

LIMESTONE RESPONSE TO STRESS: PRESSURE SOLUTION AND DOLOMITIZATION¹

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ABSTRACT: Limestones that have been subjected to overburden or tectonic stress can be expected to have changed by some combination of deformation (plastic or brittle), neomorphism (as micrite conversion to microspar or aggrading pseudospar), and solution. Specific limestone units (beds, structures, or grains) may be preferentially resistant or responsive to change and with or without impurities (especially magnesium ions and clay particles) that will influence the character of change.

Three styles of pressure solution response are recognized in Paleozoic limestones studied from Arizona, western Maryland, and southeast Kansas. *Sutured-seam solution* (common stylolites and grain-contact sutures) occurs in limestones that have structural resistance to stress and very little clay or platy silt content. *Non-sutured seam solution* (microstylolites, microstylolite swarms, and clay seams) occurs in limestones that have significant amounts of clay or platy silt. These limestones may be structurally resistant or responsive. Stress is accommodated both by solution and by lateral movement along microstylolite surfaces. Dolomite rhomb growth may or may not occur along microstylolite surfaces. *Non-seam solution* (pervasive solution thinning of a unit) occurs in clean limestones that have little or no structural resistance to stress. Dolomite growth is always observed to be associated with non-seam solution, but pervasive pressure solution without associated dolomitization should also be possible.

Where clean, structurally resistant limestone units interface with responsive limestones or silty, clayey limestones, solution surfaces are not sutured.

Nodular limestones are a characteristic product of non-sutured seam solution in silty, clayey limestones. Form and scale of fitted nodules may or may not be influenced by primary structure.

The three forms of limestone pressure solution produce some types of finely crystalline stratigraphic dolomite, provide local sources of magnesium for dolomitization and calcite for porosity-filling cement, and severely distort primary sedimentary structures or create secondary structures.

INTRODUCTION

The purpose of this paper is to document the occurrence and importance of three basic types of pressure-solution features in limestones and to show that an understanding of some dolomites depends on proper recognition of the role of pressure solution.

The author's observations on products of pressure solution bear directly on five related problems in carbonate rocks, some of which have been the subjects of interesting but inconclusive discussion in the recent literature.

1) What is the origin of those ancient dolomites that *appear* delicately related to

primary sedimentary structures, e.g., laminated dolomites and dolomite layers and laminae intercalated with limestone (Murray and Pray, 1965; Zenger, 1972; Gebelein and Hoffman, 1973)?

2) What are the sources of carbonate for cementation (Bathurst, 1971, p. 415, 439-440) and the sources of magnesium for dolomitization (Pettijohn, 1957; Beales, 1965; Schmidt, 1965; Gebelein and Hoffman, 1973)?

3) What factors caused the unusual sedimentary structures, such as ribbon structures in limestones and massive to laminated dolomites, that are invariably associated with undoubtedly primary sedimentary structures (Matter, 1967; Lucia, 1972, p. 176; Wilson, 1975, p. 265)?

4) As these unusual structures commonly occur in specific zones of cyclic carbonate

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sequences, what do they record of the depositional environment? It is difficult to make a rigorous comparison with modern carbonate cycles when certain structures have no apparent modern analogues.

5) How do we explain the apparent compaction structures displayed in certain limestones (Murray and Pray, 1965; Bathurst, 1971; Shinn and others, 1977)?

It is the author's conclusion that these five problems have grown into major enigmas because carbonate sedimentologists have overlooked the major role and varied expression of stress response in limestones. In a real sense we have been approaching aspects of these problems with the wrong questions.

Recognition of the spectrum of responses of limestones to overburden or tectonic stress is a key to the proper understanding of carbonate rocks. Folk (1965) addressed this problem in his 1965 paper on limestone recrystallization in which he compares the inversion and neomorphic processes observed in limestones with those in metals. Folk emphasized that, whereas strained or unstrained recrystallization in metals occurs in the absence of interstitial solutions, "most of the reactions (in sedimentary carbonates) take place by migrations of ions through interstitial solutions at low temperatures" (Folk, 1965, p. 19). In limestones, unlike metals, solution or partial solution is a clear alternative to recrystallization, the dissolved ions being transferred to other areas by interstitial solutions.

Pressure solution has been recognized for many years as the cause of sutured stylolite seams and grain-contact sutures (e.g., Sorby, 1879, 1908; Stockdale, 1922, 1926, 1936, 1943; Dunnington, 1954), yet few geologists have attempted to assess the general significance of pressure solution in limestones or to include it in a general scheme of limestone diagenesis.

Barrett (1964), Mimran (1977), and Garrison and Kennedy (1977) provide evidence that many clay seams are related to limestone pressure solution. Wanless (1973b) has shown that swarms of microstylolites along which clays are concentrated are common products of pressure solution in clayey limestones and can generate nodular limestones.

Dunnington (1967), Geiser (1974), and Al-

varez, Engelder and Lowrie (1976) have shown that laterally directed pressure during tectonic folding can cause an immense amount of solution shortening of Paleozoic limestone units. Much of this solution occurred along wavy "spaced solution cleavage surfaces" oriented at sharp angles to primary layering.

Most recently, Logan and Semeniuk (1976) have offered evidence that pressure solution, in the form of various types of stylolitic solution acting at grain to formation scale, causes radical changes in the primary limestone fabric, form and morphology. The conclusions of Logan and Semeniuk are contrasted with those of the author at the close of this paper.

An Approach to Carbonate Rocks

In considering the response of limestones under stress, it is useful to consider limestones as packages of crystals which (a) will have differing resistance or responsiveness to change and (b) will or will not contain impurities that would cause them to behave differently than when pure. Change under stress can take the form of physical compaction, physical deformation (plastic or brittle), neomorphism (as micrite conversion to microspar or aggrading pseudospar), or solution. Influencing impurities can be chemically inert particles (as silici-clastic sand, silt, and clay), ions in calcite structure (as magnesium, Folk, 1974), or other ions available to the interstitial fluid (free ions, adsorbed ions, ions in unstable minerals). Impurities can modify either the physical or chemical response of the limestone to stress.

A resistant unit is an entity of grain to bed scale having *structural resistance* to change. A unit may be resistant because of crystal size, mineralogy, crystal chemistry, grain/crystal packing, fabric, permeability and extent of precursor cements. A structurally resistant unit, when stressed excessively, will first yield at foci of stress, along slightly less resistant internal surfaces and at boundaries with other units. The bulk of the unit will remain unchanged. "Unit," as used here, is comparable to "iden" defined by Logan and Semeniuk (1976).

A responsive unit is one that does not have internal structural resistance to stress. This

unit, if homogeneous, will respond to excessive stress, if uniformly applied, by uniform change throughout the unit. Analogues are a sponge squeezed between two plates or a spring stretched. Change may be uniform compaction, deformation, neomorphism, or solution. If the responsive limestone unit is not homogeneous or if the applied stress is not uniform, the extent of change will be variable through or along the unit. Pressure solution in responsive units would not form seams but rather would be pervasive through a unit.

Of the many impurities in limestones, two appear to have fundamental influence on resultant response to stress—fine, platy, insoluble minerals and magnesium ions. Very fine-grained insoluble minerals, concentrated by pressure solution, can form surfaces or zones of structural weakness, along which lateral motion (shear) can occur to relieve local stress anomalies. Dolomite may form in limestone units in which significant magnesium is released (or available) during pressure solution (or neomorphism, Folk, 1974). If this occurs, dolomite crystals may eventually become a grain-supporting framework, inhibiting further pressure solution.

Carbonate rock sequences are composed of stacks of units (layers, zones, beds, laminae, grains) of differing structural resistance and impurity content. Using this general approach, it becomes apparent (a) that stylolites should not be the only type of solution response to stress and (b) that pressure solution is an integral part of a general system of response to stress that includes compaction, deformation, neomorphism, local-source replacement or precipitation (dolomitization), and metasomatism.

Hypothesis

From the above considerations of limestone response to stress, we should expect three basic styles of pressure solution response. These are:

- I) *Sutured-seam solution*—(common stylolite and grain contact suture);
- II) *Non-sutured seam solution or solution-dolomitization*—(microstylolites, microstylolite swarms, and clay seams with or without dolomite growth along seams); and
- III) *Non-seam (pervasive) solution-dolomitization (or solution)*—(massive to thinly laminated dolomitic limestone and dolomite units).

Sutured solution surfaces (I: stylolites and grain contact sutures) form within or at boundaries between units having structural resistance to stress and little or no platy insoluble material. Response to stress is solution along the stylolite surface, the adjacent limestone remaining unresponsive. Slightly greater and slightly less structural resistance of elements along a solution surface cause irregularity of solution surface.

Non-seam pressure solution (III: pervasive) occurs in units having no internal structural resistance to stress and insignificant platy insoluble material. The unit will respond by dissolution throughout rather than along selected surfaces. Pervasive limestone pressure solution is recognizable where pre-existing grains are either concentrated as an insoluble residue, or are associated with smaller amounts of dolomite which formed as a reactate mineral within the unit; "reactate" is defined by Logan and Semeniuk (1976, p. 6) as a mineral formed in association with and because of pressure solution conditions.

Non-sutured solution surfaces (II: microstylolites, microstylolite swarms, and clay seams) form in or towards the margins of limestone units that contain a significant amount of fine platy insoluble material (clay, platy silt and possibly carbonaceous material). Non-sutured solution tends to form anastomosing swarms of thin seams, because platy material along a seam (a) chokes the seam as an effective pathway for fluid migration and (b) acts as a glide surface along which stress can be relieved by lateral slippage. This inhibits sutured growths along the solution surfaces. Non-sutured solution surfaces form in both resistant and responsive limestones because of fine platy impurities. Dolomitization can be intimately associated with seam growth. Nodular limestones are a typical result of non-sutured seam solution.

The intermediate (partial limestone solution) and end (complete limestone solution) products of each pressure solution type are distinct. These three basic types of pressure

solution or solution-dolomitization, together with stress-induced deformation and neomorphism, are a dominant cause for the resultant spectrum of observed modifications to carbonate rocks.

The following sections discuss and give evidence for these three proposed styles of pressure solution, a description of the types of limestone with which they are associated, and an assessment of the distortion that pressure solution causes to primary rock fabric.

Observations and concepts used in this paper are based on study of the following rock units: Muav Limestone (Cambrian), Arizona; Hualapi Limestone (Pliocene), Arizona; Conococheague Limestone (Cambrian), Beekmantown Group and St. Paul Group (Ordovician), and Tonoloway Limestone and Helderberg Limestone (Devonian) in western Maryland and Virginia; Upper Pennsylvanian limestones of southeast Kansas; and Lower Cretaceous Limestones beneath Key Largo, Florida.

SUTURED SEAM SOLUTION

Stylolites are irregular, commonly discontinuous surfaces that cut limestones (and sandstones) and have a cross section resembling the trace of a stylus on a chart recorder. Relief along stylolite surfaces can be anywhere from less than 1 mm to tens of centimeters. That stylolites are caused by stress-induced solution is documented by Sorby (1879, 1908), Stockdale (1943), Dunnington (1954), Bathurst (1971), and Logan and Semeniuk (1976).

Stylolites are "sutured" (pillar and socket) interpenetrating surfaces of two rock, grain or crystal units (Fig. 1). They can be recognized in thin section as grain or crystal contact sutures and in hand specimen and outcrop as planar to interweaving sutured surfaces. Sutured solution seams that result from overburden stress tend to be horizontal (e.g., cross laminae, unconformities). Where a rock unit has been under tectonic stress, stylolites may occur at sharp angles to primary layering. Stylolites can thus form (a) solution surfaces within a unit, (b) solution surfaces between two units, and (c) solution surfaces lying at large angles to primary layering and not influenced by it.

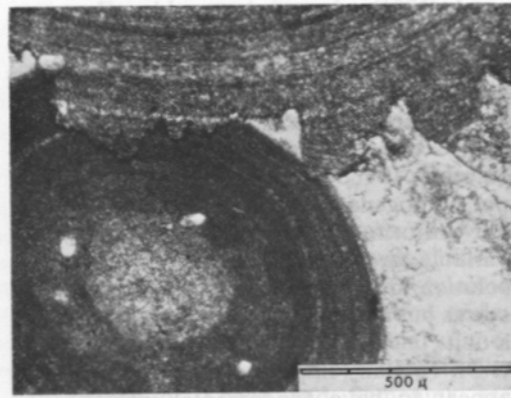


FIG. 1.—Interpretation of pisolite, oolite and now pseudospar matrix along sutured stylolite seam. Conococheague Limestone (Cambrian), Ashton, Maryland. Thin section photomicrograph under plane polarized light.

Sutured stylolites occur only in or at boundaries of limestone units having structural resistance to stress—skeletal and non-skeletal grains and crystals, grain-supported beds, and units strengthened by large biogenic structures, earlier cementation or precursor neomorphism.

The stylolite surface will concentrate insoluble grains. Stylolites are deeply sutured only if the host units are low in platy mineral content. In fine-grained limestones sutured stylolites occur only where there is very little clay mineral content. Coarser and oriented crystalline elements and structures and tightly packed crystal groups tend to be more resistant to solution and will preferentially penetrate and cause preferential solution of the adjacent limestone (see also Sorby, 1879).

There is controversy as to whether fluids move preferentially along the stylolite surface or perpendicular to it. Dunnington (1967) and Harms and Choquette (1965) have documented zones of anomalously low porosity and by inference permeability, just above and below stylolites, suggesting that at least some of the material dissolved along the stylolites may migrate only a short distance before reprecipitating.

If a zone of limestone is completely dissolved by sutured-seam pressure solution, the end product should be a mass of insoluble residue irregularly laminated or layered. Clay and fine platy minerals will comprise only

a minor portion of the residue as compared to coarser grains. Insolubles are characteristically siliciclastic but may include dolomite.

Resultant Characteristics

Sutured stylolite solution has two important features: 1) the response to stress is solution along distinct surfaces, the surrounding portions of the limestone being non-responsive, although pressure dissolved carbonate may reprecipitate as cement in rock adjacent to the seam (Bathurst, 1971, p. 770); and 2) surfaces of the units on either side of the stylolite are interpenetrating pillars and sockets. Shortening of the units due to solution along the seam must parallel the direction of maximum stress. The stylolite is a fitted jigsaw surface, along which no lateral motion (shear) can occur without extensive brittle fracture of the limestone (see, Carannante and Gozzetta, 1972).

NON-SUTURED SEAM SOLUTION

Limestones containing a significant content of fine insoluble platy particles (clay, fine micas) commonly have anastomosing swarms of fine clay seams. These have been termed clay seams (Barrett, 1964), horsetails (Roehl, 1967), wispy laminae (Lucia, 1972, p. 170), wavy laminae (Reinhardt and Hardie, 1976), pseudostylolites (Shinn et al, 1977) and microstylolites (Wanless, 1973b). In the following discussion, *microstylolite* is used for a single clay film surface, *microstylolite swarms* for anastomosing swarms of *microstylolites* about small limestone clots, and *clay seams* for thicker seams of clays and platy silt containing little calcite. A *microstylolite* is a very thin undulating surface with a relief on the order of only 20 to 40 microns (Figs. 4, 5). Fine silici-clastic clay and platy silt occur as films along these surfaces. Dolomite may be present along any of these surfaces or seams. The origin of microstylolites, microstylolite swarms, and clay seams as pressure solution seams, their significance in the modification of primary limestone characteristics, and their association with dolomite formation are best considered by illustrative examples. For these, we will examine (a) nodular limestone in the Muav Limestone, (b) the Beekmantown Limestone

where subjected to tectonic stress, (c) other nodular limestones and limestones with clay seams.

Muav Limestone

Lithology.—A nodular, clayey limestone facies occurs in the Middle Cambrian Muav Limestone through the Grand Canyon, Arizona, dominating the formation in the east and central portions of the Canyon. Nodular limestone is typically very thinly bedded, slightly silty microsparite or pelmicrosparite with silty to clayey dolomitic interlayers and partings. Each limestone bed is distorted to varying degrees into a nodular, boudinage-like pattern (Fig. 2). Rarely, thin continuous sandstone beds interrupt the nodular limestones. Nodular limestone facies grades vertically into very thinly interbedded arenaceous limestone and dolomitic shale which are not distorted into nodules, and into very thinly interbedded pelmicrosparite and dolomite made irregular by dolomitic burrows and finely sutured stylolite seams.

Previous descriptions of the Muav Limestone have used the terms marbled or mottled limestone facies (McKee, 1945). The term mottled has come to imply burrowed, and although burrowing is abundant, the nodular form appears not to be the result of organism activity.

The light gray limestone beds and nodules characteristically have a microspar fabric (Fig. 3a). Nodules are sometimes faintly peloidal, the peloids ranging from 60 to 220 microns in size. Angular quartz and feldspar grains occur (1) as silt (finer than 30 microns) scattered through the beds and peloids, (2) as isolated laminations of fine sand (grains finer than 170 microns), and (3) in some cases as a thin basal zone of sandy laminae (grains to 300 microns). Mica flakes are common in certain beds. Insoluble silt and illitic clay comprise 12 to 14 weight percent of the limestone nodules and are randomly dispersed through the limestone along microspar crystal boundaries. Fine dolomite rhombs (smaller than 30 microns) are scattered through most limestone beds and nodules. These rhombs are clear and tend not to stain with potassium ferricyanide (for iron). Larger dolomite rhombs (up to 120 microns in size) occur in the limestones only along microstylolites penetrating the nodules

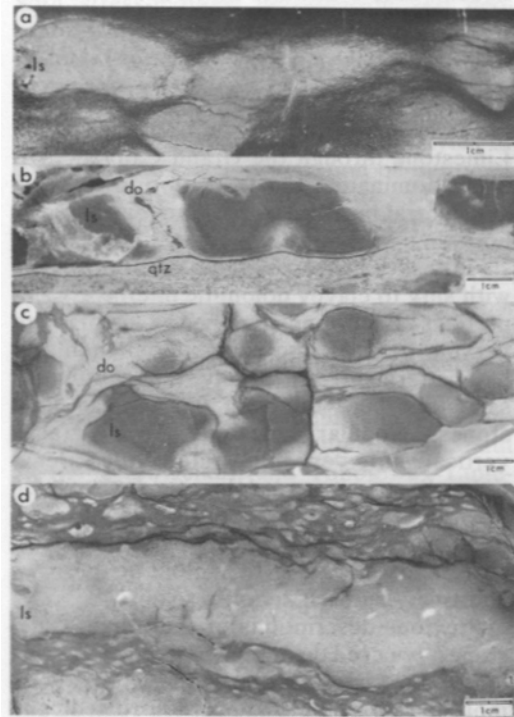


FIG. 2.—Nodular limestone, Muav Limestone (Cambrian). a) Lightly etched slab of limestone composed of faintly peloidal microsparite nodules (light gray) and seams and microstylolite swarms of dolomitic shale (dark gray, stained by potassium ferricyanide solution); central Grand Canyon, 0.5 km west of Bright Angel Trail, 192 m above base of Cambrian. b) Limestone nodules (dark) with interlayers of dolomitic shale above a sandy layer (quartz). Faint sandy laminations are traceable from nodule to nodule through the thinned dolomitic zone between nodules. Microstylolite thinning and dolomitization at upper left and lower center of nodule is associated with burrow tubes. Polished slab from central Grand Canyon, 0.2 km west of Pipe Springs, 147 m above base of Cambrian. c) Disoriented limestone nodules (dark) in silty dolomitic shale. Polished slab impregnated with polyester resin from central Grand Canyon, east of Bright Angel Trail. d) Interbedded microsparite (light) and dolomitic shale seams in which the thinner limestone layers have been disrupted into nodules and the thicker limestone layers are modified by microstylolites but not generally disrupted into nodules. Subhorizontal burrow tubes (convex upward clots) of limestone occur in dolomitic shale seams; randomly oriented spar-filled burrow tubes (white) are preserved in limestone layers. This is the same burrow tube distribution as observed in the interbedded sandstone and shale of the underlying Bright Angel Shale. Slab impregnated with polyester resin from central Grand Canyon, 0.2 km west of Pipe Springs, 182 m above base of Cambrian.

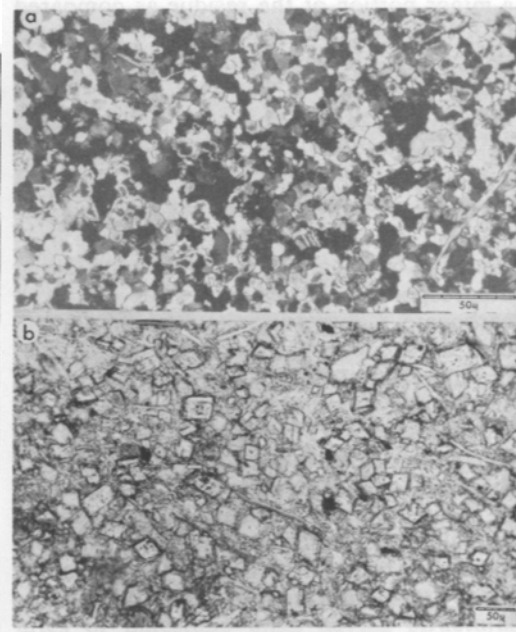


FIG. 3.—a) Microspar from nodule similar to that illustrated in Figure 2a. Mica flakes (elongate grains) are disoriented, clays are squeezed along microspar crystal boundaries, and widely scattered dolomite rhombs are small and unzoned. Ultrathin section, crossed nicols. b) Thin section photomicrograph of dolomitic shale portion of sample in Figure 2a. Mica flakes and clay particles are somewhat oriented. Dolomite rhombs are distinctly zoned and not generally intergrown. Plane polarized light.

(Fig. 4) and as aureoles adjacent to burrow fillings. Larger rhombs along microstylolites are zoned. Zones are visible because of included clay and increase in ferrous iron content (judged from potassium ferricyanide stain) toward the margins of rhombs. Many beds and nodules contain a small amount of trilobite debris (now sparry calcite) commonly as a thin basal lag.

Tan to greenish dolomitic interbeds contain a large amount of fine quartz, feldspar and mica silt (mostly less than 30 microns) and illitic clay among which individual larger rhombs and partly intergrown mosaics of dolomite from a loose sucrosic fabric (Figs. 3b, 5). Rhombs are 30 to 70 microns across. Larger rhombs are zoned as described above. Interbeds are mostly quite crumbly because of the disorientation of platy minerals about dolomite rhombs and the lack of sufficient binding by dolomite intergrowths.

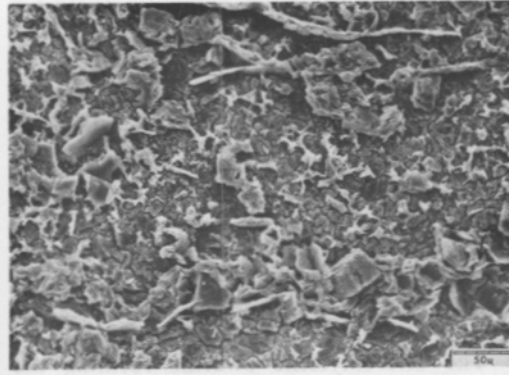


FIG. 4.—Clay and platy silt are concentrated along microstylolite seams penetrating the edge of a microspar nodule illustrated in Figures 2a and 6. Zoned dolomite rhombs to 50 microns in size occur only along microstylolite seams. Note dolomite rhomb overgrowing mica flakes in lower center and right (arrows). Intervening microspar contains clay along crystal interfaces and unzoned dolomite crystals less than 30 microns in size. Scanning electron photomicrograph.

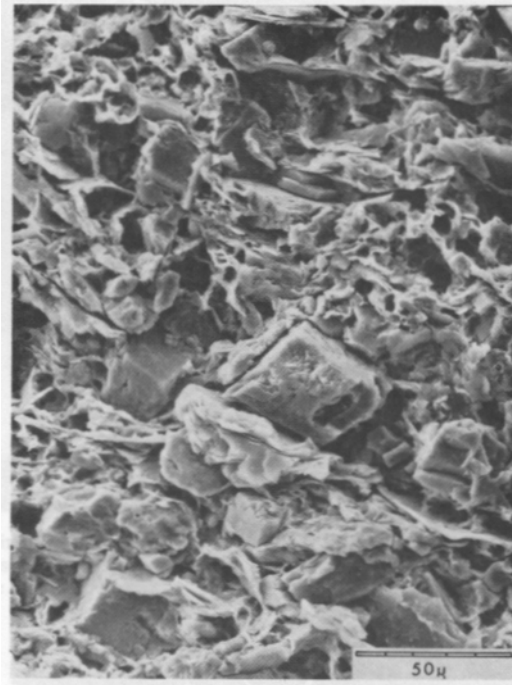


FIG. 5.—Dolomitic shale (clay seam) in thinned zone between limestone nodules contains dolomite rhombs packed in a matrix of partly disoriented clay or platy silt. Scanning electron photomicrograph from sample illustrated in Figures 2a, 3b, and 6.

Laminated spar or dolospar-cemented sandstone beds, 0.5 to 3 cm in thickness, are common in the more silty nodular limestones. These are either continuous beds with horizontal, low-angle or current-ripple laminations or lenticular starved ripples. Because these beds have silici-clastic sand framework support they are not nodular, but the thinner beds may be gently deformed around adjacent limestone nodules. Also present in the more silty nodular limestones are thin layers of greenish-tan siltstone or green shale (only slightly dolomitic). These layers are quite deformed around adjacent nodules.

Layered or platy limestone, interbedded with dolomitic shaly limestone occurs in limestones which contain a large amount of silici-clastic or carbonate sand. Reticulate or stylolitized limestone occurs in zones in which the limestone beds and dolomitic interbeds contain little or no platy silici-clastic fine silt and clay (less than five weight percent of limestone beds).

Microstylolites.—Microstylolites are intimately associated with the nodular limestones (Figs. 4, 6). This is most evident in polished and etched specimens and thin sections, but poorly visible in most outcrops.

Microstylolites tend to occur in “swarms” of subhorizontal interconnected surfaces in

the dolomitic shale interbeds, in the dolomitic shale areas between limestone nodules (Fig. 5) and in a “gradational” zone 0.5 to 2 mm in thickness at the top and bottom boundaries of nodules (Fig. 7). The swarms of microstylolites extend into the sides of nodules and fade out (Fig. 6).

Four observations demonstrate that the dolomitic shale areas between and adjacent to nodules have undergone differential solution thinning by microstylolite formation due to pressure solution.

1) The limestone nodules contain preserved features of primary depositional origin—vague peloids, scattered skeletal grains and undistorted burrows. These features indicate that the limestone nodules have been unaffected by major diagenetic alteration or volume reduction (Fig. 2b, d). In contrast, these attributes are distorted or absent in dolomitic shale.

2) Faint silici-clastic laminations, when

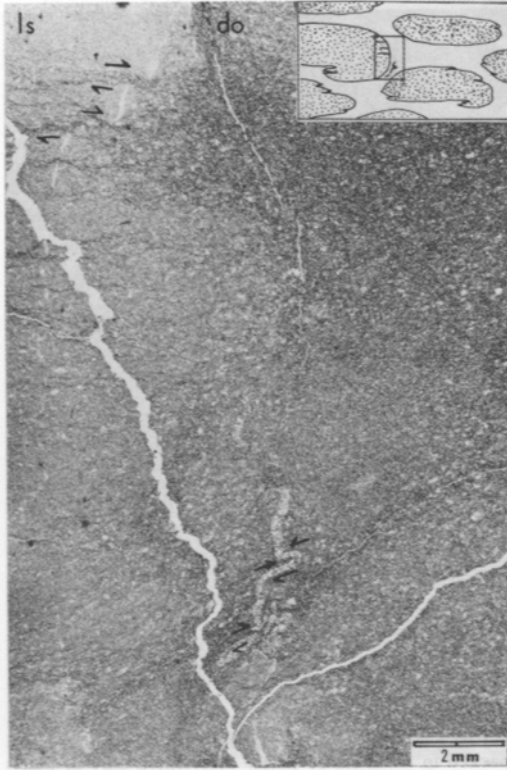


FIG. 6.—Limestone nodules are dotted on location sketch. Photomicrograph from ultrathin section (8 microns) shows (a) microstylolites penetrating nodule edge (upper left), (b) spar-filled tension fractures in isolated clots and deformed by glide shear along bounding microstylolites (clear sinuous fractures in upper left), and (c) deformed quartz-silt-filled burrow tube in dolomitic clay seam between nodules (lower center). Two large white fractures formed during thin section preparation. Plane polarized light; from sample in Figure 2a.

present, are traceable from nodule to nodule through the intervening zones of dolomitic shale containing microstylolites (middle of Fig. 2b). These laminae always converge in the shale zone between nodules, demonstrating differential solution thinning in the area between nodules.

3) Clots of limestone are common in dolomitic shale zones between nodules. These clots, bounded by microstylolites, appear to have been separated by microstylolite swarms "eating" into the edges of the nodules as illustrated by Figures 6 and 7.

4) Thin burrows filled by quartz silt in the

areas of microstylolitic dolomitic shale between nodules are drastically squeezed and distorted (Fig. 6).

Near the ends of limestone nodules, small, vertical, spar-filled fractures commonly extend into the top and bottom of the nodule (Fig. 6). These fractures also are common in the larger of the limestone clots. They indicate tension fracturing due to preferential thinning between nodules, and movement sub-parallel to the layering (see also McCrossan, 1958).

The microstylolite swarms forming the dolomitic shale (clay seam) zones between nodules do not display fracturing. Rather, distortion of the quartz-silt-filled burrows and lateral displacement of limestone clots are evidence of differential lateral shear or flowage distortion (Fig. 6). Each microstylolite surface with its thin film of insoluble clays and platy silt (Figs. 4, 6) appears to have been a surface of lateral shear.

Origin of Nodular Bedding.—It is concluded here that these nodular limestones in the Muav Limestone were formed from continuously layered, slightly shaly pelmicitic interbedded with calcareous shales. This interpretation is based in part on the fact that this facies is gradational with distinctly interbedded platy limestones and dolomitic shales of the Muav Limestone and also with interbedded sandstones and green shales of the subjacent Bright Angel Shale, and also on the evidence for deformation by microstylolite formation.

Previous interpretations of nodular limestone are diverse. Several authors have considered nodules to be intraformational conglomerate or burrow-mottled structures (see Wilson, 1975, p. 78, 265). Others have recognized that nodular structure is a post-depositional modification and have suggested as causes simple boudinage (van Tuyl, 1916, p. 360), large-scale lateral stretching during compaction of hilly unconsolidated lime mud deposits (McCrossan, 1958), concretionary growth (Raiswell, 1971), early diagenesis on the sea floor (McKee, 1945; Jenkyns, 1974; Muller and Fabricius, 1974), and patchy early cementation followed by compaction and then pressure solution (Garrison and Kennedy, 1977).

Many of these nodular limestones appear

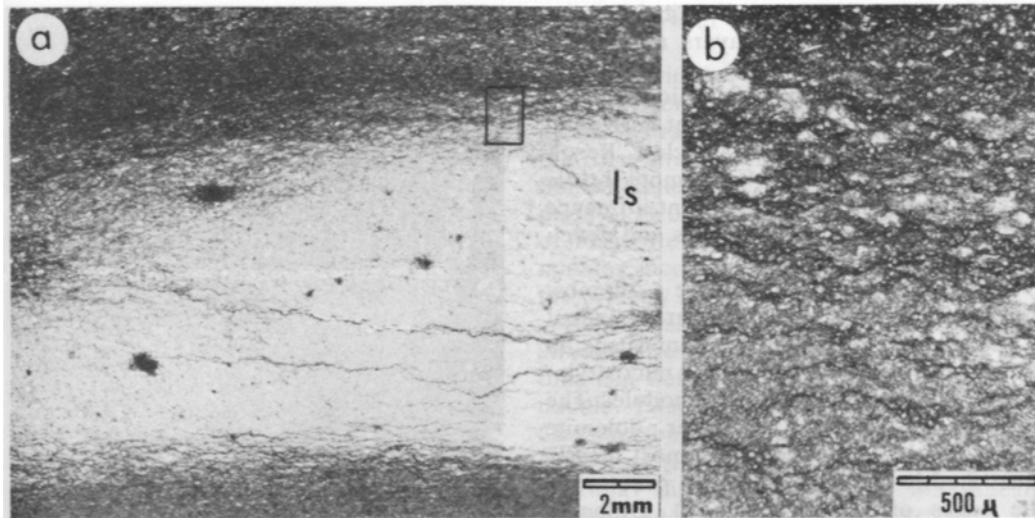


FIG. 7.—Thin-section photomicrograph of microstylolite swarms in transition zone between limestone nodule (light) and dolomitic shale seam (dark). Figure 7b is closeup of boxed area in 7a and shows isolated microspar clots becoming smaller and more isolated upwards. Plane polarized light; from sample in Figure 2a.

to be very similar to those in the Muav Limestone. Those who interpret nodular limestones as primary features or early diagenetic structures may have failed to recognize that “gradational” nodule boundaries are zones of microstylolite swarms. Presence of a primary peloidal fabric in the Muav Limestone nodules and the fine clots of limestone among microstylolite swarms adjacent to the nodules discount a concretionary growth origin. The widespread occurrence of nodular limestone and its presence in small channel fills in the Muav Limestone is inconsistent with an origin by lateral stretching.

Nodular bedding is here interpreted as a product of pressure solution along non-sutured (microstylolite) seams. The unique association of microstylolites with limestones containing a certain amount (at least 10 percent in the author's experience) of siliclastic clay and platy silt indicates that fine platy minerals are important to the formation of microstylolites. Under pressure from overburden, the limestone beds are locally subjected to excessive stress. At these stress foci limestone solution occurs, concentrating platy insoluble material along a small solution seam. This seam acts as both a pathway for the removal of dissolved carbonate and a

site at which insoluble clay and silt concentrate. The solution seam (microstylolite) apparently becomes inactive while still very thin, probably for two reasons. First, the concentration of fine silt and clay should quickly choke the solution seam as an effective pathway for the fluid migration required for stylolite growth. Second, the thin concentration of clay and platy silt acts as a favorable glide plane along which a component of the locally accentuated stress can most easily be relieved by lateral shear. These processes produce a new zone of maximum stress either farther along the limestone bed, laterally extending the microstylolite, or at a different horizon, producing a new microstylolite. Continuation of these processes forms the observed “swarms” of microstylolites.

Thinning of a limestone layer between adjacent nodules by microstylolite solution is gradual (tapered) and less than 30 percent in most of the Muav Limestone. In local zones, especially those containing less silt and clay or dolomite, thinning between nodules is both abrupt and extensive, as much as 80 percent.

Nodules most commonly have a three-dimensionally “fitted” or closely packed form in which the nodules of one layer fit

into the thinned zones of microstylolite swarms or seam of the layers above and below.

Lateral displacement along microstylolite swarm zones can exert significant horizontal stress on limestone nodules and clots. Resultant tension fracturing of the more brittle limestone may have an important influence in decoupling clots from nodules and developing nodular form.

Dolomite.—Zoned dolomite rhombs, mostly 30 to 120 microns in size, are abundant in the microstylolitic dolomitic interbeds, in areas between nodules and along microstylolites marginal to and penetrating nodules. The intimate association of larger dolomite rhombs with microstylolites is most clearly illustrated in the microstylolites penetrating the edges of nodules (Fig. 4). Dolomite rhombs associated with microstylolites are coarser than the unzoned rhombs scattered through the limestone beds, and are so abundant that they cannot be explained as a simple residue from solution of the precursor limestone. Rather, some attribute of the microstylolite growth must have provided preferential conditions for at least part of the dolomite growth.

Microstylolites From Tectonic Stress

The Ordovician Beekmantown Limestone of western Maryland and Virginia provides two good examples of microstylolite formation under tectonic stress.

The first example is found in quarry exposures of the Beekmantown Limestone near Harrisonburg, Virginia (Betts' Quarry, 2.1 km east of town off old route US 33; see Brent, 1960, p. 88). This is in the Great Valley west of the Massanutten Synclinorium in an area where local thrusting and folding caused maximum tectonic stress to be applied nearly parallel to bedding. Microstylolites, swarms of dolomitic microstylolites, and seams of dolomitic clay occur in the limestone at a sharp angle to primary layering (Fig. 8). Microstylolite swarms isolated within the slightly shaly limestone beds show that these are local dissolution surfaces and not dolomitic-clay injections by shear stresses. All the features described earlier are present—lateral shear along microstylolites, associated dolomitization, and retention of primary fab-

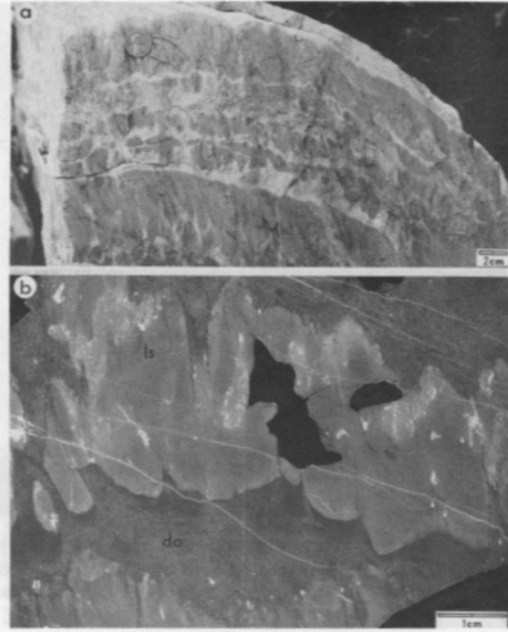


FIG. 8.—Nodular limestone from tectonic stress. Beekmantown Limestone (Ordovician) from Betts quarry, 1.4 miles east of Harrisonburg, Virginia. a) Small compressional fold with limestone layers (dark) disrupted into a nodular pattern by microstylolites and dolomitic clay seams that trend nearly perpendicular to primary layering. This microstylolite solution “cleavage” slightly fans about the fold axis. Field photograph. b) Positive print from acetate peel showing dark microstylolite swarms (clay and dolomite) dissecting microspar layers (horizontal) into nodules. Darker beds are dolomitic. Small spar-filled tension fractures (white) extend subparallel to layering. Black blobs at center right are imperfections in peel.

ric in limestone. These microstylolite swarms commonly produce a nodular bedding pattern in the limestones at a sharp angle to primary layering (Fig. 8a, b). In some units the limestone lenses are elongate with tapered ends much like the “flaser” structures described in Cretaceous chalks by Garrison and Kennedy (1977). These nodules have a “fitted” pattern as described in the Muav Limestone, a feature that has been termed spaced cleavage by Geiser (1974).

This example demonstrates that the production of “fitted” nodular bedding as a result of microstylolite formation is an expectable product of pressure solution and need not be determined (though it may be) by primary sedimentary structures. (The

same fitted "spaced solution cleavage" pattern can also be observed in the Cambrian Harpers Phyllite of the Appalachians.) This example also demonstrates that pressure solution of clayey limestones can and does produce inhomogeneity in a once-homogeneous medium (see also Logan and Semeniuk, 1976). Jenkyns (1974, p. 264) and other authors have previously suggested that creation of nodules and clay seams by pressure solution would have required initial inhomogeneity.

The second example of microstylolite formation in response to tectonic stress is in an exposure of Beekmantown Limestone in the quarry 0.5 km south of Williamsport, Maryland, just east of the Chesapeake and Ohio Canal. There the Beekmantown stands nearly vertical on the western flank of the Blue Ridge-Catoctin Mountain anticlinorium. Biosparite beds in the Beekmantown are distorted into a classic boudinage pattern (see also Cloos, 1947 and 1951, p. 162 and plate 15). Above and below these beds are nodular limestones in which the layering conforms to irregularities in the large boudinaged surface. The nodular limestones are not disrupted by large tension fractures even when they directly adjoin tension fractures in the boudinaged unit. Rather, extensive lateral shear flowage along the maze of fine microstylolitic and clay seams permitted the nodular limestones to respond by deformation that leaves little pronounced evidence in outcrop. In response to the asymmetrical stress vectors here, the nodules are about 50 percent longer parallel to the least stress axis than along the intermediate stress axis.

Other Aspects of Nodules and Microstylolites

The Chambersburg Limestone (Ordovician) of western Maryland is a slightly shaly biomicrite of shallow marine to shelf origin (Reinhardt and Hardie, 1976). It is characteristically nodular in form but differs in several ways from the formations described above, in that the microstylolite solution surfaces associated with nodules have little or no associated dolomite. This has also been found in most of the red nodular limestones of the Mediterranean Triassic (Jenkyns, 1974). Thus, dolomite may or may not be

associated with non-sutured seam pressure solution.

Nodules in the Chambersburg Limestone, although forming a "bedding" parallel to primary stratification, offer little evidence that they are confined by primary layering. Some nodules (to 15 cm in thickness) include parts of two to four distinct primary layers of biosparite and sparse biomicrite. Adjacent nodules incorporate different groupings of the primary layers.

Course skeletal material may provide structural resistance to a limestone zone and thus can define the position and size of a nodule. Examples of this are found in the Chambersburg Limestone, the Helderberg Limestone (Devonian) of western Maryland, the Muav Limestone and the Mediterranean Triassic. In the Triassic, Jenkyns (1974, p. 253) notes that "ammonite molds always act as nodules."

From the examples cited above we see that nodular bedding may or may not be defined by precursor characteristics of the limestone. As the nodular facies of the Muav Limestone is both similar in layering character to and gradational into very thinly interbedded sandstone and shales, the general thickness of the nodular forms and the now contorted limestone and dolomite interlayering can be inferred to be an alteration from interbedded limestone and limy shale. The example of nodular bedding due to stress, however, demonstrates that a fitted nodular pattern will tend to form from clayey limestones even in the absence of primary structure influences. Thus, occurrences of nodules and their organization into apparent layering must be interpreted with care.

Microstylolites Without Nodules

Non-sutured solution seams need not form a nodular pattern. In the Pennsylvanian mud banks of southeast Kansas described by Harbaugh et al (1965), clayey biomicrites contain irregular, commonly unconnected zones of microstylolite swarms.

Clay Seams

Many silty or clayey limestones contain seams as much as 2 cm in thickness of shale, silty shale or dolomitic shale. Some of these seams are quite continuous laterally while

others fade into adjacent limestone through a zone of microstylolites. The upper and lower boundaries between clay seams and limestone are commonly zones of microstylolite swarms. Clots of limestone within the clay seams are uncommon to rare. Clay seams, because they show gradations to microstylolite zones are interpreted to be the end product of microstylolitic dissolution of clayey limestones. Clay seams (with or without dolomitization) may be controlled in their distribution by precursor composition (as the dolomitic shale interbeds in the Muav Limestone), may be due to excessive stress on a shaly limestone by an adjacent structurally resistant limestone, or may be essentially random products of pressure solution.

Nodules can become quite isolated entities within clay seams (Fig. 9b). Where this occurs they may take on a more equant form (through continued pressure solution under more homogeneous stress field) and may be

rotated from their original orientation if the clay seam undergoes significant shear motion to relieve stress (see also Jenkyns, 1974).

Microstylolite solution selectively removes finer crystalline material. Coarse crystalline calcite grains may thus be selectively preserved in microstylolite swarms or clay seams (Fig. 9a, b; see also Jenkyns, 1974). Selective preservation of coarse skeletal material (especially crinoid columnals and shells) in clay seams can easily be misinterpreted, both by considering the clay seam as a different depositional feature than the limestone and by distinguishing the remnant fauna in the clay seams from that in the limestone.

Nodular Structure in Chalks

In a recent article, Garrison and Kennedy (1977) ascribe different origins to "flaser" chalks and nodular chalks from the upper Cretaceous of southern England. They sug-

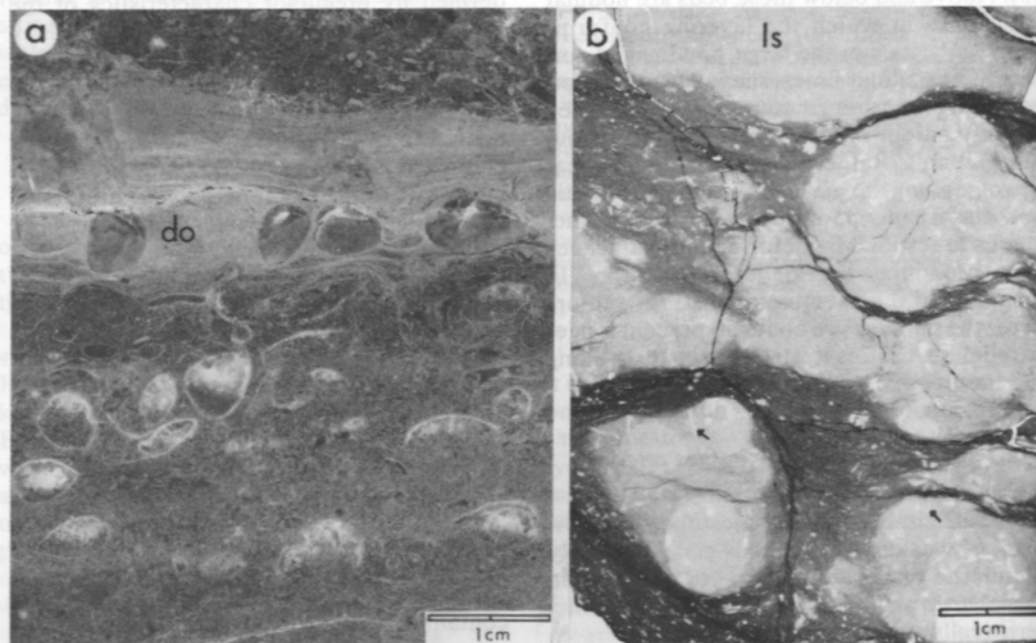


FIG. 9.—Brachiopod shells acted as resistant units in a zone (light gray) that otherwise has been altered by pressure solution to a dolomitic clay band. Limestone (dark) and cement (white) is preserved within most shell "nodules." Etched slab from Helderberg Limestone (Devonian), Western Maryland Railroad cut 1/2 km east of Tonoloway Ridge, Maryland. b) Isolated biomicrite nodules (light) from Chambersburg Limestone (Ordovician) are surrounded by laminated dolomitic clay seams with pronounced flow distortion. Microstylolite swarms (dark) and spar-filled tension fractures (white; arrows) disrupt nodules. Coarse skeletal material is preferentially preserved in dolomitic clay. Positive print from acetate peel of specimen from road cut on U.S. 40 just west of Conococheague Creek, Western Maryland.

gest that flaser chalks (elongate tapered lenses of limestone bounded by clay solution seams) are products of pressure solution, whereas nodular chalks (more round edged and commonly isolated limestone nodules in a clay seam matrix) result from early cementation of nodules followed by preferential pressure solution of calcium carbonate from uncemented matrix. This author, in contrast, considers that the tectonically-stressed examples (Fig. 8) clearly demonstrate that both styles are simply a product of pressure solution. Variation in resultant shape, closeness of nodule packing, elongation of nodule ends, and sharpness of boundaries reflects variation in original clay content and distribution and other attributes of precursor fabric and composition.

Garrison and Kennedy also interpret the Upper Cretaceous limestones of southern England as having undergone significant to major compaction before pressure solution. In contrast, the evidence in all the nodular and clayey limestones examined by this author indicates that nodule cementation, "matrix" deformation and pressure solution are concurrent aspects of one process, rather than three time-separated events. Local reprecipitation of calcite is an expectable by-product of pressure solution (de Boer, 1977).

Resultant Characteristics

Limestones containing clay or fine platy silt respond to pressure solution by forming many small interconnected solution seams. Once formed, the microstylolite seams are potential shear surfaces which, in conjunction with continued pressure solution (forming more microstylolite surfaces), provide a compound mechanism for response to stress. Solution surfaces, though wavy, are not sutured. Individual seams are only a few microns in thickness. With continued solution, many microstylolite seams form and may become an interconnected maze in which small lensoid limestone clots are isolated.

If solution of limestone is carried to completion, the end product is a seam, layer or lens of laminated clay, shale, platy silt or dolomitic shale. Grains of more coarsely crystalline calcite tend to survive non-sutured pressure solution and may be concentrated in such seams.

Pressure solution can 1) form microstylolites along boundary zones of resistant clayey limestone units (limestone beds in Muav Limestone), 2) along specific zones in a resistant unit (much as sutured stylolites do), or 3) throughout more responsive clayey limestone units (top of Figure 14a and dolomitic shale interbeds in Muav Limestone). In the third case, incomplete dissolution will produce a rock comprising myriads of small limestone clots in a swarm of microstylolites.

NON-SEAM (PERVASIVE) PRESSURE SOLUTION

Many limestones with little clay content display a delicate interweaving of layers, laminae and structures of limestone and dolomite. Some workers consider these to be delicately preserved primary sedimentary structures in which highly selective dolomitization may have occurred much later (Gebelein and Hoffman, 1973). Others have noted evidence for compaction that has distorted the form of primary structures. This seems generally to be considered a physical squeezing phenomenon (Shinn et al, 1977).

A careful look at Cambro-Ordovician limestone of western Maryland, however, provides evidence that, while certain primary structures or portions of structures are well preserved (always as dominantly limestone), they are associated with dolomitic zones that are diagenetic distortions of primary structures caused by pervasive solution and dolomitization of limestone units or portions of units. Simple compaction is not important. The examples chosen to illustrate non-seam pressure solution-dolomitization are cases in which limestone layers laterally become dolomitic at a reduced volume.

Example 1

A mudcracked zone in the New Market Limestone (St. Paul Group, Ordovician) of western Maryland contains "lenses" of clean micritic limestone centered around large mudcracks (Fig. 10a, b). Between these limestone lenses, the layers "gradationally" thin and become laminated micritic dolomite. Numerous fine laminae can be traced laterally from one micritic lens to another through the intervening micritic dolomite. Dolomite content of limestone laminae increases laterally to about 60 percent in association with

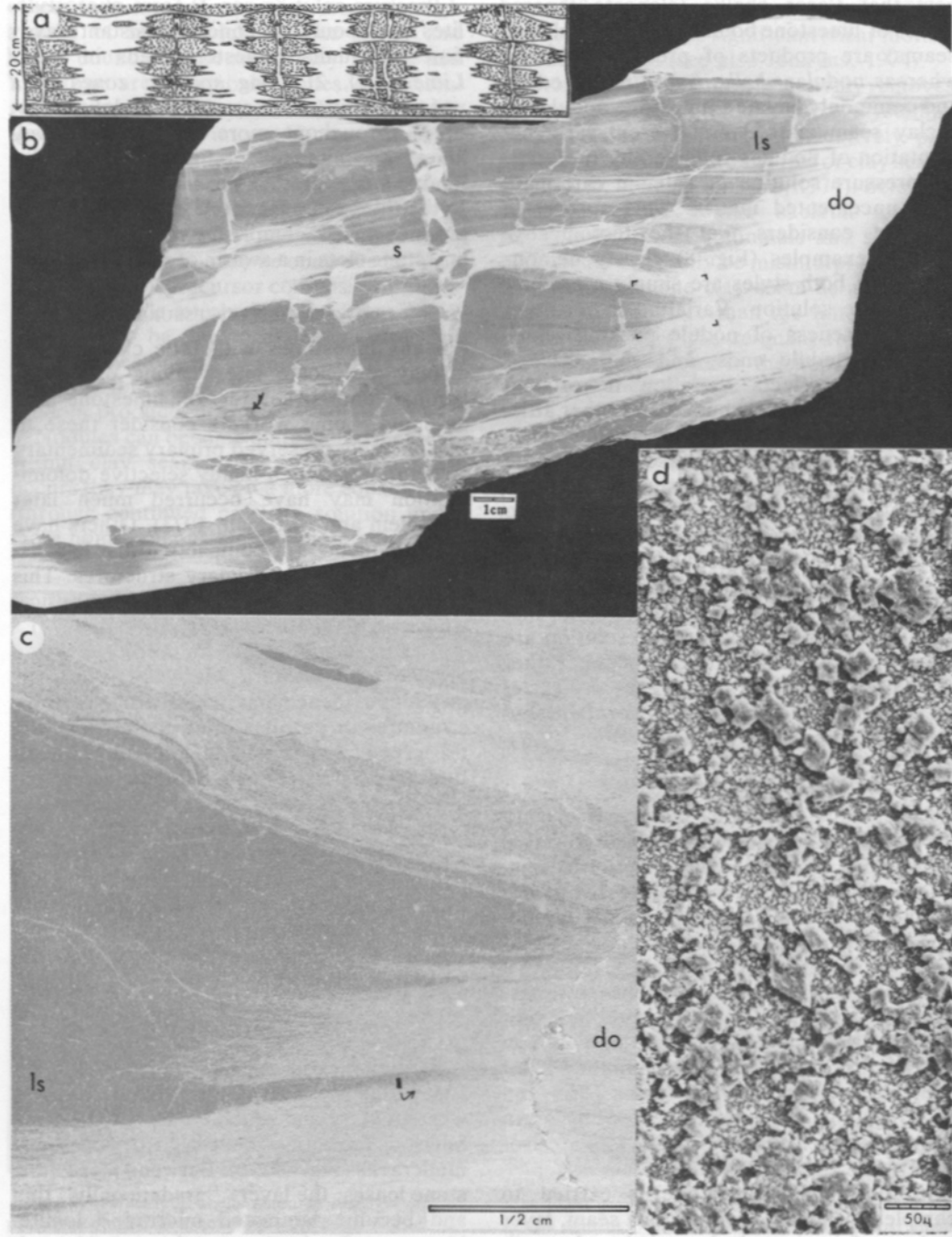


FIG. 10.—Limestone lenses about desiccation cracks in New Market Limestone, pasture southwest of St. Paul's Church, Washington Co., Maryland. a) Sketch of outcrop on which dotted areas are limestone and clear areas are dolomitic. b) Etched slab of three limestone lenses (dark) about dolomitic desiccation crack. Away from cracks laminae in micritic limestone lenses gradually thin and become micritic dolomite (do). Dolomite seams (s) disrupt desiccation pillar and laterally thicken and become micritic dolomite. Note thin stylolite (arrow)

a gradual decrease in thickness to about 21 percent of that in the adjacent limestone (Fig. 10b, d). Certain limestone laminae or zones extend farther than others before thinning and becoming dolomitic. The relative persistence of a certain lamina remains similar as traced from micrite lens to lens (Fig. 10b).

In some cases, the transition from micrite to micritic dolomite is through a swarm of very fine microstylolite-like seams containing dolomite but essentially no clay (Fig. 10c). Most commonly, however, the change is simply a gradual increase in the abundance and size of dolomite concomitant with bed thinning. Dolomite rhombs in the laminated dolomitic areas are zoned, 10 to 30 microns in size and commonly slightly intergrown (Fig. 10d). Dolomite rhombs in limestone are widely scattered and less than 10 microns in size. This example contains very little silici-clastic sand, silt, or clay.

At certain levels, the mudcrack "pillar" and adjacent micritic lens are disrupted by a subhorizontal seam of dolomite in the form of 10–30 micron rhombs. Seams can be traced laterally into laminated micritic dolomite that is similar to that described above. A decrease in thickness of about 40 percent occurs in passing from micritic dolomite to dolomite seam. The micritic limestone lenses are rarely cut by very thin, stylolite seams with suture relief of 5 mm (arrow in Fig. 10b).

This feature, although containing elements that appear to be primary in origin, is clearly not a primary structure per se. As the lateral change in layer thickness is associated with a corresponding change in composition, simple physical compaction has not been important. Rather, the dolomitic zones have formed from differential solution thinning from limestone with associated growth and concentration of dolomite. The area in the vicinity of the mudcrack tended to remain preferentially resistant to pressure solution. The areas between were responsive to pressure solution which occurred not along a single seam but pervasively. Certain laminae

were more responsive to pressure solution than others. In this example, the solution of a 10 mm thickness of limestone has produced a 60% dolomitic laminae 2.1 mm in thickness. One hundred volumes of limestone has produced about 13 volumes of dolomite.

Structural resistance to pressure solution was provided by some attribute of the mudcracks or the adjacent limestone, such as grain size, early cements, or permeability difference. In the same way that a shell may provide structural resistance that now defines a limestone nodule, here the mudcrack zones acted as structural pillars defining a limestone lens.

Example 2

The "ribbon limestones" so characteristic of the cleaner Cambro-Ordovician limestones consist of laterally continuous dolomitic laminae or layers and rather lensoid limestones (Fig. 11a; see also illustrations in Matter, 1967; Reinhardt and Hardie, 1976; Sando, 1957). In outcrop, the dolomitic layers vary from featureless to laminated. Lenses commonly contain apparent cross-laminations (of quartz) and in some cases look like starved ripples. On careful examination, however, there is clear evidence that the lensoid form is produced by differential solution of previously more continuous limestone layers. Peels or etched slabs of ribbon limestones show four related sets of features demonstrating that the limestone lenses are not starved ripples or other primary structures.

a) As quartz sand laminae approach the base or the top of a limestone bed, there is a corresponding increase in the amount of insoluble residue along the base (or top) of the bed (arrows in Fig. 11c). This quartz concentrate extends as a thin layer between limestone lenses (Q in Figs. 11b and c).

b) At the end of a limestone lens all the laminae in the limestone converge and the lens shows convex outward surfaces (Fig. 11d).

in lower part of central lens. c) Closeup of area boxed in (b) shows laminae laterally thinning and becoming dolomitic (light). At bottom left and lower central, lateral change is through a zone of swarms of very fine dolomite seam (no clay). Negative print from acetate peel. d) Scanning electron photomicrograph from boxed area in (c) shows intergrown rhombs in dolomitic micrite (bottom), scattered small dolomite rhombs in micritic laminae (in area of lateral transition) and two thin dolomite-rich seams in micritic zone (center and near top).

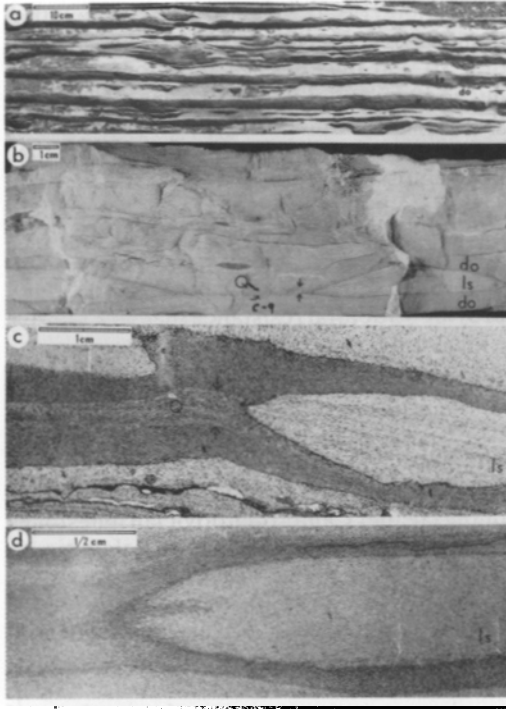


FIG. 11.—Ribbon limestone. a) Field photograph of typical ribbon limestone with continuous dolomite layers (light) and discontinuous limestone layers. New Market Limestone; location as in Figure 10. b) Quartz sand laminae in limestone lenses at base of sample pinch as lenses thin, and quartz is concentrated in thin dolomitic lamina (arrows) between lenses. Weathered slab of Conococheague Limestone (Cambrian), Corwell's pasture, 1 km south of Clear Spring, Washington Co., Maryland. c) As quartz sand laminae in limestone lens intersect base of lens, quartz content of laminated dolomite just beneath increases. Thin quartzose dolomite laminae persist from lens to lens. Positive print from acetate peel; Conococheague Limestone, Downs pasture, 6 km north of Clear Spring, Washington Co., Maryland. d) Limestone lens laterally tapering and becoming dolomitic. Resulting distinctive dolomite lamina can be traced from lens to lens in hand specimen. Positive print from acetate peel; Conococheague Limestone, Downs pasture.

c) Associated with this thinning is an increase in amount of dolomite and size of the rhombs.

As with the first example, these limestone lenses have been created by pervasive solution-dolomitization of parts of previously more continuous limestone beds. The limestone lenses are most commonly arranged

in a fitted pattern much like that of nodular limestones. There is generally no apparent cause for the pattern of limestone lenses; instead, the fitted lensoid limestone pattern seems to be a "spaced" product of pressure solution. This kind of pressure solution is less capable of lateral shear motion than that in clayey nodular limestones, and these lenses are more tapered and pointed than are nodules.

In the example in Fig. 11b, c, the more continuous dolomitic layers do not contain quartz sand whereas the limestone layers do. It can thus be concluded that *this* ribbon limestone originally consisted of coarser and finer limestone layers—the finer-grained layers being responsive to complete pervasive solution-dolomitization at spaced intervals. That the continuous dolomitic layers are the result of pervasive solution-dolomitization is examined further in Example 4.

Example 3

The lower part of the sample used for Example 1 contains a double limestone bed with dolomitic burrow fillings (Figs. 10b, 12). Laterally this unit thins and becomes dolomitic, the dolomite burrow fillings taking on the appearance of dolomite clasts in a micritic dolomite matrix (Fig. 12). As with the previous examples, the lateral change can only be explained by a solution-dolomitization process. Here, however, is evidence that a

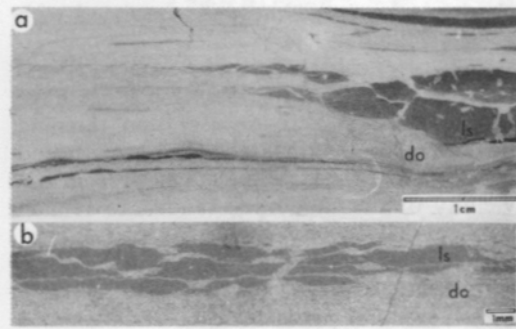


FIG. 12.—a) Edge of limestone lens (dark) with dolomitic burrow tube fillings (arrows). Limestone layers thin laterally and become increasingly dolomitic, and the burrow fillings take on the appearance of dolomite intraclasts. Etched slab; close up of sample illustrated in Figure 10b. b) Close up of 12a showing thin solution seams (dolomitic) connecting dolomitized burrow fillings. Negative print from acetate peel.

rock evolves from one stage to another. First, as seen in the limestone zone, the burrow fillings are preferentially dolomitized. Each burrow tube visible is connected by a very thin solution seam cutting across the limestone (Fig. 12). Dolomite rhombs, coarser than in the surrounding limestone, occur along these seams. There was thus a first stage in which the burrow fills were preferentially responsive to pressure solution and dolomitization. A part of this response was seam solution at stress foci in the contained limestone. Subsequently, parts of the remaining limestone bed responded by pervasive solution-dolomitization in the manner described in Example 2.

Example 4

In several cases continuous dolomitic layers are cut by thin desiccation-crack fillings of limestone. In these cases the limestone is strongly deformed or telescoped, demonstrating a significant thickness reduction of the associated dolomite unit (Fig. 13b, c; see also van Houten, 1964, p. 516). Building on evidence for pervasive solution-dolomitization provided by Examples 1-3, it may be seen that this example provides evidence that the continuous dolomitic layers have undergone a major volume reduction and that this volume reduction was caused by pervasive solution of limestone.

Example 5

Where an outside influence causes a stress on a dolomitic zone, the degree of pressure solution-dolomitization will be greater. Resistant intraclasts or stromatolitic lumps (Fig. 13a, d) protruding into a micritic dolomite zone cause the dolomitic laminae above to pinch (thin) and become more dolomitic (see also Bathurst, 1971, Fig. 317). The stromatolite and intraclasts acted as resistant structural units; the dolomitic layers are from limestone units that were responsive, each to a different degree.

From these examples, it is concluded that pervasive pressure solution dolomitization is an important cause of some finely crystalline stratigraphic dolomite. A solution-dolomitization origin is most apparent where a unit undergoes lateral change from limestone to dolomite (Examples 1-3) or where solution-

dolomitization is associated with limestone anomalies (Examples 4, 5). There is, however, clear evidence through the Paleozoic ribbon limestones (Sando, 1957; Reinhardt and Hardie, 1976), the more confused lumpy limestones (Matter, 1967), and finely interlaminated (cryptalgal) limestones and dolomites (Gebelein and Hoffman, 1973) of western Maryland and Virginia that pressure solution-dolomitization has formed the dolomitic zones and, as a result, slightly to severely deformed the primary sedimentary structures.

Resultant Characteristics

Non-seam (pervasive) pressure solution is only recognized where associated with the formation and concentration of dolomite. Pervasive pressure solution-dolomitization occurs in limestones that have very low silt and clay content and have little structural resistance during response to applied stress. Pervasive pressure solution-dolomitization causes a reduction in thickness of affected units. This is closely associated with an increase in abundance of dolomite rhombs (by growth, not as an insoluble concentrate). Pervasive solution-dolomitization is most apparent where there is evidence of some lateral variability in intensity of the process (Examples 1-3) or some evident distortion about associated limestone features that remained resistant (Examples 4, 5).

Partial pervasive solution-dolomitization will result in an essentially randomly mixed fabric of micrite or microspar and dolomite. Complete pressure solution-dolomitization yields a vaguely laminated dolomitic zone that contains little silici-clastic silt or clay.

BOUNDARY MORPHOLOGIES

Limestone types producing the basic forms of limestone pressure solution commonly adjoin one another. Where similar types of limestone are in contact the result will be as described above. Where unlike limestone types are in contact, the boundary pressure-solution response may be quite different (Fig. 15). For ease in the following discussion, Roman numerals are used to define the basic limestone types as follows:

I = clean structurally resistant limestone (sutured seam solution),

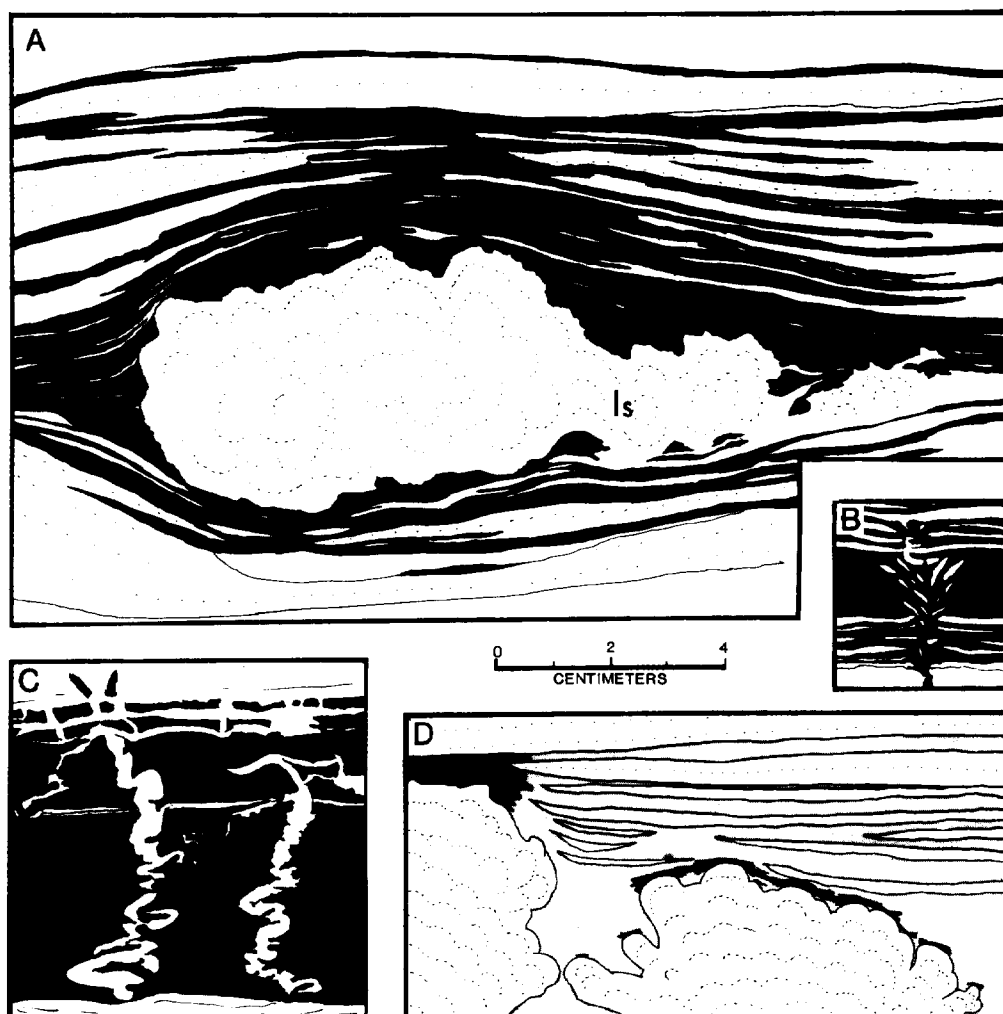


FIG. 13.—Sketches from field photographs of causes and results of non-seam pressure solution in ribbon limestones. White is limestone, shaded is dolomitic and black is dolomite. Conococheague Limestone (Cambrian), Ashton, Maryland. a) Resistant limestone stromatolite caused local solution-dolomitization of surrounding limestone layers. b) Limestone desiccation crack filling is broken and telescoped by volume reduction during solution-dolomitization of the associated layer. c) Limestone desiccation crack fillings folded and faulted by volume reduction during solution-dolomitization of associated layers. d) Partial to intense solution-dolomitization in stress foci adjacent to resistant limestone stromatolites.

II = clayey or shaly limestone, structurally resistant or responsive (non-stutered seam solution or solution-dolomitization), and

III = clean responsive limestone (pervasive solution-dolomitization).

Here, as in the previous sections, both structurally resistant and responsive clayey/shaly limestones are considered as one type because distinct microstylolites develop in

both. Most important are boundaries between I-II and I-III.

I-II Boundaries

At I-II boundaries sutured seams will not occur because lateral movement along microstylolites or clay seams will distribute stress foci over a broader area. The resulting boundary if both units are undergoing pres-

sure solution, will be a wavy to planar zone of microstylolite swarms or clay seams (Fig. 14a). Sutured seams normally should not be able to penetrate into a clayey limestone (but see "Response Evolution" below).

Coarser crystalline and cleaner type I limestones are commonly much more resistant to pressure solution than type II. In these

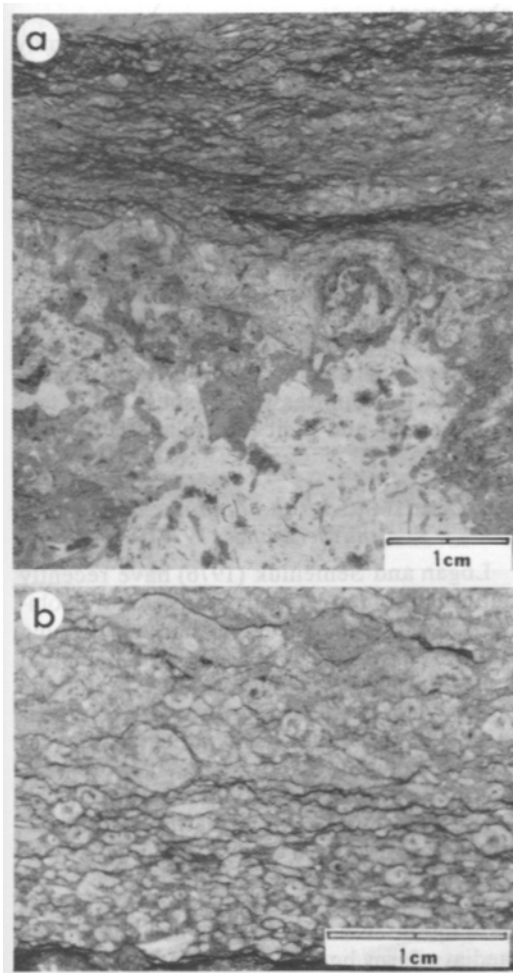


FIG. 14.—a) Undulating boundary between resistant grainstone (lower) and clayey nodular limestone (upper). Polished slab of well core from lower Cretaceous between 2,500 and 3,500 m beneath northern Key Largo, Florida. b) Microstylolite and stylolite solution has created laminae in clayey limestone matrix about skeletal grains. Polished slab of well core from Lower Cretaceous between 2,500 and 3,500 m beneath northern Key Largo, Florida.

cases, whether as beds, structures (e.g. stromatolite heads) or grains, the type I unit may protrude well into the II limestone, causing accentuated pressure solution and flowage. Coarse skeletal material, being more coarsely crystalline than the associated type I or adjacent type II limestone, may be more resistant to pressure solution and be concentrated in microstylolite swarms or clay seams. Biomicrites (skeletal wackestones) with significant clay or platy silt in their matrix may evolve by pressure solution into a skeletal packstone with thin microstylolite seams about each grain (Fig. 14b).

I-III Boundaries

A type I limestone will not suture against a type III limestone. As type III limestone will respond to stress pervasively, the contact with type I limestone will be no more prone to pressure solution than the zone within the type III unit. Thus, if a type III limestone is to undergo preferential pressure solution, it will do so pervasively. If the type I limestone has an irregular surface, the protruding features will cause accentuated pressure solution-dolomitization in stress zones in the adjacent type III limestone (Fig. 13a, d; see example 5 in "Non-Seam Pressure Solution").

Where type I limestones are undergoing pressure solution against a type III limestone, solution will occur at the boundary, but there will not be solution interpenetration for one of two reasons. Either the type III limestone will not respond to a point of stress by pressure solution only at that point, or as the type III limestone undergoes pressure solution-dolomitization, the dolomite rhombs eventually come into contact with one another, causing the type III unit to become increasingly resistant to further pressure solution and, at some point, more resistant than the adjacent type I limestone. In other words, the type III limestone will respond pervasively until it becomes resistant to further change.

Minor Influence of II or III on a Type I Limestone

Where a type I limestone contains thin lenses, laminae or grains of type II or III limestone, the II or III limestone may be

reduced to thin clay, dolomitic clay or dolomite seams. Adjacent type I limestones may be in partial contact or be brought into partial contact by either shear along these seams or stylolite penetration through very thin zones in the seams. In such cases, sutured pressure solution could take place. The clay-dolomite seams, acting as solution boundaries and glide surfaces, would impose a very irregular pattern on the resultant stylolitic pressure solution. Lumpy limestone (Matter, 1967) and reticulate limestones (described previously in "Nodular Muav Limestone" section; Wanless, 1973a) are examples.

DISCUSSION

The preceding sections present evidence for the interpretation that pressure solution of three basic forms has significantly modified the character of many ancient limestones. Three basic forms of response to pressure solution can be expected in limestones depending on whether the limestone units are structurally resistant or responsive and whether they contain platy insoluble impurities. In clean limestones composed of structurally resistant units, pressure solution will form sutured seams and grain contact sutures. In limestones with more than about 10 percent clay or platy silt, pressure solution will concentrate clay as a film along microstylolites. Lateral shear along these glide planes will cause migration of stress foci creating anastomosing swarms of microstylolites rather than one large seam. In clean limestones without structurally resistant units, response to pressure will be pervasive solution through a zone rather than solution focused along a surface. If magnesium is available during pressure solution, dolomite may grow in the vicinity of the surface or zone of solution. These conclusions are summarized in Figure 15.

It is important at this point to consider how the pressure solution features observed fit into a general system of stress response in limestones. This is followed by a comparison of the author's conclusions with those of Logan and Semeniuk (1976), a discussion of the problem of limestone response evolution, and a reconsideration of the carbonate problems that were mentioned at the outset.

Stress Response in Limestones

This article has examined only pressure solution response in limestones in which compressional stress has caused significant pressure solution. Pressure solution is most certainly more complex in incipient and immature stages (Bathurst, 1971, p. 499; Neugebauer, 1974; Mimran, 1977), in areas where metasomatic fluids were active, and in situations where there is a significant shear component.

Solution is only a part of a general family of potential stress responses including compaction, deformation, neomorphism, some types of local-source dolomitization, and metasomatism. Indeed, few changes are single process responses. Tectonic deformation of ooids (Cloos, 1947), for example, involves neomorphism, pressure solution and reprecipitation and is intimately associated with solution seams, formation of dolomite and chert, and brittle fracture (Fig. 1). A meaningful analysis of diagenetic history must evaluate the spectrum of potential responses to compressional, shear, and tensional stress and their interrelationships.

Comparison with the Findings of Logan and Semeniuk (1976)

Logan and Semeniuk (1976) have recently published a major treatise on pressure solution as applied to the Devonian of the Canning Basin, Australia. There are two fundamental issues on which the author's interpretations differ from those of Logan and Semeniuk. First, those authors have indicated that laminated dolomite is the end result of pressure solution, with "stylo-nodular" form being an intermediate phase. This author, distinguishing three basic styles of pressure solution, recognizes three potential end products each of which may or may not have associated dolomite. Nodular bedding is not an intermediate form but the result of a distinctive and basically different form of pressure-solution response in limestones of different lithology from those in which pervasive solution occurs and sutured stylolites develop. Although differing in views on specific processes, Logan and Semeniuk and the author agree that nodular limestones and many la-

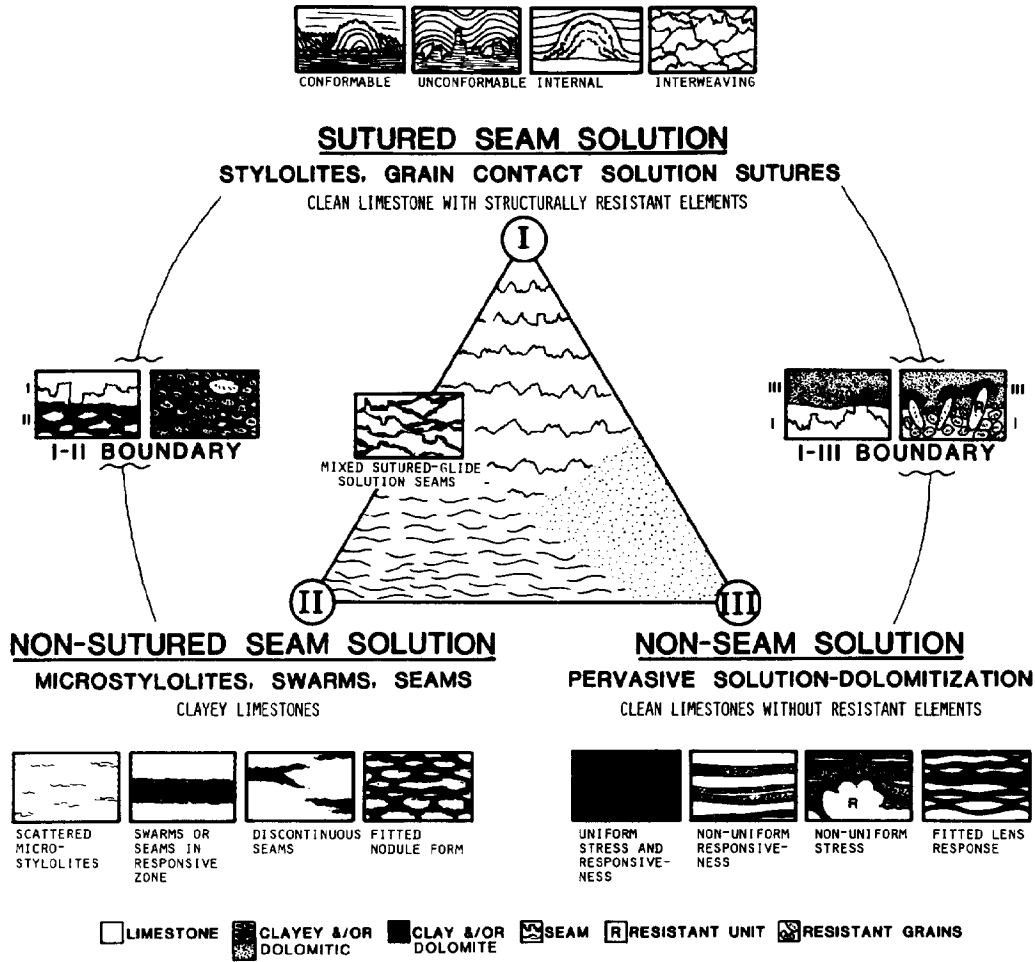


Fig. 15.—Summary diagram of characteristics of and controls on pressure solution types with sketch examples. *Clean* means without significant clay or platy silt.

minated dolomites are products of pressure solution.

Second, Logan and Semeniuk (1976) envision pressure solution as a progressive feature acting similarly at all scales from grain to stratigraphic unit and having little regard for minor variations in primary rock fabric. In contrast, this writer maintains that the primary sedimentary structures and their contained compositional, textural and fabric attributes are strong controls on the course, style, and resulting features of pressure solution. Whereas Logan and Semeniuk view the

product as reflecting a pressure solution or "stylo-" form, the author considers most resultant structures as a minor to severe diagenetic distortion of primary rock character.

Logan (pers. comm.) and the author are in agreement that nodular bedding and ribbon limestones need not have anything to do with primary layering or sedimentary structures. A major challenge of the future will be to reexamine our assumptions about the primary character of limestone units and sequences.

Response Evolution

Pressure solution both constantly modifies the fabric of the associated limestone and provides a continuing supply of calcium carbonate that can be locally reprecipitated (Boer, 1977).

While a thorough evaluation is not yet possible, this study provides several observations which suggest that some cementation is associated with pressure solution. Layers that have resisted pressure solution generally have primary fabrics and do not appear to have undergone significant compaction. Porosity of these units is much reduced, however, from what must have initially been present. Most of the porosity loss must have been caused by addition of calcite cement during the time that solution and neomorphic processes were active (see also Bathurst, 1971, p. 417, 504). Such zones of preferential cementation, whether primary structures or randomly-spaced features between zones of preferential solution (nodules), may become increasingly resistant structural units. The small stylolite in Figure 10b, for example, suggests that this limestone lens evolved from a responsive to a resistant unit.

A limestone unit's response to stress can change through time in several ways. First, a limestone unit may evolve from inactive to active. Certain units will respond to increasing stress before others or in preference to others. Second, pressure solution-dolomitization of a type III unit will become increasingly resistant as the dolomite content increases (at a reduced unit volume). Third, cementation in silty limestone nodules of type II during pressure solution of an adjacent part of the unit may decrease the ratio of clay to calcite in the nodule sufficiently to cause it to act more like a type I limestone. Jenkyns (1974) also notes that stylolite seams may form between adjoining nodules. Cementation in limestone lenses of type III ribbon limestones may cause them to increase in strength and subsequently respond as a type I limestone (see the fine sutured stylolite in limestone lenses of Fig. 10b). Fourth, limestone may become less responsive because (a) shear motion along seams can more easily relieve stress and/or (b) permeability

is sufficiently reduced to inhibit effective fluid migration.

Problems

In light of the interpretations outlined in this paper, the five carbonate problems presented at the beginning of this paper can be reassessed and a new one considered.

Stratigraphic Dolomite.—Dolomite which occurs interlayered, interlaminated or interwoven with distinctly primary structures of limestone commonly appears to have had a diagenetic origin intimately associated with rock volume reduction by pressure solution (see "Dolomite" in "Non-Sutured Seam Solution" and examples 1-5 in "Non-Seam Pressure Solution). Dolomite can be an important "reactate" mineral produced during pressure solution of some type II and III limestones.

It is, of course, recognized that certain ancient dolomites may be partially or wholly formed by penecontemporaneous (Illing et al, 1965; Shinn et al, 1965) or prestress diagenetic processes (Deffeyes et al, 1965; Folk, 1973). In the variety of ancient limestones examined by the author, however, pressure solution-dolomitization is an important influence on dolomite distribution. Pressure solution-dolomitization must be considered as a common and expected result of stress response in limestones.

Dolomite generated during pressure solution has certain characteristics that together serve as distinguishing criteria. In clayey limestones, dolomite that grew along microstylolites during or after pressure solution will tend to be cloudy because of contained clay particles. This could only occur after clays were concentrated. Larger rhombs will occur only along microstylolites and in clay seams. Rhombs will partly overgrow larger insoluble particles such as platy micas. In those clayey and clean responsive limestones in which limestone layers can be seen to thin laterally because of pressure solution, the thinned zone will display a lateral increase in the absolute abundance of larger rhombs. Larger rhombs will tend to be zoned, the outer portion being different from that of the small rhombs scattered through adjacent limestone. The core of larger rhombs, how-

ever, tends to be clear and stain like the small rhombs in the limestone. In the examples studied, outer parts of larger rhombs are at least slightly higher in iron as revealed by potassium ferricyanide stain. In clean limestones, larger rhombs commonly contain small disoriented dolomite rhombs as inclusions. Dolomite commonly forms an intergrown mosaic in the solution-thinned zones of clean responsive limestones (bottom of Fig. 10d).

This study has neither addressed the subject of dolomitization of coarse-grained or reefal carbonate sediments nor determined how the magnesium released by sutured stylolite solution is redistributed.

Source of Ions.—The extensiveness of pressure solution suggested by this study indicates that much of the magnesium for dolomitization and calcium carbonate for pore filling cementation can be quite local in origin. This supports some recent interpretations by Oldershaw and Scoffin (1967) and Lloyd (1977) that carbonate diagenesis (cementation) can be a largely closed-system process.

Referring back to Example 1 of non-seam pressure solution-dolomitization, an apparent 100 volumes of limestone evolved under pressure solution-dolomitization to 13 volumes of dolomite. Assuming that the original limestone had initial porosity of 50 percent, it would have had to contain an average of about 14 mole percent $MgCO_3$ if all the magnesium were derived from the zone of pressure solution. The amount of magnesium could have been less if some was supplied by local interstitial waters, organic material, or from nearby limestone areas, or by penecontemporaneous dolomite. Because of pressure solution, however, the source for magnesium need no longer be a mysterious problem requiring special outside influences to cause widespread dolomitization in limestones of many depositional origins.

Why do certain limestones not contain dolomite as a by-product of pressure solution? Nodular limestones containing little or no dolomite along the microstylolite seams tend to have formed in shelf (portions of Chambersburg Limestone) to deeper water (post Paleozoic, e.g., red nodular limestones of Mediterranean Triassic) environments. These environments should have contained

low to negligible amounts of magnesium calcite.

The source of calcium carbonate for porosity filling cementation and addition during neomorphism may now be considered from a new point of view, in light of the large volumes of calcium carbonate released by the three styles of pressure solution recognized here.

Stratigraphic and geochemical documentation are now needed to determine the overall importance of pressure solution to cementation and dolomitization.

Sedimentary Structures.—Many unusual sedimentary structures (e.g., ribbon, lumpy and nodular forms) in limestone-dolomite sequences are due either to solution distortion of primary features or to pressure solution-dolomitization. We need to reassess the origin and significance of these unusual structures—to discern to what extent observed structures were defined by precursor attributes in the limestone and to reconstruct these attributes. To continue forcing some observed sedimentary structures into primary sedimentary categories per se or to continue paleoenvironmental reconstruction of limestones through casual field observation of structures, is to avoid the reality that change has very often occurred.

Sedimentary Sequences.—The conclusions of this study suggest a new approach from which to assess carbonate sequences and cycles containing unusual elements. One aspect is particularly open to reassessment. The Paleozoic platform limestones of the Appalachians (e.g., Conoccocheague Limestone, Beekmantown Limestone, New Market Limestone, Tonoloway Limestone, Wills Creek Limestone) contain meters-thick zones or portions of cycles that are dolomite or dolomitic. As pointed out to the author by L. A. Hardie (pers. comm., 1977) the dolomitic zones of cycles in the New Market Limestone are not pure dolomite and gradually increase in limestone content upwards. Only in the upper, dolomite-poor portions are distinct primary sedimentary structures apparent. Are these dolomitic zones a product of extensive pressure solution-dolomitization? Did they contain more magnesium to start with? Many of the structures in dolomitic zones resemble those of type III limestone solution-dolomitization, such as

"intraclasts" like those produced from burrowed limestone (see Example 3 of "Non-Seam Solution"), laminated dolomite, and somewhat deformed desiccation crack fillings.

Compaction.—It is a conclusion of this paper that secondary compaction—that is, distortion by physical squeezing which causes porosity reduction—is a relatively unimportant process in most carbonate rocks (see, however, Mimran, 1977). Rather, pressure solution processes such as described in this article are mainly responsible for the significant volume reduction and the distorted structures that have been interpreted by some workers as simple compaction features. The wispy laminae produced by squeezing modern carbonate muds (Shinn et al, 1977) are mainly squashed organic material and should not be compared with microstylolites in limestones. Solution is necessary to concentrate clays along microstylolite surfaces.

The End Product.—As the results of this study and others (e.g., Oldershaw and Scoffin, 1967; Lloyd, 1977) indicate that some carbonate diagenesis can be a closed-system process, we should ask whether the three styles of pressure solution can commonly continue to completion (total limestone solution). Do the processes of pressure solution gradually reduce the porosity and permeability of a unit to a point where it cannot effectively eliminate material in solution? Will pressure solution in a limestone trend towards a final stable form, the extent and form being controlled by limestone attributes defined earlier as well as by pressure and temperature conditions and water chemistry? Bathurst (1971, p. 500–501) also expresses this concern. Perhaps the adjustment of fabric and the production of dolomite continue well after exchange or any other mass transfer with the external system has ceased.

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