STYLOLITES: CHARACTERISTICS AND ORIGIN

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A senior thesis submitted to fulfill
the requirements for the degree of
B.S. in Geology and Mineralogy
Winter Quarter, 1984

The Ohio State University

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Abstract

Stylolites are alternating interpenetrating columns of stone that form irregular interlocking partings or sutures in rock strata. They are most common along bedding planes of limestone but some are oblique or even perpendicular to bedding. Although the vast majority of stylolites occur in calcareous rocks, stylolites have been found in sandstone, quartzite and gypsum. The word "stylolite" refers to each individual column of stone. A cross section of a group of stylolites parallel to their length presents a rough, jagged line called a "stylolite seam" that resembles the sutures of a human skull. Stylolites always have a dark colored "clay" cap at the ends of the columns. The sides of the columns are typically discolored with a thin film of clay and show parallel flutings or striations that parallel their length. The shapes of individual stylolites vary greatly from broad flat-topped columns to pointed, jagged and tapering forms. After much controversy concerning the origin of stylolites, it is generally believed that they form by a process of chemical solution under pressure in lithified rock along some crack or seam. The interteething is produced because of differential solubilities and pressures within the rock unit. The clay cap on the stylolites is the non-soluble residue of the dissolved rock. Stylolites are only one of the possible end products in the spectrum of limestone responses to stress. They form in limestone units that have structural resistance to stress and contain relatively little clay or silt. Stylolites may play a major role in initiating or preserving oil accumulations in limestone. Where they are formed due to tectonic compression, stylolites may be useful in providing information on paleo-stress patterns.

General Characteristics of Stylolites

Stylolites are alternating interpenetrating columns of stone that form irregular interlocking partings or sutures in rock strata. They are most common along bedding or lamination planes of limestone. Stylolites produce an interteething of rock by alternations of downward and upward projections of columns. The downward projecting stylolites originate from the overlying strata, and vice-versa. The columns show the same lithological characteristics as the strata from which they project. Some stylolites form a parting between distinctly different lithological units. Individual columns measure from small fractions of an inch to more than a foot (figure 1). The stone is commonly so firm at the stylolite that it will break elsewhere rather than directly along the stylolite. A cross-section of the stylolites parallel to their length presents a rough, jagged line called a "stylolite seam" that resembles the sutures of a human skull or the trace of a stylus on a chart recorder (figure 2). This is the most familiar characteristic of stylolites. Stylolites always have a brown to black "clay" cap at the ends of the columns. The color of the cap is dependent on the color of the associated limestone. The thickness of the cap is proportional to the column length; those on longer stylolites are as much as a half inch thick. Some of the caps have a compact, laminated appearance. All stylolites show parallel flutings, or striations, on the sides of the columns that resemble slickensides of fault planes (figure 3). These striations parallel the direction of penetration of the columns. The sides of the columns are typically discolored with a thin film of clay. Stylolites begin as a barely detectable smooth crevice or suture that grades laterally from slightly-undulating to finely-toothed to a fully-developed form. The seam

FIG. 1 .—Thirteen-inch stylolite in the buff Salem limestone. From a quarry of the Consolidated Stone Company, Dark Hollow district, Lawrence County, Ind.
(from: Stockdale, 1921)

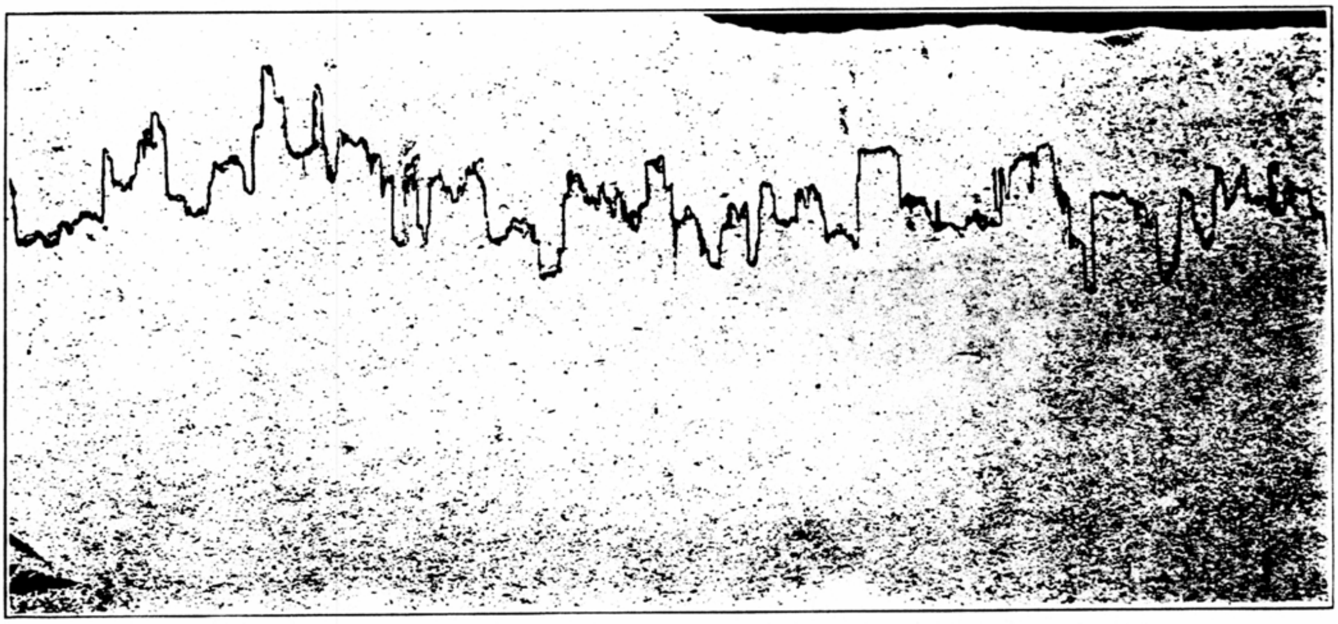

FIG. 2 .—Typical stylolite-seam as it appears on a sawed surface of the Salem limestone. Note the irregularity in size and shape of the interpenetrating parts. About one-half natural size.
(from: Stockdale, 1921)

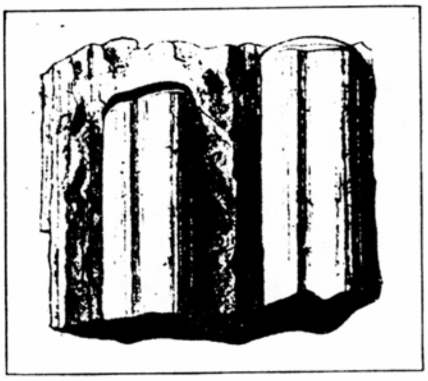

FIG. 3 .—Stylolites in the Muschelkalk, showing striated side-surfaces and clay caps. From Rüdersdorf, near Berlin. Original in Marburg Museum. (from: Stockdale, 1921)

can be several feet to as much as several hundred feet in length. Seams commonly are parallel with rock stratificaton, but some are oblique or even perpendicular to bedding (figure 4). Some units contain numerous stylolites with seams that cross, penetrate and partially eradicate one another (figure 5). Some stylolites are formed by two or more small partings joining to form one, larger parting (figure 6). In this case the larger seam has columns with lengths about equal to the combined lengths of the smaller seams and a clay cap about equal in thickness to the combined thicknesses of the caps on the smaller seams (Stockdale, 1921). Stylolites occur in many formations throughout the world. In the U.S., they are most common, and best developed, in the Holston formation (Ordivician) of Tennessee and Mississippian limestone of Indiana such as the Salem formation. The shapes of the individual stylolites vary greatly. The larger and best developed stylolites tend to have column tops that are relatively flat but slightly convex (figure 7). The larger major columns may have ends marked by subordinate penetrations. Some seams are very regular and uniform with evenly spaced columns, whereas others are highly irregular and jagged with pointed columns. Caps formed by a fossil occur on the column ends of some stylolites and can have an influence on the shape of their column.

FIG. 4 .—Stylolite-seam which leaves the bedding plane and cuts across the lamination of the upper stratum at an angle of about 20 degrees. From a quarry of the Consolidated Stone Company, Hunter Valley district, Monroe County, Ind. (from: Stockdale, 1921)

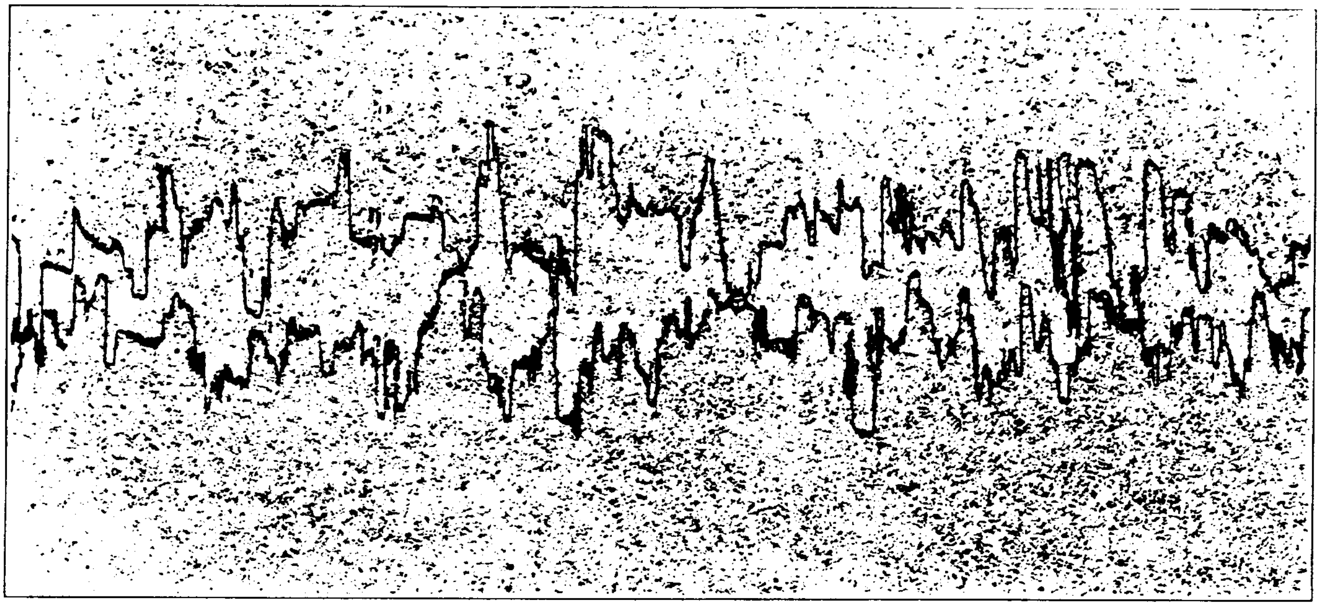

FIG. 5 .—Two parallel stylolite-seams of the Salem limestone, which, in places, touch and partially penetrate one another. (from: Stockdale, 1921)

FIG. 6 .—Branching stylolite-seam in the Salem limestone. Note that the combined thickness of the black clay of the two branching seams is equivalent to that of the major, single seam. (from: Stockdale, 1921)

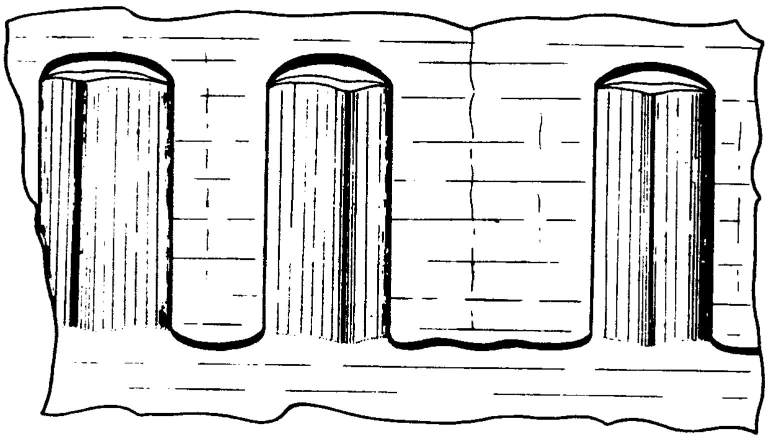

FIG. 7 .—Diagrammatic sketch of the large, perfectly formed stylolites of the Salem limestone, such as are found in the Dark Hollow district, Lawrence County, Ind. In this specimen the block has been broken along the side-surfaces of the upward-penetrating columns, showing the striations; and thru the downward-pointing columns, exposing the lamination and texture of the rock. One-fourth natural size. (from: Stockdale, 1921)

Early Observations and Terms

Stylolites have been observed and described since the middle of the 18th century. Indeed, many interesting and varying theories were put forth in attempts to explain this strange phenomenon. An American, Eaton (1824), thought they were of organic origin, possibly the columns of fossil corals, and named them "lignilites". Vanuxem (1838) believed that they were the result of crystallization of epsom salts and termed them "epsomites". Hunt (1863) followed Vanuxem's crystallization hypothesis and called them "crystallites". An elaborate erosion theory involving subaerial exposure and dessication of limestone oozes was put forth by Plieninger (1852). Zelger (1820) advocated a gas theory in which stylolites were formed by escaping gases through soft sediment. Quarrymen working in the Indiana Limestone gave them the descriptive terms of "crow feet" or "toe nails". The term, "stylolite", was first utilized by Kloden in 1828. He believed that they were the remains of a distinct species of organism to which he gave the name "stylolithes sulcatus"

The earliest investigations and theories on the origin of stylolites were dominated by the Germans. They applied the term "Drucksuturen", meaning pressure sutures, to the irregular, finely serrated, jagged lines or sutures common in thick limestone and dolomite in Germany (Stockdale, 1921). When these serrations were shorter, less than 3/4", and the interlocking parts were conically pointed rather than columnar, they were called simply "Druck". These finer seams do have clay-partings and finely striated side surfaces, the fundamental difference being size. Rothpletz (1900) proposed that the two were of different origin being "morphologically and genetically quite different." Druck, he concluded, was the result of rock pressure and solution in <u>lithified</u>

limestone. This he based on observations of partially removed fossils adjacent to the seam. On the other hand, he considered Drucksuturen to be the result of pressure of overburden in a plastic, non-lithified limestone deposit. In contrast, Fuchs (1894), Reis (1902), and Wagner (1913) thought that the two resulted from the same processes, with Druck being a "young", less developed stylolite.

Some early studies made an analogy between stylolites and Gerolleindrucke -impressed or pitted pebbles. It was found that some conglomerate pebbles, mostly limestone, can become impressed into one another with the contact between the two showing minute, jagged interteething, similar to Druck. In non-fractured samples it was evident that this contact was formed by an actual removal of material rather than mechanical distortion or displacement of material. Rothpletz (1900) concluded that solution took place with removal of material at points where the two pebbles meet.

In the 1920's and in fact until fairly recently, there were two principle contrasting theories under controversy, with the others being dismissed as hypothetical with little supporting evidence. The first of these, the "Pressure Theory", was originated by Quenstedt in 1837 and supported by Gumbel (1888), Rothpletz (1900) and more recently Shaub (1939). This theory states that stylolites are the result of differential compression of sediment before lithification. This involves plastic deformation of two distinct beds of calcium carbonate ooze, separated by a layer of shells and a layer of clay. There would be different pressure resulting from difference in lithologies of the limestone beds. The thin layer of shells would be more resistent to pressure than the surrounding material, which would be deformed more readily, resulting in the characteristic columns. Thus, one should find a fossil cap on top of most, if not all, the columns. Columns that are perpendicular to bedding were produced by vertical pressure due to the weight of overburden. Rothpletz (1900) devised a more plausible pressure theory. He claimed that the differential pressure resulted from differential and irregular hardening of the plasic mass by uneven introduction of a cementing agent (Stockdale, 1921).

One of the strongest advocates of a pressure origin of stylolites is Shaub (1939) who proposed a "pressure-contraction" theory. He states that stylolites are a result of differential pressure and compaction prior to lithification. This entails a plastic transfer of material by flow without removal of any rock substance. This readjustment and rearrangement followed a removal of pore water on top of an original, primarily deposited clay band. Following compaction there is a slow, ordered transfer of material perpendicular to the pressure, (Shaub, 1939). Shaub proposes that contraction action assists in pulling material laterally by cohesive action between particles as the pore water is removed. He presented a photograph (figure 8) which he claims provides conclusive evidence of stylolite development prior to rock consolidation. The photo shows what Shaub termed a "Keystone offset" in a stylolite occuring in the Tennessee marble. He states that the displaced section (G) is of greater length than the gap at H. He assumed that if this offset was formed after rock lithification then some type of faulting would be involved and the adjacent rock would be badly broken (Shaub, 1949). Instead, Shaub claims that either the displaced section was stretched or the gaps were shortened by plastic adjustment.

The second principle theory, which is today regarded as the most plausible, is the "Solution Theory". It was first proposed by Fuchs (1894) and states that stylolites are formed in <u>hard</u>, lithified rock by chemical solution,

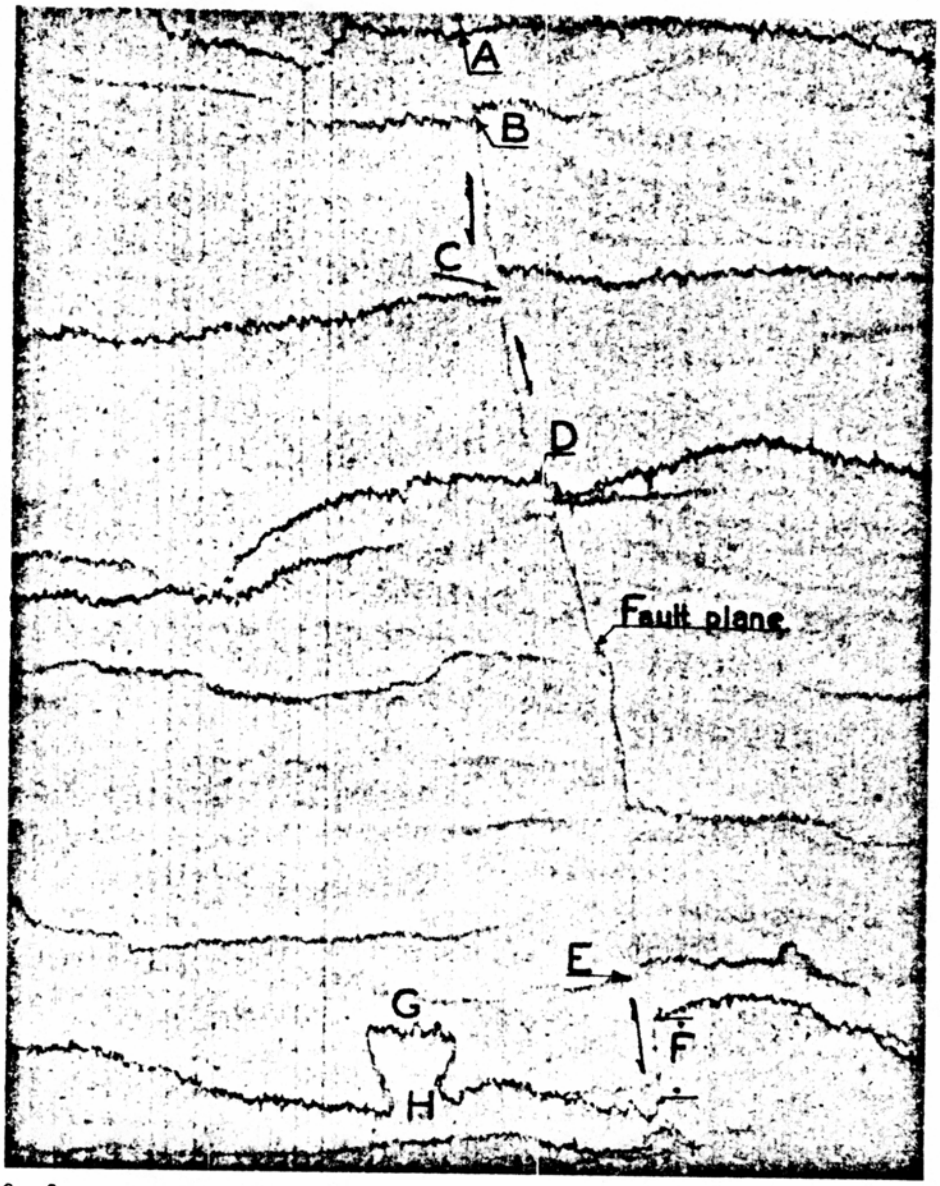

fig. 8. .—Photograph of an area about 20×24 inches in a marble panelled wall of a room in the Hotel Cleveland, Cleveland, Ohio. The variable throws of the stylolite seams at the fault are explicable if the fault blocks moved relative to each other and perpendicularly to the plane of the section. The "keystone offset" at G–H can be interpreted as an oblique section through a normal stylolite column. Time of origin of the stylolites cannot be deduced with certainty from this evidence. (Photograph reproduced by kind permission of B. M. Shaub, and of the editor, from *Jour. Sedimentary Petrology*, vol. 19, no. 1, p. 34, fig. 3.) (from: Dunnington, 1954)

under pressure, along some crack or seam. The interteething is produced by differential resistence to solution of adjacent strata. The clay cap on stylolites is the non-soluble residue of the dissolved rocks. Fuchs claimed that the striations on the sides of the stylolite columns are the result of movement parallel to the columns. He concluded that stylolites never occur singly and are not confined to stratification planes. If fossils are present, they appear broken off by the stylolite, with portions removed by solution. Investigations by Reis (1902) supported Fuchs' theory. He claimed that removal of hard stone is evidenced by partial dissolving and removal of fossils and oolites. The residual clay, on the tops and sides of the columns, served as protection for the unattacked portion of rock.

Perhaps the most conclusive and exhaustive investigations of stylolites were conducted by Wagner (1913). He used the evidence of Fuchs and Reis in describing and discussing many complex stylolite structures such as crossing, curved, and vertical stylolites as well as the more typical horizontal ones. The key to his investigation, as well as to that of others that favored the solution theory, is that there is actual removal of rock material. Wagner found no evidence of mechanical deformation or disintegration of fossils associated with stylolites. He stated: 1) rocks above the stylolite seam were undisturbed - contrary to what one would expect had the stylolites formed by plastic deformation in unconsolidated sediment; 2) the solution zone is perpendicular to the direction of greatest pressure; 3) at places of highest pressure, the greates amount of solution would occur; 4) the side surfaces of the columns, parallel to the pressure, remain unattacked and become smoothed and striated due to movement perpendicular to the seam; 5) younger stylolites can penetrate and partially eradicate older ones and 6) the size and form of the stylolite depends on the nature of the associated rock.

Stockdale has been the principal proponent of a solution origin of stylolites. His "pressure-solution" theory states: "Stylolite phenomenon result from differential chemical solution of hardened rock, under pressure, on two sides of a bedding plane, lamination plane, or cevice, the undissolved portions of one side fitting into the dissolved out portions of the opposite, with interfitting taking place slowly and gradually as solution continues" (Stockdale, 1921). The undulating irregular appearance of the stylolite surface results from differential solubility of various parts of the rock. Stockdale states that the small thickness of residual clay found on the seam is a product of solution of much greater thickness of parent rock with the thickness of the seam depending on the purity of the limestone and the amount of rock dissolved. The solution is caused by circulating ground water containing carbonic acid. Solution begins along certain bedding planes or crevices that provide pathways for circulation. If resistance to solution is variable on one side of this initial crevice the carbonic acid will attack the less resistant parts. The portions undergoing solution alternate from one side of the seam to the other producing small scale undulations (figure 9).

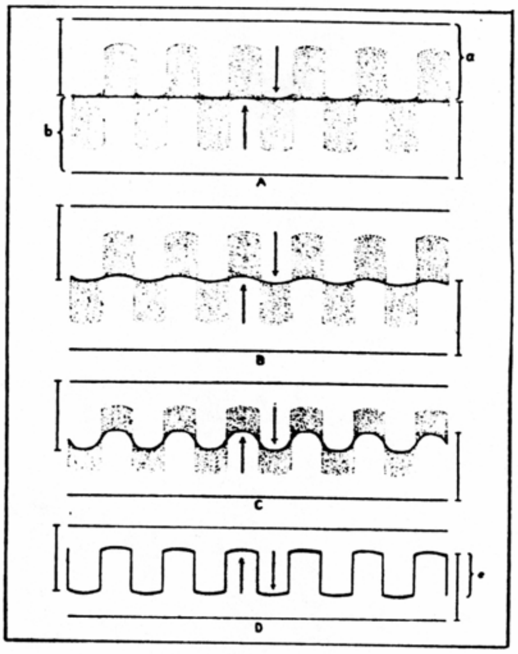

FIG. 9.—Diagram illustrating the development of stylolites from an ideal situation. The dotted areas are those to be removed by solution, representing slightly less resistant portions of the rock. In *A*, no solution has taken place. The limestone beds, *a* and *b*, are separated by an even bedding plane. A slight amount of solution has taken place in *B*, producing an undulating seam. Greater solution has taken place at the stage *C*, giving more pronounced undulations. Pressure is greatest at the crests and troughs of the undulations. A final development of columns is shown in *D*. A dark residue remains at the end of each column. The amount of thinning of the beds is indicated by *e*. (from: Stockdale, 1926)

According to Stockdale, after formation of this intial undulation, the effect of pressure enters into the process. The pressure from the overburden is greatest at the crests and troughs of the undulations. Due to this higher pressure there will be a greater rate of solution at these points (figure 9). The sides of the undulations will undergo less solution due to lower pressure levels. The effect of this is a deepening and lengthening of interpenetrating parts and a gradual development of the characteristic stylolite forms. In this way the column orientation develops parallel to the direction of greatest pressure - usually vertically due to the weight of overburden. The striations or slickensides on the column sides are the result of slow slippage in the hardened rock. This polishes and grooves mineral matter that is deposited on the sides of the columns from supersaturated solutions. The length of the stylolites are thus proportional to the amount and length of time that solution took place as well as the solubility of the stone. The insoluble material is left along the zone of solution forming the clay caps. Perhaps when this insoluble residue accumulates to a certain point, it acts to prevent further solution resulting in a final stable form.

In 1943, Stockdale defended his theory that stylolites are secondary phenomenon - that they post-date rock lithification and are produced by solution under pressure. He tried to limit his discussion to those structures that are "genuine" stylolites, rather than doubtful, rare features. His aim was to assemble numerous findings from the field and to arrive at conclusions deductively, paying most attention to findings that were commonest to most occurrences. The fundamental issue hinges upon two lines of investigation. One is the time of formation of stylolites, or age relationships between stylolites and other features. The second is determination of whether or not rock removal took place.

The evidence was found to be overwhelming that stylolites form after rock lithification. Included in this evidence is the occurrence of stylolites in metamorphic rocks such as marble and quartzite. If the stylolites were primary, they surely would have been distorted or destroyed by the metamorphic processes. Stylolites have been found along unconformities, particularly at the base of the Columbus Limestone (Devonian). The material below the unconformity definately did not remain unconsolidated for thousands of years. Stylolites commonly occur along faults and fractures. Faulting and fracturing succeeds rock hardening so stylolites must also. The relation of stylolites to chert in some limestone also indicates a secondary origin of the stylolites. Some chert develops by replacement of limestone. That some stylolites develop after the chert had formed is indicated by some cherts being impressed into bordering limestone with growth of stylolites into the chert. Some "negative" evidence also supports a secondary origin. If stylolites are primary, one should find them in unconsolidated sediment but none are found. Numerous stylolites have been found that are subsequent to secondary structures and characteristics to which hardening is a prerequisite (Dunnington, 1954). Calcite veins have been abruptly terminated and laterally displaced by stylolite seams (figure 10). Stylolites have developed after recrystallization, dolomitization, and brecciation. Stylolites have also been found cutting initally indurated elements such as oolites, fossils, and pebbles (figure 10).

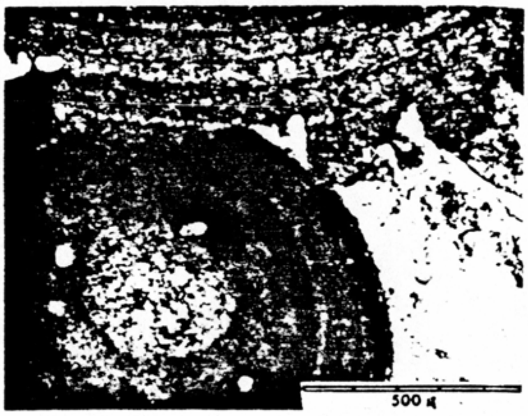

FIG. 10a —Interpretation of pisolite, oolite and now pseudospar matrix along sutured stylolite seam. Conococheague Limestone (Cambrian), Ashton, Maryland. Thin section photomicrograph under plane polarized light. (from Wanless, 1979)

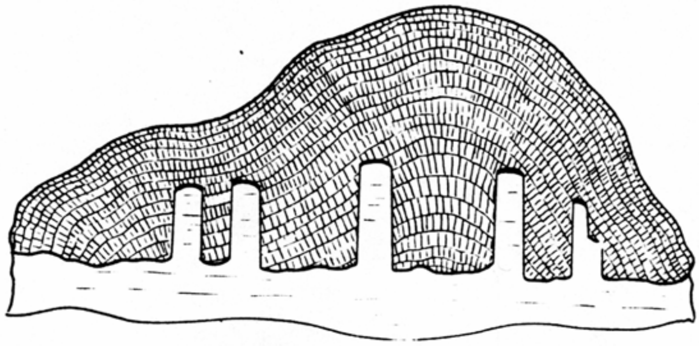

FIG. 10b.—Diagram of a stromatoporoid into which a series of stylolites have penetrated. Note that the fossil structure has been actually removed where the upward-pointing columns occur. From a specimen in the Geological Museum, Ohio State University. About one-third natural size. (from: Stockdale, 1921)

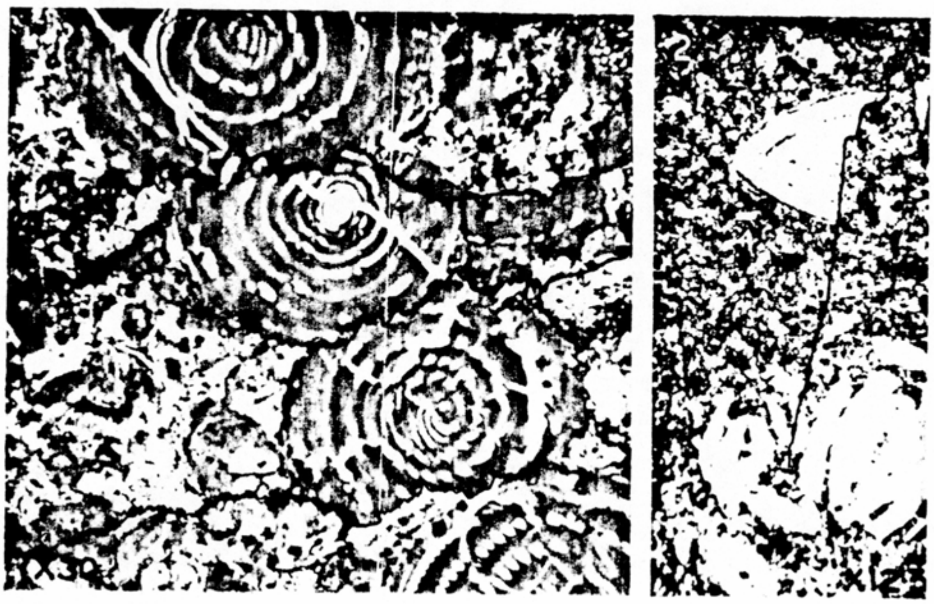

figure 10c. — stylolite-fossil relations (from: Dunnington, 1954)

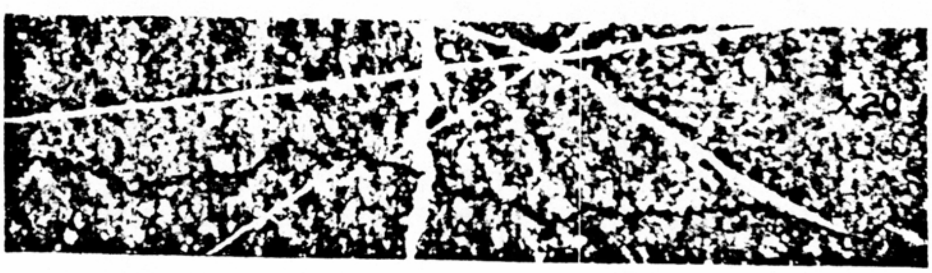

figure 10d. — stylolite displacing calcite veins (from: Dunnington, 1954)

Evidence of actual rock removal most vigorously refutes Shaub's "pressure theory" (Stockdale, 1943). Presence of small stylolites on impressed pebbles definately indicates that rock removal has taken place. Stockdale found very significant evidence in a dark, well-laminated limestone that contains stylolites (figure 11). The laminations above and below the stylolite, as well as within the columns, are undisturbed, not bent or misshapen. For this to take place the laminations had to have been cut out and removed. Further evidence is supplied by penetration of smaller stylolite seams by larger, later forming ones.

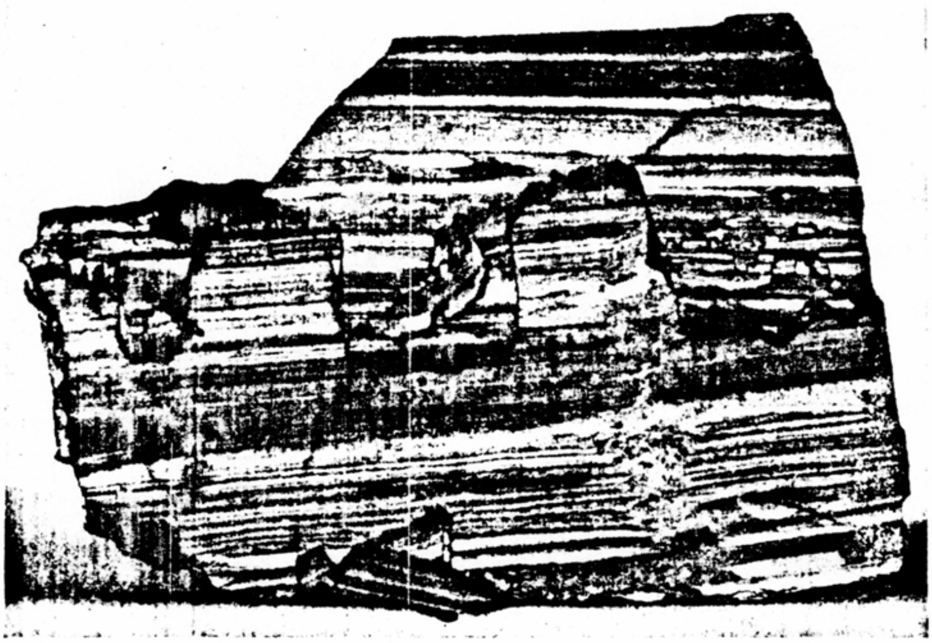

FIG. 11. Large, well-developed stylolites in laminated limestone. Note that the parallel laminae carry without interruption across the rock both above and beneath the large columns of the major stylolite-seam and that there is no mashing, bending, nor distortion of these laminae. The smaller, minor stylolite-seams, which occupy positions in only the alternating columns, give evidence of multiple "stylolite-history." The tilted segment in the middle is a remnant, bounded by stylolite-seams, whose position was shifted to accommodate adjustments and vertical thinning compelled by differential solution along the smaller stylolite zones. Note, furthermore, that the black clay "caps" are quite thick at the major stylolites and comparatively thin along the small ones. The exceptional thickness of this clay residue is because the limestone is quite argillaceous and much solution has been required to produce such large stylolites (Specimen, courtesy of Dr. E. R. Cumings, Indiana University).

(from Stockdale, 1943)

Chemical Analyses of Stylolites

Stockdale (1921) made chemical analyses of the material along stylolite seams in attempting to find evidence that the clay seams are in fact residue of the dissolved "parent" limestone. If the pressure-solution theory is correct, there should be a definate chemical relationship between the clay caps and their associated limestone. The clay should contain a concentration of the less soluble constituents in the limestone with the soluble constituents being leached away and generally absent. He found that in most specimens, the clay cap contained 0-10 percent calcium carbonate, the rest being lost due to it's high solubility. He also found constituents of lower solubility such as, silica, alumina, and iron oxides, were retained in greatest quantities in the residual clay. Most importantly, it was determined that the clay and the parent limestone had almost exactly the same ratios of silica:alumina. From this Stockdale concluded that the clay fulfilled the requirements of a residuum from solution of the limestone. If the clay were an original, once continuous deposit, as Shaub's pressure theory suggests, one would not expect such a definate relationship between the clay and the limestone. Schwander, Burgin, and Stern (1981) also reported "a close geochemical relationship between elemental ratios of insoluble chemical main constituents of stylolite fillings and their host rocks". Their quantitative chemical analyses indicate that calcium, and partially magnesium, have been dissolved, leading to an enrichment process of clay minerals, quartz, K-feldspar and pyrite. They are also found that all the stylolites they examined contained at least some calcite. They believe that the amount of depletion, or rock reduction, by pressure solution can be estimated by comparing the calcite content of the host rock with that of the stylolite. On this basis they came up with a loss of approximately six percent which is somewhat lower than other reported values. Stockdale (1926) attempted to estimate the volume reduction associated with stylolitization by forming ratios of certain clay minerals contained in the host rock versus ratios of the clay minerals contained in the clay residue assuming calcite-free stylolites. Stockdale calculated rock reductions of up to 40% within particular units. In any case where stylolites develop, removal of rock thicknesses take place of an amount at least equal to the length of the columns (Stockdale, 1926). Stockdale suggested that since the column ends may have been attacked by solution, thus having their growth in length retarded, one is led to suspect greater thinning than is indicated by the actual length of the individual stylolites. From measurements of the number of stylolite seams, average length of the stylolite columns, and the minimum loss by solution along each seam, Stockdale calculated the total minimum loss and percentages of approximate minimum loss by solution of several different units. Following this type of calculation, Stockdale made a "safe" estimate that at least five percent of the Columbus Limestone (Devonian) had been removed by solution.

A Petrographic Study of Stylolites

In an attempt to clarify the problem of stylolite genesis, Brown (1959) made an analysis of authigenic quartz crystals associated with stylolites of Carboniferous limestone from North Wales. With the aid of the petrographic microscope, he hoped to determine the degree of preferrred orientation of the quartz along the stylolites and measure the attitudes of the [0001] axes. He found that the authigenic quartz grains, 50-500 microns in size, were concentrated along the stylolite seam, particularly at the tops of the stylolite columns. These grains were almost perfectly euhedral, many showed a small nucleus of detrital quartz around which the crystals grew, and many contained relic inclusions of calcite, all of which indicated that the quartz indeed was authigenic in origin. This quartz developed at the expense of the limestone groundmass. Brown also found a lower concentration, and a random orientation, of the quartz grains in the limestone matrix. In contrast, on sections cut perpendicular to bedding and parallel to the stylolite columns, most of the [0001] axes were parallel to the direction of the sides of the columns. At the tops of the columns, the vast majority of the [0001] axes were parallel to the column tops - at right angles to those on the limbs (Figure 12). These facts suggest that at least some, if not all, stylolites develop by the pressure-solution mechanism supported by Stockdale (Brown, 1959). Brown concluded that there must have been solution and crystallization along the stylolite in order for the authigenic quartz to develop. This chemical solution allowed concentration of detrital quartz along the stylolite with the

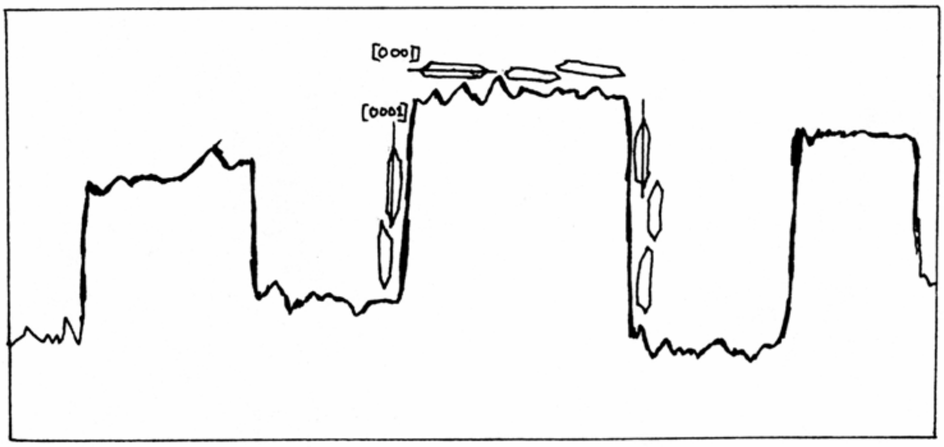

figure 12.— orientation of authigenic quartz along stylolite column.

authigenic quartz occuring as enlargements of the detrital grains. According to Brown, some directive force must have been involved during crystal growth in order to achieve a preferred orientation of the crystals. The quartz shows the greatest degree of orientation along the flat tops and bottoms of the columns - perpendicular to the direction of the greatest compressive stress resulting from the weight of overburden. Brown conclusively states that since the authigenic grains represent a post-induration process, stylolites develop after rock induration.

Dunnington, in 1954, presented some interesting evidence defending stylolite development post-dating rock induration. He looked at the observations of Shaub (1949) - "proving origin of some North American stylolites prior to consolidation" and pronounced these as inconclusive. In response to Shaub's "keystone offset", which Shaub concluded formed by plastic deformation in unconsolidated sediment, (figure 8) Dunnington claims that this offset is perhaps a double step structure where the seam abandons one horizonntal plane for another. Such step structures are indeed quite common along stylolite seams. The connection between the two horizontal planes is commonly via a vertical plane, scoured by vertical grooves or slickensides (Dunnington, 1954). Another possibility is that Shaub neglected to take into consideration a third spacial dimension. Perhaps the keystone offset was "produced" by an oblique section cut through a normal column. Dunnington suggests that random orientations of planes through normal stylolites can produce "anomalous" traces and forms, such as keystone offsets and curved seams, that one would not expect to be produced by the processes of pressure-solution in lithified rock.

Stylolites in Sandstone, Gypsum, and Quartzite

Although the vast majority of stylolites occur in calcareous rocks, stylolites have been observed in sandstone, quartzite, and gypsum. Small, lesser developed, but morphologically typical stylolites were described by Price (1934) from the Pottsville Sandstone (Pennsylvanian) and White Medina Sandstone (Silurian) of West Virginia. Both of these sandstones are particularly pure, containing over 95% silica. No residue other than quartz and small amounts of iron-oxide were observed along the stylolite structures. Stockdale (1936) found irrefutable, perfectly formed stylolites, up to one inch in length, in quartzite boulders near Breckenridge, Colorado. Even more impressive was Stockdale's discovery of stylolites in mildly-metamorphosed, tilted quartzitic sandstone beds in place at the Cumberland Escarpment, in Eastern Tennessee. These stylolites, which had columns averaging one inch in length with striated sides and a typical clay cap, provided valuable evidence of development at a time after metamorphism took place. Because of it's relatively high solubility one would expect to find many stylolites in gypsum, but in fact such is a rare occurrence. Stockdale did find some small-scale (1/4-1/2 inch columns) irregular closely-spaced mainly pointed or tapered stylolites in Permian gypsum beds at West Amarillo Creek, Texas. Although sandstone and quartzite are among the least soluble rocks, Stockdale claims that the pressure-solution theory satisfies the problem of stylolite origin in these rocks. When one considers the time over which the processes operate, and the pressure involved, some solution of quartz could readily take place. On the other hand, Stockdale states that the rarity of stylolites in such rocks refutes Shaub's pressure theory. If the pressure theory is correct, one should commonly find stylolites in non-calcareous rocks because no solution is involved. In fact, part of the quartz cement in sandstones that contain stylolites can be attributed to solution of quartz along the stylolite followed by precipitation in the adjacent sandstone from interstitial water percolating through the rock (Fuchtbauer, 1978). A study of cementation in the Simpson and St. Peter Sandstones by Heald (1956) resulted in the conclusion that pressure solution at grain contacts has modified grain shapes and reduced porosity. The amount of pressure solution appears to be sufficient to account for most of the secondary quartz in particular samples of sandstone.

Wanless (1979)included stylolites in a general scheme of limestone responses to pressure solution. He stated that stylolites are only one of the possible end products in the spectrum of limestone stress (figure 13). Wanless

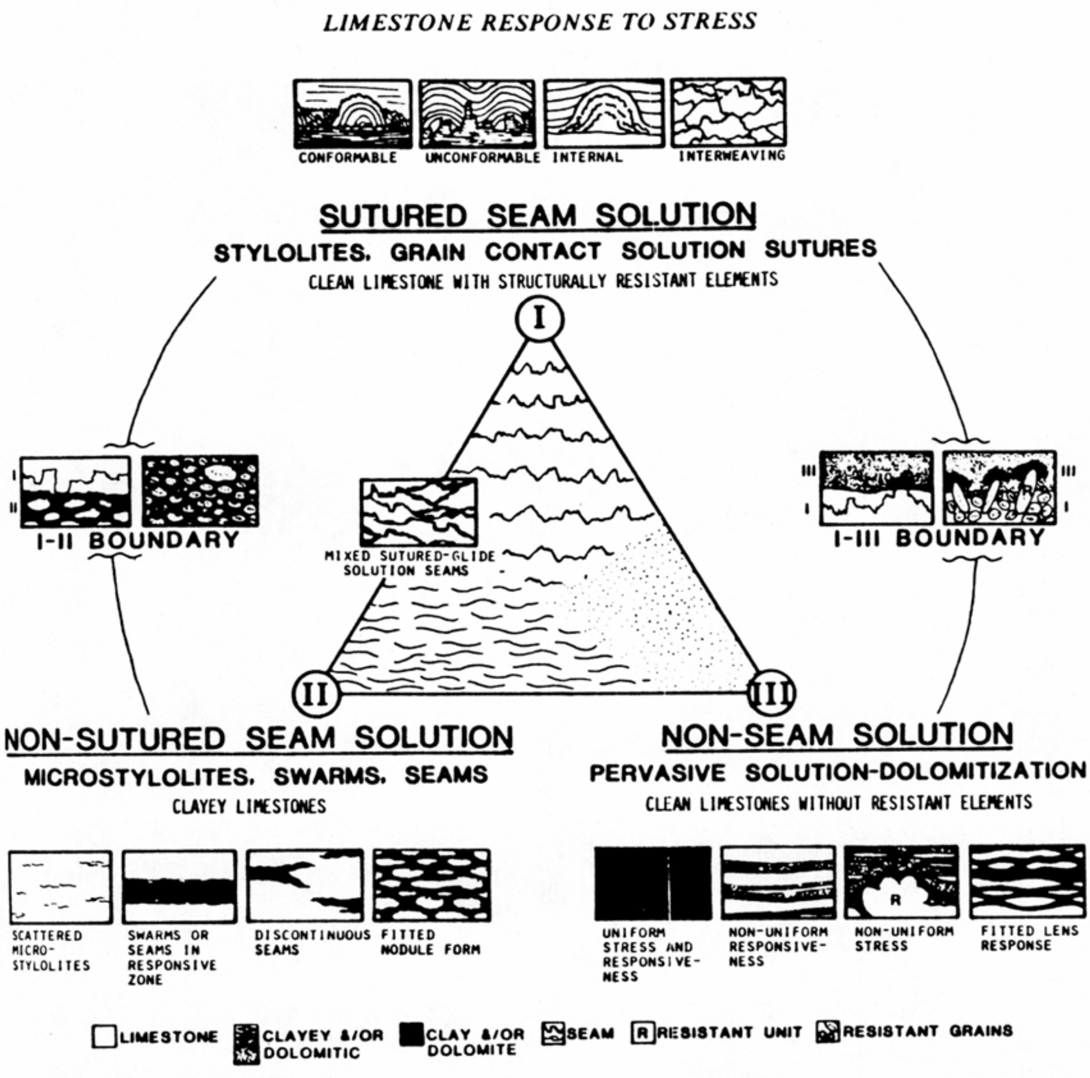

FIG. 13.—Summary diagram of characteristics of and controls on pressure solution types with sketch examples. *Clean* means without significant clay or platy silt. (from: Wanless, 1979)

proposed that there are two impurities that have a fundamental influence on limestone responses to stress. The first of these are fine platy insoluble minerals that can form surfaces or zones of structural weakness, if they are concentrated by pressure solution, along which lateral motion can occur to relieve local stress anomalies. The second of these are magnesium ions, which can lead to formation of dolomite within the limestone. Based on the kind and amount of impurities, as well as other lithological characteristics, Wanless recognized three possible types of responses.

The first of these, which includes stylolites, he termed "suture-seam solution". This type of response occurs within or at the boundary between limestone units that have structural resistance to stress and contain relatively little clay or silt. The slightly greater or lesser resistance to stress of the adjacent units causes the irregularities observed along stylolite seams. Because structrual resistance to stress is seen as a prerequisite to stylolite formation, Wanless claims that stylolites should be most common in units containing skeletal and non-skeletal grains, grain supported beds, large biogenic structures, or those involving early cementation. He proposes that stylolites can occur in fine-grained limestone only when it contains very small amounts of clay minerals. The end product of "sutured-seam solution" is a mass of insoluble residue, concentrated along distinct surfaces, with the surrounding portions being unaffected.

A second possible type of response is called "non-suture seam solution". This occurs in limestone that contains more than ten percent clay or silt. Included in ths category are microstylolites: very thin, undulating but not sutured, surfaces with relief between 20 and 40 microns, along which fine silici-clastic clay and platy minerals occur as films. Microstylolites tend to occur in interconnected swarms and are commonly associated with, and perhaps the producer of, nodular limestone. The higher concentrations of silt and clay tend to choke off the microstylolite seams as a pathway for fluid migration and removal of dissolved carbonate so they eventually become inactive - preventing development of "full grown" stylolites.

The third possible type of response envisioned by Wanless is called "non-seam" or "pervasive" pressure solution. This occurs in limestone with little structural resistance to stress and relatively low clay content. Solution takes place in zones rather than along a particualr surface or seam. If magnesium is available, pervasive solution commonly involves dolomitization of the limestone resulting in formation of interweaving of limestone and dolomite zones. This can produce a distortion of primary sedimentary structures and create secondary structures such as laminated dolomite and "ribbon" structures.

Stylolites and Oil Migration - Accumulation

Ramsden (1952) and Dunnington (1954) considered the influence of stylolites on subsurface fluid movement involved in oil migration and accumulation. They noted that if development of stylolites involves a removal and net compaction of material as much as 40%, as Stockdale suggested, then 40% of the contained fluids must also be released by lateral migration. Dunnington suggests that the pressures involved with stylolite formation can produce ideally localized forces adequate to expel the contained fluids, impelling them up-dip. On the other hand, some of the calcium carbonate and other materials that are dissolved during stylolite formation must leave the stylolite seam and be precipitated in adjacent pore spaces resulting in an decrease of porosity/permeability which prevents oil migration. Thus, in certain cases, by preventing oil migration, stylolites may preserve early oil accumulations in place. In fact, economic accumulations of oil in limestone are very common either in fractured rocks or in notably stylolitic rocks (Ramsden, 1952). Stylolites may be more than an unimportant geologic curiosity. They may play a major role in intiating or preserving oil accumulations in limestone.

Stylolites as Paleo-stress Indicators

A fairly recent development in the study of stylolites is their use as paleo-stress indicators. Where tectonic compression is greater than overburden compression stylolites will form parallel to the tectonic compression, possibly at large angles to primary layering. These tectonic stylolites are referred to as "horizontal stylolites" because the columns develop in a horizontal direction due to horizontal compression. Buchner (1981) utilized these stylolites in a discussion of the formation of the Rhinegraben. Data on paleo-stress patterns were obtained by determination of the average bearing of the axes of horizontal stylolite columns, which corresponds to the average direction of maximum compessive stress at the time of their origin (Buchner, 1981). He recognized two major sets of seams in the Rhinegraben, with differing orientations, indicating two different regimes of horizontal compression. The earlier set was found to be superimposed by and interrupted by the later formed set. In this way he was able to determine relative age relationships between the two generations of compression. Perhaps stylolites shall prove to be useful in obtaining paleo-stress patterns in other areas as well.

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