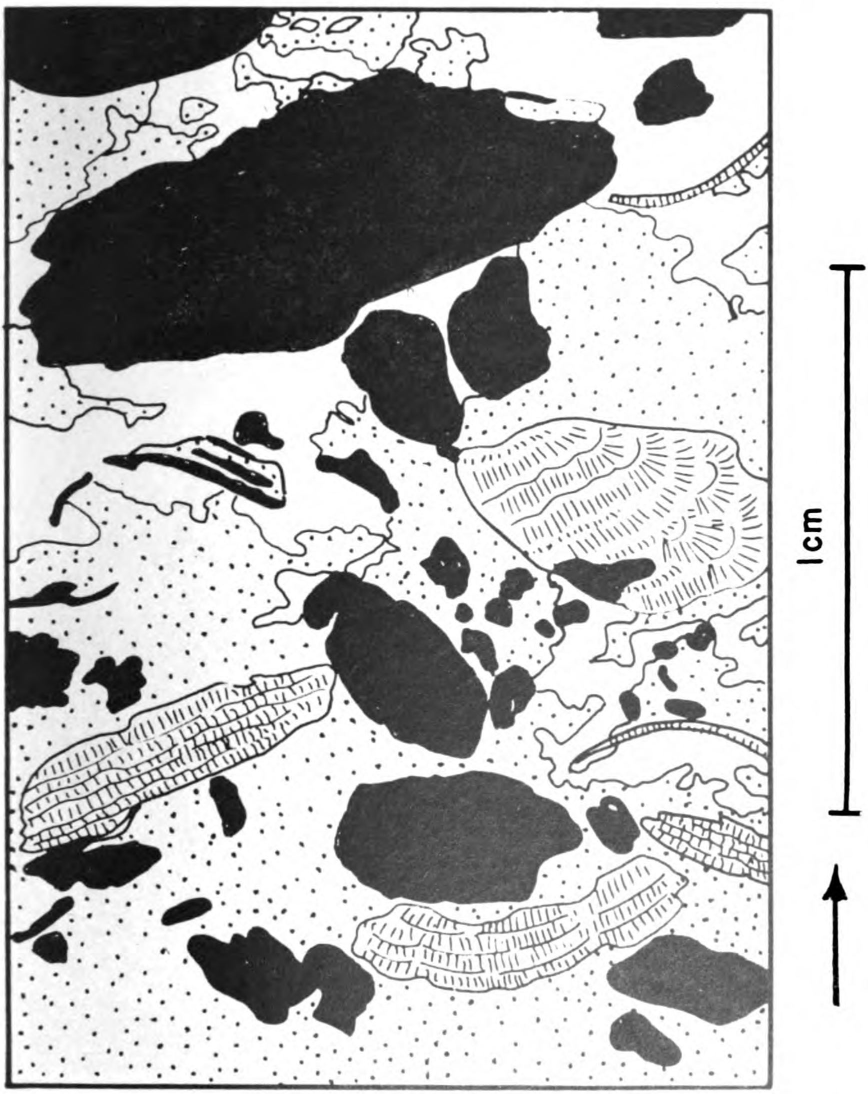


Fig. 6.—Drawing to accompany Plate 6. Intraclasts of encrusting calcite are **hachured, intraclasts of** other material are black, fine sediment is stippled, and **void-filling calcite cement** is clear. Arrow points to top of bed.

volume occupied by cement in some specimens (Pl. 6 and Fig. 6). It is suggested that such large proportions of void space could not have

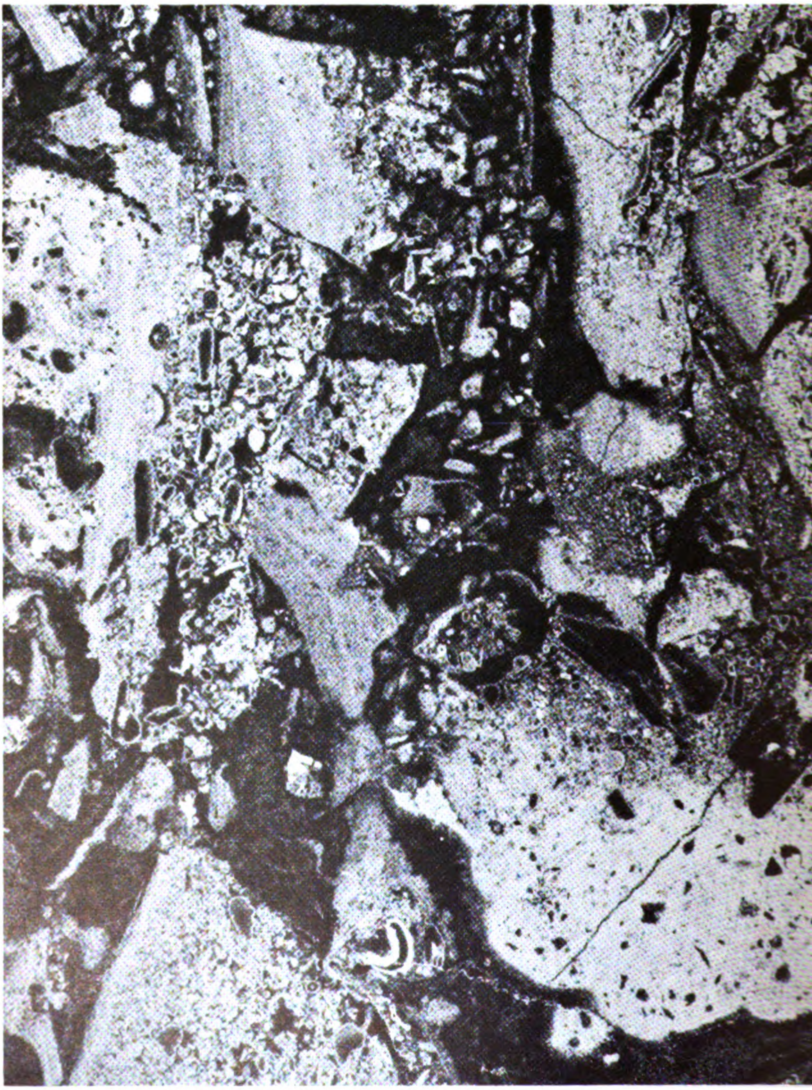


PLATE 7.—Limestone breccia consisting of fragments of sediment (light) separated by void-filling calcite (dark). Specimen from Magdalena Limestone of Hueco Mountains. Negative print made by direct projection of thin section, × 6½. See Figure 7 for clarification of details.

persisted after the load of overlying sediments produced compaction; the voids must have been already almost filled.

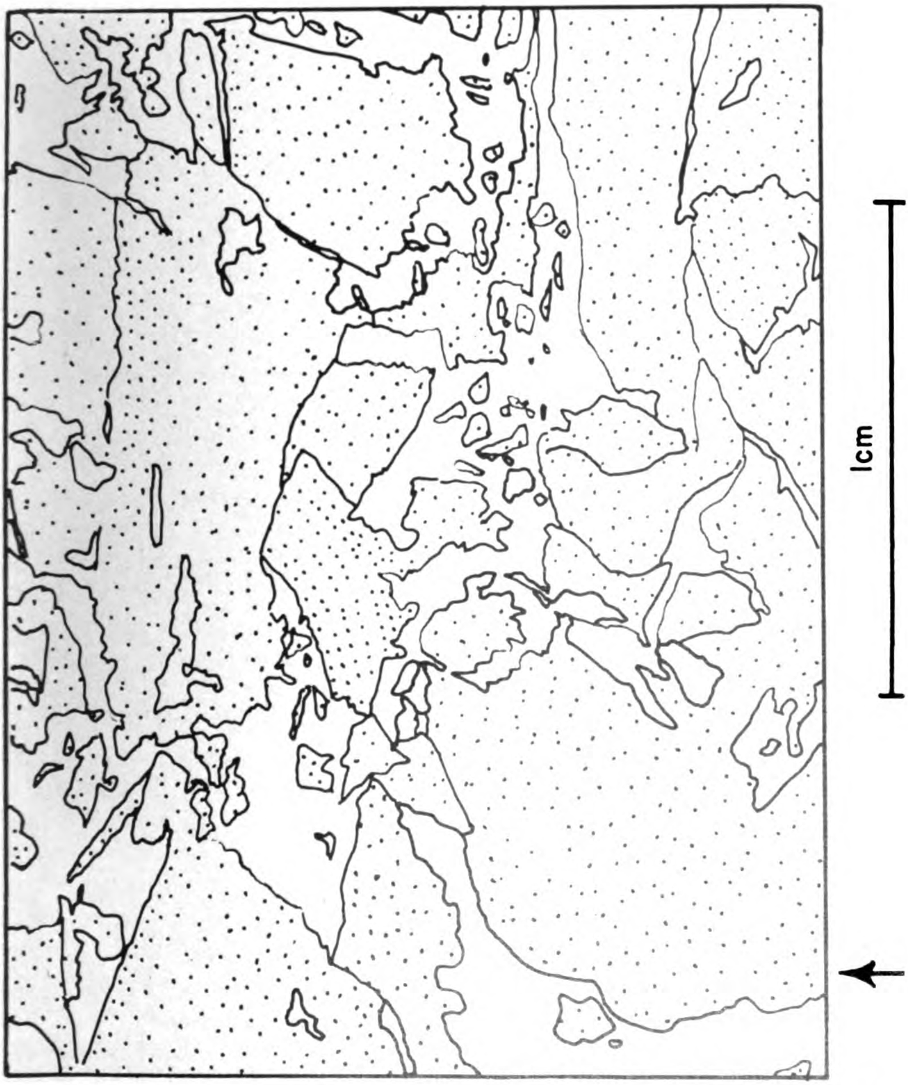


FIG. 7—Drawing to accompany Plate 7. Sediment is stippled and void-filling **calcite is clear. Arrow points** to top of bed.

Breccia Fillings

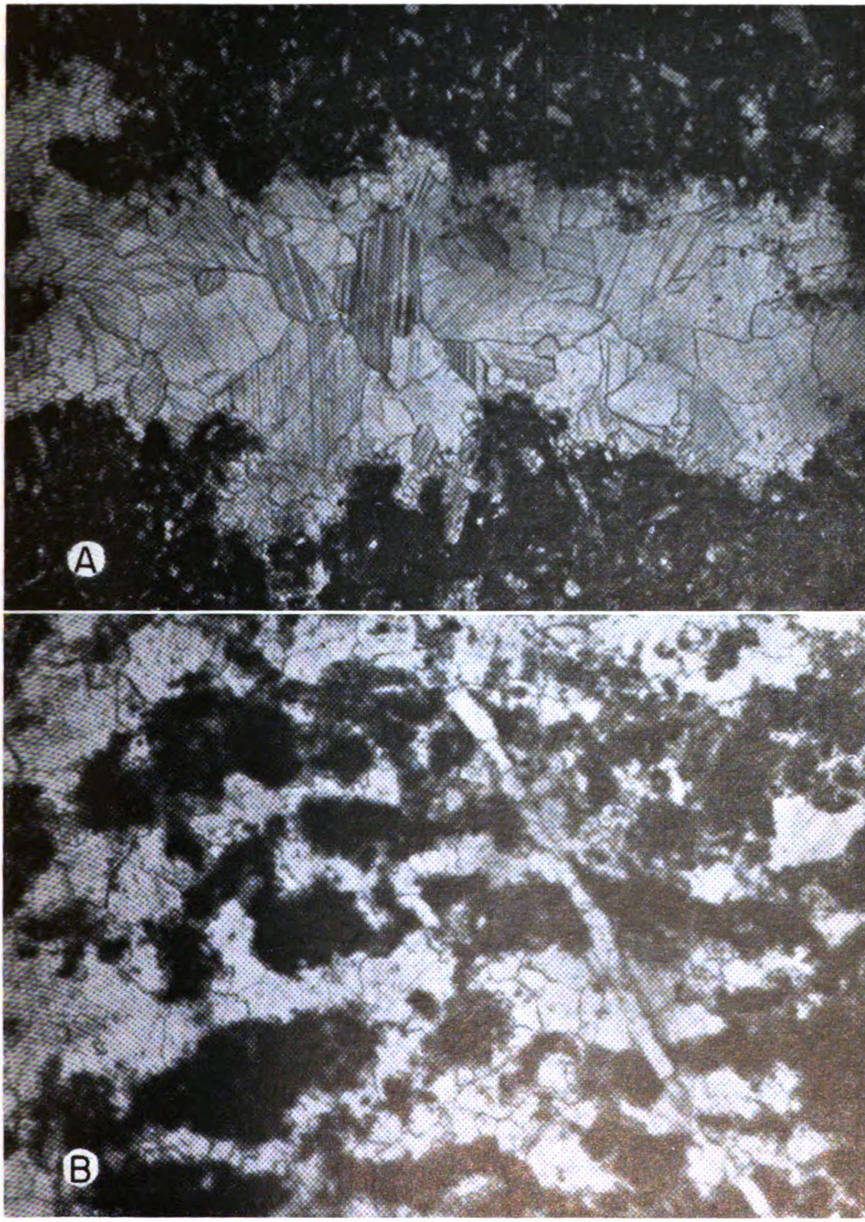
The age relations of limestone breccias and associated void-filling calcite are complicated by the fact that breccias may be formed at different times relative to the age of a sediment. They may be formed (1) during deposition, (2) after deposition but before complete consolidation of the sediment, and (3) after complete consolidation. Most breccias examined in this study seem to be the second subtype, having formed principally after deposition but before complete consolidation.

Shrinkage or contraction accompanying partial consolidation probably strongly influenced development of breccias, the loss of volume inducing partial collapse of the sediment. The semi-consolidated sediment seems to have slumped down unevenly, breaking into fragments in the process. The example shown in Plate 7 and Figure 7 is more or less typical of breccias encountered in some of the limestone examined in this study. In this example, the breccia consists of angular fragments of previously aggregated fine sediment. The fragments are separated by void-filling calcite. The fragments show little evidence of crushing and some, though separated from each other, can be matched on their broken edges. Some breccia-bearing beds adjoin beds where no brecciation has occurred. Presumably the cause of brecciation is depositional rather than tectonic, thus requiring partial consolidation of the sediment. Reasoning thus, it is suggested that most of the brecciation occurred after the sediment was sufficiently consolidated to possess some coherence, but before it was completely consolidated.

The conditions that bring about contraction and development of voids in fine carbonate sediments are poorly understood. Loss of moisture by drying of sediments where exposed at low tide on tidal flats is probably an important cause. Compaction, in contrast to contraction, however, seems incapable of causing voids to form even though compaction also results in loss of volume.

The age relations of void-filling calcite in breccias similar to that illustrated in Plate 7 and Figure 7 seem simple. Precipitation of the calcite must have occurred after brecciation and, therefore, after at least partial consolidation of fine sediment, but most of the filling must have been completed before the overlying load of sediment became very great, for otherwise the voids would probably have been at least partly eliminated by compaction.

PLATE 8.—Void-filling calcite occupying irregular former openings (Stromatactis). Fine sediment is dark; void-filling calcite is light. Specimens from Magdalena Limestone of Caballo Mountain, New Mexico. Positive photographs of



thin sections. A. Individual irregular opening. See Figure 1D for clarification of details of central part of photograph. ×26. **B.** Void-filling calcite occupying former openings that formed an intricate network of interconnected voids in fine sediment. Calcite-filled post-lithification fracture cuts diagonally across photograph. ×40.

Filled Irregular Openings

Irregular openings (Stromatactis) and pre-lithification cracks filled with void-filling calcite are very common in limestone. These assume a variety of shapes and in many examples form an intricate network. It is possible that some irregular openings were formed as gas pockets (Cloud, 1960), but most are probably a result of contraction and partial collapse of the sediment in a partly consolidated state. The proportion of void-filling calcite is probably a rough measure of the volume lost during contraction, which seems to have been appreciable in many specimens.

The term "Stromatactis" was originally given by DuPont (1881) to masses of crystalline calcite in Devonian limestone of the Ardennes in Belgium, in allusion to the possibility that the masses might represent a kind of reef-building stromatoporoid. Although the question of organic versus inorganic ultimate origin of the Belgian examples remains unsettled, most geologists who presently employ the term use it as a sedimentary structural term and not as a name of an organism. Masses of visibly crystalline calcite that may be described as Stromatactis have filled irregular cavities in fine sediment (Pl. 8 and 9A and Fig. 1D). Some cavities received thin deposits of fine sediment on their lower surfaces before being filled with crystalline calcite (Bathurst, 1959b).

The age relations of void-filling calcite in irregular openings and pre-lithification cracks are probably identical to those of void-filling calcite in breccias formed prior to complete consolidation. The calcite was precipitated in voids after partial consolidation and before complete consolidation of the sediment.

Filled Interiors

Formerly hollow interiors of shells and leaflike algae (Pl. 9B and 10A and Fig. 8) provided space for void-filling calcite to form. The hollow interiors became available for filling upon death of the organism and decay of its soft tissues. If the soft tissues decayed rapidly, the voids may have become available for filling before the shells or algal fragments were incorporated in the sediments.

Calcite Intraclasts

Intraclasts consisting wholly or partly of void-filling calcite are common in certain limestones. The intraclasts represent void fillings that were formed elsewhere and then transported and redeposited. In the examples shown in Plate 10B and Figures 9 and 10 many of the intraclasts contain fine sediment in addition to void-filling calcite.

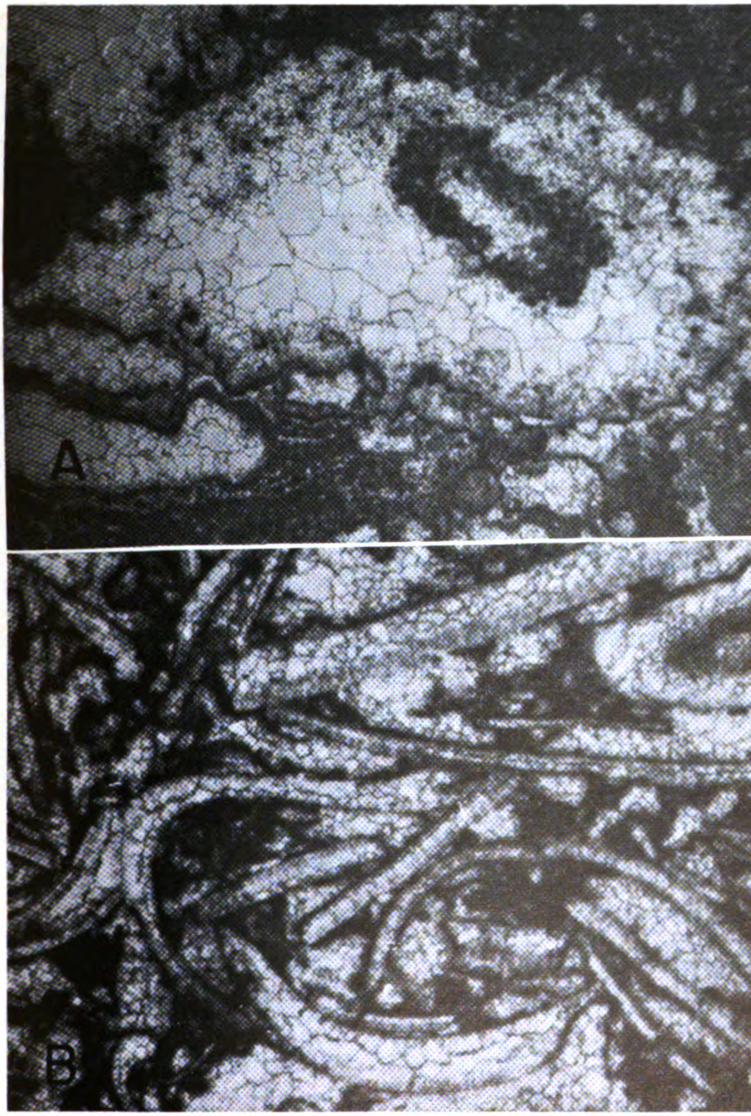


PLATE 9.—Specimens from Magdalena Limestone of Hueco Mountains. Positive photographs of thin sections. **A.** Void-filling calcite occupying irregular former opening. Filling bears close resemblance to intraclasts consisting chiefly of void-filling calcite illustrated in Plate 10B, × 18. **B.** Limestone consisting mainly of fragments of leaflike algae. Interiors of algae are occupied by void-filling calcite. Enlarged view of single algal "leaf" is shown in Plate 10A. ×23.

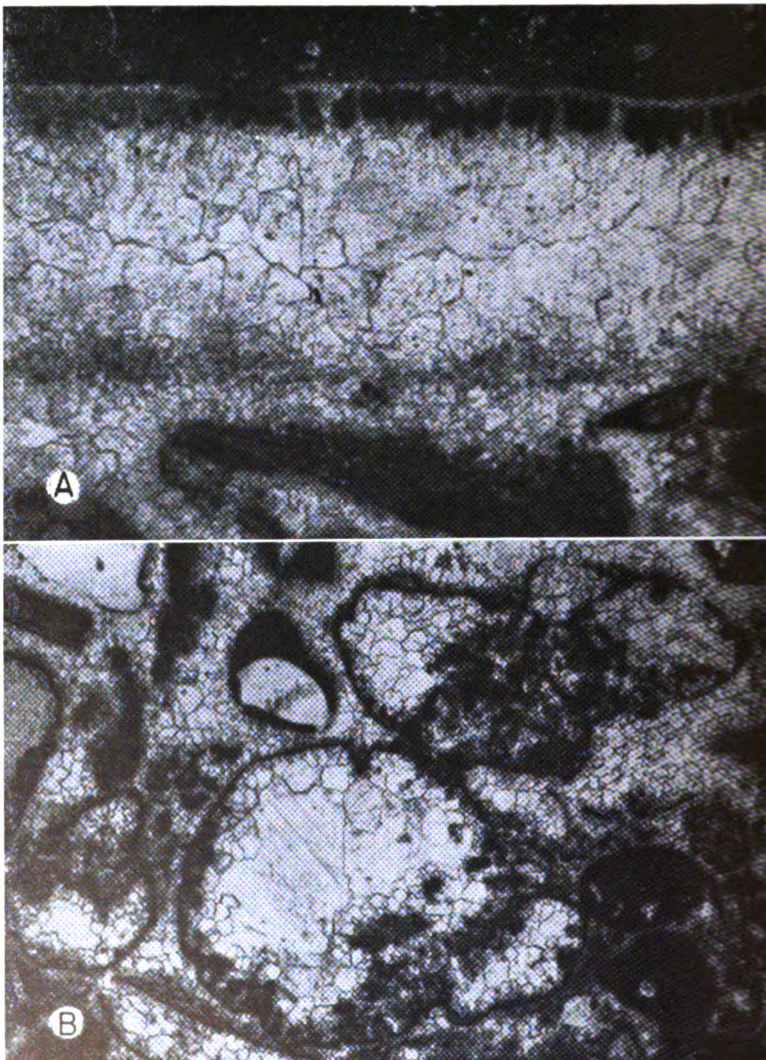


PLATE 10.—Specimens from Magdalena Limestone of Hueco Mountains. Positive photographs of thin sections. **A.** Interior of leaflike algal fragment occupied by void-filling calcite. Alga resembles *Eugonophyllum* (Konishi and Wray, 1961). Void-filling calcite is light; fine sediment is dark. Dark objects lying close to upper border of algal fragment are part of wall structure of alga. See Figure 8 for clarification of details. ×36. **B.** Transported intraclasts consisting chiefly of void-filling calcite. Intraclasts are surrounded by cement consisting of younger void-filling calcite. Void-filling calcite is light; fine sediment is dark. See Figures 9 and 10 for clarification of details. ×25.

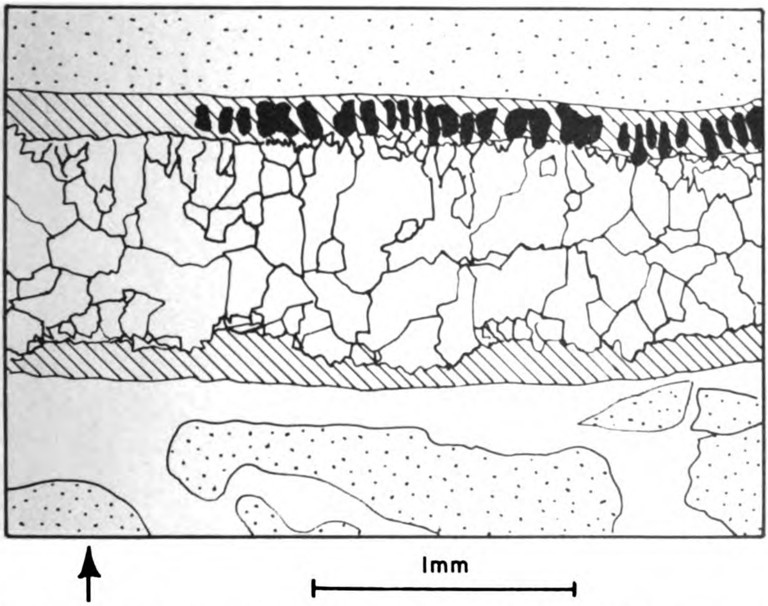


FIG. 8.—Drawing to accompany Plate 10A. Walls of algal fragments are diagonally ruled; fine sediment is stippled; black objects are wall structures of alga; void-filling calcite is clear, boundaries between individual crystals inside algal fragment being shown by fine lines. Arrow points to top of bed.

Several important conclusions concerning age relations may be drawn from the presence of intraclasts consisting of void-filling calcite: (1) The voids necessarily were filled before the intraclasts were torn loose. (2) Fine sediment surrounding the voids and later incorporated in some intraclasts must have been partly consolidated and must have possessed some degree of coherence before the intraclasts were formed, although the fine sediment was probably not yet completely consolidated. (3) Void filling and partial consolidation probably occurred at shallow depth below the sea floor where the sediment could be eroded readily and intraclasts formed. Somewhat similar conclusions have been drawn by Schwarzacher (1961, p. 1495) in a study of Lower Carboniferous reefs in northwestern Ireland.

Filled Post-lithification Fractures and Other Openings

It is possible to make a general distinction between fractures formed before lithification and those formed after lithification. Cracks or fractures formed before final consolidation or lithification generally do not cut across skeletal fragments, whereas those formed after final

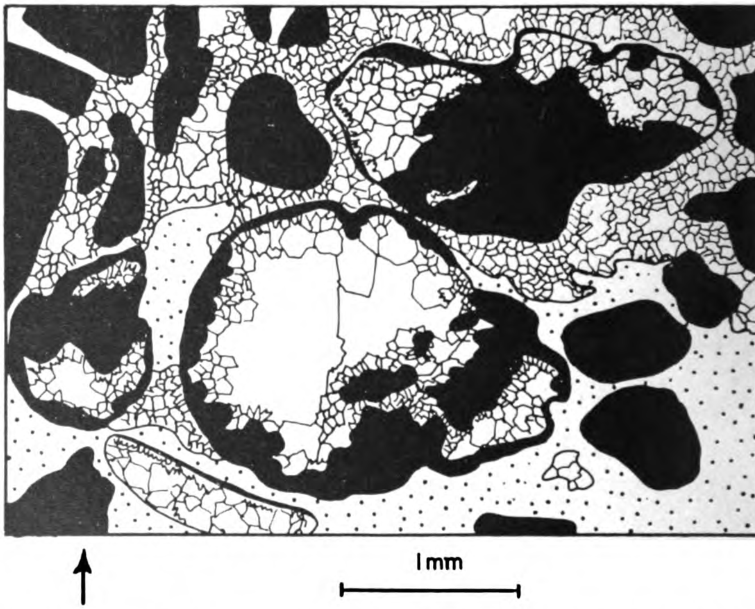


FIG. 9.—Drawing to accompany Plate 10B. Boundaries between individual crystals of void-filling calcite are shown by fine lines; fine sediment incorporated within intraclasts is black; fine sediment outside intraclasts is stippled. See Figure 10 for differentiation of two generations of void-filling calcite. Arrow points to top of bed.

consolidation cut across skeletal fragments and other features of the rock. Both, of course, provide space for void-filling calcite to form. Calcite filling post-lithification fractures is necessarily grouped with the youngest of the forms of void-filling calcite, although its age relative to the age of surrounding sediment is generally very indefinite.

No tabulation of the modes of occurrence of void-filling calcite would be complete without mentioning second- and multi-generation calcite-filled voids produced by leaching and subsequent filling after final consolidation.

SUMMARY

Age relations, evidence, and depositional and diagenetic significance of the four types of visibly crystalline calcite described in this paper are summarized in Table 4. In addition, the major conclusions are presented in greater detail below:

1. Four types of visibly crystalline calcite were observed in the late Paleozoic limestones examined in this study: (A) grain-growth cal-

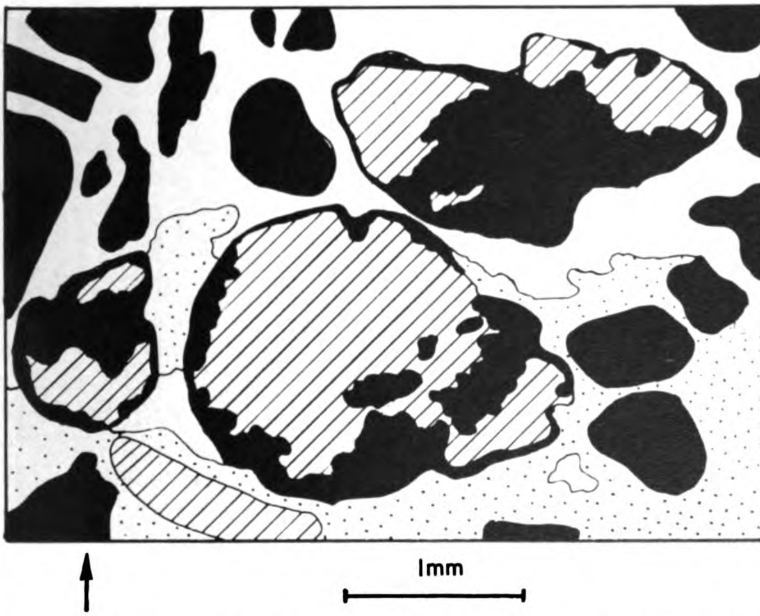


FIG. 10.—Drawing to accompany Plate 10B and Figure 9 showing relative ages. Void-filling calcite within intraclasts (diagonally ruled) is older than void-filling calcite occurring as cement (clear) between intraclasts. Fine sediment incorporated within intraclasts (black) was consolidated before fine sediment between (stippled) intraclasts. Arrow points to top of bed.

cite characterized principally by the irregular size and shape and random orientation of crystal grains; (B) blade calcite characterized by flowerlike aggregates of tapered, bladelike crystals that show undulatory extinction under polarized light, indicating strain; (C) encrusting calcite characterized by aggregates of fibrous to irregular crystals, some of which are arranged radially; and (D) void-filling calcite characterized by orientation of crystals perpendicular to walls of filled voids, accompanied by a general increase in crystal size from the walls toward the center of the filled void.

2. Grain-growth calcite and blade calcite have probably been produced by recrystallization in the solid state. In grain growth, crystal boundaries migrate, larger crystals taking the place of many small crystals. Blade calcite is probably a product of low-grade metamorphism.

3. Encrusting calcite and void-filling calcite have formed by precipitation. Encrusting calcite seemingly formed by precipitation in and around algal tissues, although some may be of inorganic origin. Void-

TABLE 4.—*General summary of age relations, evidence, and depositional and diagenetic significance of types of visibly crystalline calcite.*

	Grain-growth calcite	Blade calcite	Encrusting calcite	Void-filling calcite
Time of origin of visibly crystalline calcite relative to time of deposition of surrounding sediments.	Later.	Later.	During.	Later, except where present as intraclasts.
Time of origin relative to time of partial consolidation of sediment.	Poorly known.	Later.	Before, except for partly consolidated intraclasts.	Variable, but probably soon after partial consolidation in many examples. See Table 3.
Evidence for time of origin.	Little evidence, except localization adjacent to void-filling calcite in some examples.	(a) Crystals cut across skeletal fragments as well as fine sediment. (b) Not present as intraclasts. (c) Undulatory extinction of crystals under crossed nicols, indicating strain.	(a) Localization on upper surface of skeletal fragments. (b) Presence as transported intraclasts. (c) Incorporation of fine sediment particles.	(a) Some specimens fill openings probably produced by contraction of partly consolidated sediment. (b) Presence as transported intraclasts.
Depositional and diagenetic significance.	Development possibly stimulated adjacent void- by presence of filling calcite.	Strained crystals may have formed under stress within completely consolidated sediment.	(a) Probably of algal origin; formed at surface of sea floor in sunlit waters. (b) Served as sediment-binding agent.	Early filling probably inhibited compaction of incompletely consolidated sediment.

filling calcite was formed by inorganic precipitation in water-filled voids.

4. The principal modes in which void-filling calcite occurs are (1) beneath "umbrellas" provided by leaflike algae and other sketetal material, (2) as cement, (3) between breccia fragments, (4) in irregular openings (Stromatactis) and pre-lithification cracks, (5) in formerly hollow interiors of shells and leaflike algae, (6) as transported intraclasts, and (7) filling post-lithification fractures.

5. Although the relative ages of different types of visibly crystalline calcite probably vary widely, generalizations may be drawn concerning age of the calcite relative to age of surrounding sediment and time of consolidation. (a) Encrusting calcite probably formed during deposition of surrounding sediment and is thus earliest of the calcite types to form. (b) Except for that occupying fractures or openings produced after lithification, most void-filling calcite was probably formed early in the limestone's history, during or shortly after partial consolidation. (c) The age relations of grain-growth calcite are poorly known, but it is probable that with few exceptions grain-growth calcite is not older than adjacent void-filling calcite. (d) Blade calcite, as well as void-filling calcite occupying post-lithification fractures, seems to be generally younger than other calcite.

6. Early filling of voids probably had an important effect by inhibiting compaction of the partly consolidated sediment. This may explain why limestone, in contrast to other sediments such as shale, shows so little evidence of compaction.

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