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STYLOLITES: THEIR NATURE AND ORIGIN. By PARIS B. STOCKDALE, Instructor in Geology, Ohio State University.

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By PARIS B. STOCKDALE, Instructor in Geology, Ohio State University.

Submitted in partial fulfilment of the requirements for the degree Master of Arts at Indiana University, 1921.

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Preface

THE principal reasons for the preparation of this study are: (1) to present a thoro review of the work which has been done by both American and foreign investigators on the study of stylolites; (2) to present for the first time a detailed discussion of the stylolites of the Indiana limestones, especially those found in the well-known commercial stone, the Salem limestone (known by the trade name, Bedford, or Indiana Oölitic limestone); (3) to present evidence which conclusively establishes the origin of stylolites.

The writer wishes to express his obligations and thanks to the following persons: Professor E. R. Cumings, of the Department of Geology, Indiana University; Professor H. F. Cleland, of the Department of Geology, Williams College; Professors Clyde A. Malott and W. N. Logan, of the Department of Geology, Indiana University; and Professor J. Ernest Carman, of the Department of Geology, Ohio State University.

Stylolites: Their Nature and Origin

A Study with Special Reference to Their Occurrence in Indiana Limestones

By PARIS B. STOCKDALE, *Instructor in Geology, Ohio State University*

Part I. Introduction

THERE are few of the minor, yet important, geologic phenomena whose explanation has been as unsatisfactory and under as much controversy as that of stylolites. They have been observed and described since the middle of the eighteenth century; yet today their manner of origin is held in doubt by many scientists.

GENERAL CHARACTERISTICS OF STYLOLITES

Stylolites consist of a series of alternating, interpenetrating columns of stone which form an irregular, interlocked parting or suture in rock strata (see Figs. 1, 2, 3, and 15). In their most common occurrence they are found along the bedding or lamination planes of limestone, resulting in an intricate interteething of the rock by the alternating downward and upward projection of the columns of one layer into the opposite. The length of these columns varies from a small fraction of an inch to a foot or more. The width is as variable as the length. Oftentimes the union of the stone at a stylolite-parting is so firm that the rock will split more readily elsewhere than along this jagged suture. Where this parting is cut across, as in the wall of a quarry, it presents a rough, jagged line (see Figs. 3, 15, and 26). To such a line the terms "stylolite-seam" or "stylolite-line" may well be given. Because of the intricate interlocking of the columns, these lines have been compared by Vanuxem (1838, p. 271)[1] to the sutures of the human skull (see Fig. 16).

[1] Reference to literature will be made by giving the name of the writer, date of publication, and page. The title of the paper and name of the publication can be obtained by consulting the bibliography.

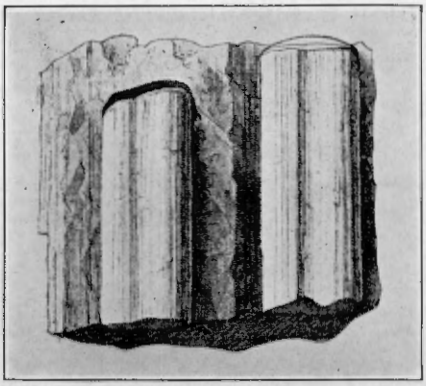

FIG. 1.—Stylolites in the Muschelkalk, showing striated side-surfaces and clay caps. From Rüdersdorf, near Berlin. Original in Marburg Museum. (From Kayser's Lehrbuch der Geologie.)

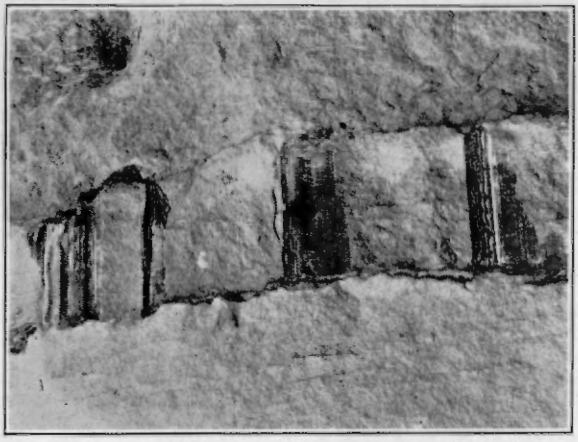

FIG. 2.—Large, perfectly formed stylolites of the Salem limestone. Note the slickensided side-surfaces and the clay caps of the columns. One-sixth natural size. From a quarry of the Consolidated Stone Company, Dark Hollow district, Lawrence County, Ind.

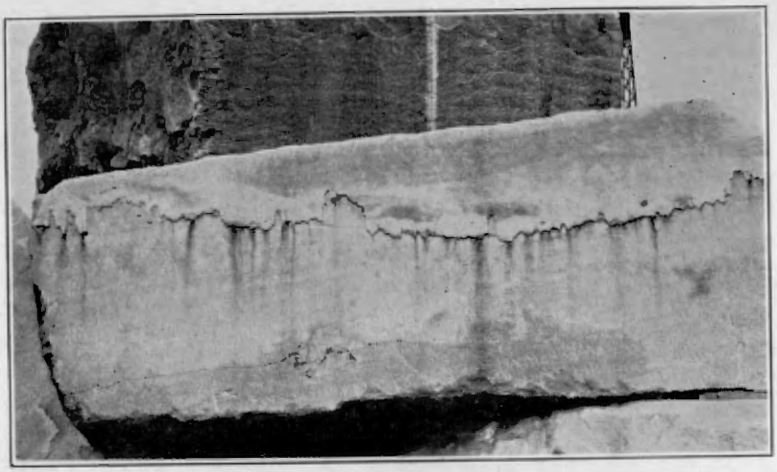

FIG. 3.—Typical, jagged stylolite-seam in the Salem limestone. From a quarry of the Consolidated Stone Company, Dark Hollow district, Lawrence County, Ind.

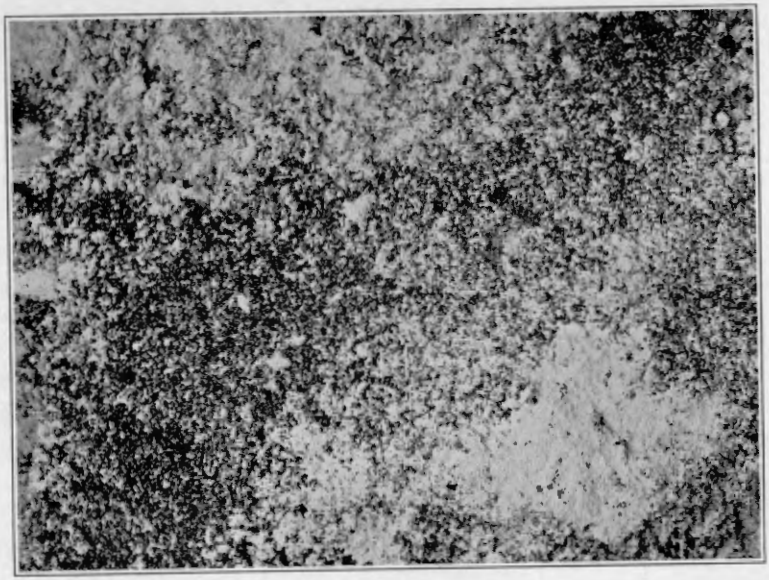

FIG. 4.—Small stylolite-surface in the Salem limestone, showing the characteristic roughness which, in itself, has the physical appearance of solution. The white portions are broken-off stylolites; the black, residual clay.

Where the stone has been split along a stylolite-parting, an extremely irregular, pinnacled surface is presented (see Figs. 4, 5, and 6). The term "stylolite-surface" might well be applied to such. The term "stylolite" (from the Greek στυλος meaning "column") applies to each individual, penetrating column. Thus it is seen that a stylolite-seam is made up of many stylolites whose direction of penetration, with few exceptions, is at right angles to it.

Stylolites are always characterized by two principal features:

1. An ever-present clay cap which comes to rest at the end (see Figs. 1, 2, 6, 11, and 26).
2. Parallel fluting, or striations, on the sides (see Figs. 1, 2, 5, 11, and 34).

The clay cap is usually thin, varying in thickness with the length of the stylolite and the composition of the stone. The caps of very small stylolites are mere films; those of long stylolites are sometimes as much as one-half inch or more in thickness. The stylolites of impure limestones and dolomites bear thicker caps than those of purer stone. The color of the cap varies usually from brown to black.

The fluting on the sides of stylolites often resembles the slickensides of fault planes. These striations are parallel with the direction of the penetration of the stylolites. The sides of the columns are usually slightly discolored with a thin film of clay. The sides often converge, but are commonly parallel, or nearly so.

Downward-penetrating stylolites are projections of the overlying stratum and show the same lithologic characteristics; while upward-penetrating stylolites bear the same relationships with the underlying stratum (see Fig. 26). The rock strata above and below a stylolite-seam appear undisturbed.

Stylolite-seams usually begin as a barely noticeable, smooth crevice or suture, grading from a slightly undulating seam into a finely toothed crevice—the teeth gradually increasing in size until typical stylolites appear (see Fig. 16). The stylolite-seam at both ends grades out into a fine suture which gradually disappears in the hard rock. The length of stylolite-seams varies from a few feet to several rods. Thus, stylolite-

FIG. 5.—Block of Salem limestone split along a large stylolite-seam. Note the slickensided side-surfaces of the exposed columns (marked by the ruler).

partings are sometimes several square rods in area. Some partings are so small, however, as to have an area of only a few square feet. Single, isolated stylolites are never found. They occur only as a series of alternating columns making up a stylolite-parting.

Stylolite-seams run most commonly in a horizontal direction, or nearly so, and parallel with the lines of stratification. Occasionally they have been observed running obliquely and even perpendicularly (see Fig. 17). They are also known to

FIG. 6.—Stylolite-surface in the Mitchell limestone, showing the thin deposit of black residual clay. The white spaces result from broken-off stylolites, and show the irregular outline of the columns.

cross one another. The chief characteristics of the stylolites are the same regardless of the direction of the seam.

Stylolite-partings are often very numerous and close together (see Figs. 16 and 32). In a single, thin stratum, there have been observed as many as a dozen or more lying directly one above the other with only a few inches of stone separating them. They have also been observed to lie one upon another and even to penetrate one another. In some stylolite-bearing strata, however, the partings are very rare and far apart.

GEOLOGIC DISTRIBUTION OF STYLOLITES

Stylolites are found in several geologic formations thruout different parts of the world. In Europe their most extensive development is probably to be found in the Muschelkalk (Triassic)[2] of Germany. In America their occurrence is especially noticeable in the Mississippian limestones of Indiana, the Niagaran limestones[3] of New York, and the Ordovician marbles (Holston formation)[4] of Tennessee. Their presence, however, is by no means limited to the above-mentioned geologic strata. The Indiana limestones offer examples of the largest and best-developed stylolites in America.

The Muschelkalk of Germany probably presents the most complex stylolitic structures known. The American limestones, as a whole, show less complicated stylolites. The Tennessee marbles, however, exhibit many complexities.

An important conclusion derived from a study of the geologic distribution of stylolites is that they are present only in carbonate rocks—varieties of limestones, dolomites, and marbles. Their occurrence has *not* been observed (1) in clastic rocks—conglomerates, sandstones, and shales (with the possible exception of highly calcareous sandstones and shales, in which the percentage of soluble carbonates is extremely high); (2) in igneous rocks; (3) or in metamorphic rocks other than carbonate types.

EARLIEST OBSERVATIONS OF STYLOLITES AND TERMS APPLIED TO THEM

The earliest mention of stylolites appears to have been made by Mylius, in 1751, who described them as "Schwielen" and spoke of them as resembling "versteinert Holz". Freiesleben, in 1807, spoke of the phenomenon as "zapfenförmige Struktur der Flözkalksteine", and Hausmann later referred to it as "Stängelkalk".

[2] The most extensive paper treating of the stylolites of the Muschelkalk is that of Wagner (1913, pp. 101-128). Other late writers are Fuchs (1894, pp. 673-688), Gümbel (1882, p. 642; 1888, p. 187), Reis (1901, pp. 62-92; 1902, p. 157), Rothpletz (1900, pp. 3-32).

[3] A detailed discussion of the stylolites of American geologic formations has never been written. Earliest observations were made in the Niagaran limestones of New York. They have been described by Eaton (1824, p. 134), Bonnycastle (1831, p. 74), Vauuxem (1838, p. 271; 1842, pp. 107-109), Emmons (1842, p. 111), Hall (1843, pp. 95, 96, 130, 131), Marsh (1867, pp. 135-143).

[4] The most recent paper upon the stylolites of the Tennessee marbles is that of Gordon (1918, pp. 561-569). This discussion is very brief and not detailed.

The first mention of stylolites in America was made by Eaton (1824, p. 134), who, considering the structures to be of organic origin, named them "lignilites". Vanuxem (1838, p. 271), ascribing to stylolites an origin due to the crystallization of Epsom salts, gave them the name "epsomites". The terms given by Eaton and Vanuxem were used for some time. Hunt (1863, p. 632), accepting the explanation given by Vanuxem, used the term "crystallites". Stylolite-seams are popularly spoken of by quarrymen of the Indiana limestone districts as "crow-feet" or "toe-nails" (Hopkins, 1897, p. 142; Hopkins and Siebenthal, 1897, p. 305).

The above-mentioned terms are not used by scientists of today because they imply an origin which has not been confirmed. The term "stylolite" was given by Klöden (1828, p. 28) who thought the structure to be a distinct species of organism under the name of "Stylolithes sulcatus" (from the Greek στυλος, meaning "column"). Klöden's term is now generally accepted because it suggests a meaning descriptive of the phenomenon.

The two German terms "Drucksuturen" (pressure-sutures) and "Stylolithen" are used by some scientists as referring to analogous structures, and by others as referring to different, but similar, phenomena. A detailed discussion of this is taken up in the following chapter.

Part II. Review of Previous Investigations

EVER since stylolites were first mentioned the question of their nature and origin has been under controversy. Numerous investigations of them have been made, and several theories of their origin have been presented. The most exhaustive and conclusive studies have been made by German scientists. Publications by American observers have been few and are less satisfactory. The writer wishes to present a complete summary of the investigations of both American and foreign writers on the question of stylolitic phenomena.

PHENOMENA SIMILAR OR ANALOGOUS TO STYLOLITES

A review of previous studies made of stylolites necessitates a consideration of at least two phenomena whose nature, origin, and relation to stylolites have been under discussion. These are the phenomena of the so-called "Drucksuturen" (pressure-sutures) and "Gerölleindrücke" (impressed, or pitted, pebbles). Some observers have suggested that the origin of the often-noticed "cone-in-cone" structures may be related to that of stylolites.

1. "Drucksuturen"

The term "Drucksuturen" has been commonly used by German scientists as applying to the irregular, finely serrated, jagged lines, or sutures, common to many thick limestones and dolomites of Germany, and which in America are especially characteristic of the Tennessee marble. These veins are brown, red, black, or gray in color, depending in part upon the color of the rock containing them. Their course is usually irregular; so that they often bear an especially close resemblance to the sutures of the human cranium (see Fig. 16). The distinction between "Drucksuturen" and "Stylolithen" has been made by many German scientists, especially Rothpletz (1900, pp. 3-32), as follows: the individual, interlocking serrations of "Drucksuturen" are short in length, usually not more than one-half to three-fourths of an inch, giving a fine, narrow vein; the interlocked parts, instead of

being distinctly columnar in form with parallel sides, as are stylolites, are often more or less conically pointed (see Figs. 14 and 16). As in the case of stylolites, "Drucksuturen" are characterized by the ever-present clay partings (oftentimes only minutely visible) and the finely striated side-surfaces of the interpenetrated parts. The primary distinction, therefore, between "Drucksuturen" and stylolites, is one of size.

Many early investigators held "Drucksuturen" and stylolites to be of different origin. The latest to distinguish sharply between the two was Rothpletz (1894, 1900). In his most recent discussion he arrived at the conclusion that "Drucksuturen" and "Stylolithen" are "morphologically and genetically" quite different—the first is the result of rock pressure and solution in the hardened limestone mass; the second, the result of the pressure of the overlying sediments in a plastic, unhardened limestone deposit. The associated clay film of the "Drucksuturen", according to Rothpletz, is the solution residue of the dissolved lime mass. Rothpletz came to this conclusion after a careful study of the fossils found with the phenomena, which showed distinct signs of corrosion. Examples of fossils which were partially removed, or entirely penetrated by the teeth of the "Drucksuturen" were observed.[1]

The most recent investigators, especially Fuchs, Reis, and Wagner, hold "Drucksuturen" and "Stylolithen" to be analogous phenomena, and do not accept the distinction made by Rothpletz. They attribute to both phenomena the same origin and consider "Drucksuturen" merely as "young" stylolites—the beginnings of typical stylolite-seams.

2. "Gerölleindrücke" (Impressed, or Pitted, Pebbles)

Occurring in conglomerates of various geologic ages are found pebbles marked with depressions, or pittings, the origin of which probably has a bearing upon that of stylolites. These impressions are of two principal kinds: (*a*) one which bears evidence that it was produced by the squeeze, or pressure, of the contacting pebble, since the impressed pebble is highly fractured, the fractures radiating from the center of the pitting (see Fig. 7); (*b*) the second, a smooth, sharp type of pitting, which was apparently formed from the actual hollowing out and removal of the material formerly

[1] The work of Rothpletz on "Drucksuturen" is carefully reviewed by Wagner (1913, pp. 102, 103, 109). A discussion of Rothpletz's theory as to the origin of the so-called "Stylolithen" is taken up later, under the heading "Pressure Theory", p. 28.

occupying the depression (see Fig. 8). Pebbles bearing this type of indentation are usually not distorted or fractured. Some impressions, however, appear to be a gradation between, or combination of, the two above-mentioned types. The principal theories of their origin are two in number: (1) that

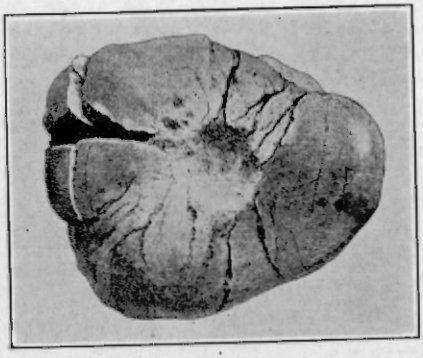

FIG. 7.—Fractured type of impressed pebble from the Karbon-formation. Original in Marburg Museum. (From Kayser's Lehrbuch der Geologie.)

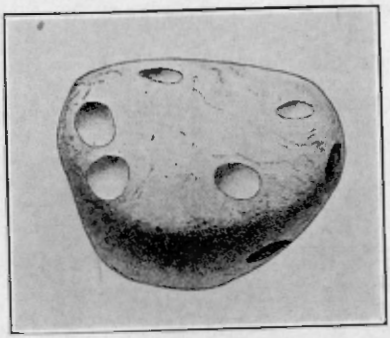

FIG. 8.—Solution type of impressed pebble from the Nagelfluh. (From Kayser's Lehrbuch der Geologie.)

they are a result of a mechanical force; (2) that they are a result of chemical action—the solution of the one pebble at the point of contact of the other. Some investigators believe the feature to have resulted while the pebbles were in a plastic, or semi-plastic state.[2]

[2] Early suggestions of this "plastic theory" were made by Hitchcock: Geology of Vermont, I, p. 28; Proc. Bost. Soc. Nat. Hist., VII, pp. 209, 353; XVIII, p. 97; XV, p. 1; XX, p. 313; Amer. Jour. Sci., 2d Series, XXXI, p. 372.

GEOLOGIC OCCURRENCE. The conglomerates which have attracted particular attention because of the occurrence of impressed pebbles are: the Nagelfluh (Tertiary) of Germany; the Devonian conglomerate of Scaumenac Bay, Province of Quebec; the Quaco conglomerate, of Quaco, N.B.; and the Bunter conglomerate (Triassic) of England. The occurrence of impressed pebbles, however, is by no means limited to the above-named formations. The most extensive studies of the phenomenon have been made in the Nagelfluh by German investigators.

PREVIOUS INVESTIGATIONS AND THEORIES OF ORIGIN. The first to mention impressed pebbles appears to have been A. Escher v. d. Linth, who, in 1833, described those of the Nagelfluh. Von Dechen, as early as 1849, discussed their presence in the Buntsandstein. The solution theory of their origin was first suggested by Sorby (1863, p. 801). His views may be summarized as follows: The impressions are formed, not so much by a mechanical hollowing out, as by chemical solution. Pressure creates heat, which in turn increases the possibility of greater solution. Thus, at the point where two pebbles are pressed against each other, active solution and removal of mineral matter takes place. Continued pressure results in continued solution and a consequent deepening of the depression. Sorby's explanation was confirmed experimentally by Daubrée.

The most exhaustive study of impressed pebbles of the Nagelfluh was made by Rothpletz (1879, 1880). His results show a special connection with the origin of stylolites. He pointed out the occurrence of two limestone pebbles impressed into one another, in which the contact, instead of being marked by a sharp line, showed a minute, jagged interteething of the two stones (see Figs. 9 and 10). Since the pebbles were of different colors, the alternating interlocking of the minute teeth was easily discernible. The teeth were covered by a thin coating of iron stain. Rothpletz (1880, pp. 191-192), accepting Sorby's theory, summarized his explanation as follows:

> While in general the one pebble received, at the point of contact of the other, an impression as a result of the solution of the lime by carbonic acid, yet, certain places withstand this solution better than others so that such places penetrate the opposite sides as pointed projections, thereby forming a sort of teething between the two pebbles.

This phenomenon, Rothpletz pointed out in his later papers (1894, 1900), is analogous to that of "Drucksuturen", even in the smallest details. However, he distinguished sharply between "Drucksuturen" and stylolites (see p. 16).

After a careful study of the pitted pebbles of the Bunter conglomerate of England, Reade (1895, pp. 341-345, pl. XI)

FIG. 9.—Diagram of the contact of two impressed limestone pebbles, showing the minute interteething. Four times natural size. See Fig. 10. (After Rothpletz.)

FIG. 10—Enlargement, 50 diameters, of the intertoothed contact of two impressed limestone pebbles, Fig. 9. (After Rothpletz.)

gave a complete summary of the evidence pointing to the theory that the "pitted pebbles are the result of contact-solution, the water being retained at these spots by capillary attraction". His most important points follow:

> If the pittings or depressions were due to mechanical pressure, the material of the pebble which was "indented" would show signs of distortion. This it never does in any of the pebbles I have examined. A reference to the photograph (pl. XI) will show this clearly. . . . The material formerly occupying the depression has been removed, not displaced.

Out of six pebbles examined only one showed signs of fracture.

It is quite evident that the "fractures" are simply joints, such as may be found in many pebbles. . . . Fractures are a sign that the material of the pebble is rigid, and that it cannot be squeezed out of shape. Their existence is, to a certain extent, evidence against the mechanical theory.

The indenting pebbles perfectly fit the indents of the pebbles. If the indents were the result of mechanical movement this would not be likely to happen in all cases. . . . When the indenting pebbles are removed the cup, or depression, is seen to be smooth, frequently having a deposit of silica over the surface (the pebbles were quartzite), sometimes one of iron.

The pittings are, in the more marked cases before me, principally confined to one side and the edges of the pebbles. The opposite side often has adherent somewhat loosely cemented sand and small pebbles. I take this, which is on the flattest side, to be the bed of the pebbles, and the pitted surface to be the top surface. Why should this be the case on the mechanical assumption?

This writer showed that the maximum amount of static pressure at any time on the Bunter rocks would not have been sufficient to crush or disturb the pebbles of the conglomerate. There is practically no evidence of lateral pressure in the locality.

But we have positive evidence that at the points of contact of the pebbles solution and deposit have been going on. In most of the depressions there is a deposit of silica which smooths the surface of the depression and unites the grains of the rock. In some places where a joint or crack traverses the depression, the silica fills it up. The grains of silica, where they are seen in the depressions of true quartzite pebbles, show like a mosaic, and appear to be flattened or cut off on their upper surface. I think it extremely probable that solution and deposit have gone on alternately. The solution of the silica has taken place, there is evidence on all hands, including the adherent sand and gravel, for solution must precede deposit. Solvent action would concentrate itself on the continually damp spots, and these are the points of contact of the pebbles, especially on the upper surface of the larger pebbles.

Gresley (1895, p. 239), in a letter to the Geological Magazine, described an indented pebble of the Bunter conglomerate, which he claimed bore unmistakable evidence that the impressions were produced by squeeze and pressure, inasmuch as the pebble was not only severely fractured into four or five pieces, but was also minutely faulted. The lines of fracture radiated from typical indentations upon opposite sides of the pebble.

In a paper read before the Geological Society of America, J. M. Clarke (1915, p. 60) discussed the deformation of pebbles of the Devonian conglomerate of the Scaumenac Bay region, and suggested that the solution theory of Sorby is inadequate and that the "effects described are in a large part actually due to forcible contact resulting from internal friction".

CONCLUSIONS. The controversy over the origin of impressed pebbles may lie in the fact that the indentations discussed are of at least two kinds, each of which may have a distinct origin. The fractured and distorted type of pebbles shows evidence of having been subjected to the pressure and squeeze of one another, and the origin of the impressions may be, for the most part, a mechanical one. However, the sharp, smooth impressions of the non-distorted, non-fractured type of pebble are undoubtedly of chemical origin—a result of the solution of one pebble at the point of contact of the other. Sufficient evidence in support of this theory has been produced by Sorby, Daubrée, Heim, Rothpletz, and Reade. The theory is accepted by Fuchs, Reis, Wagner, Kayser, and Geikie.

THEORIES OF THE ORIGIN OF STYLOLITES

1. Theories Regarded as Unestablished

The earliest theories of the origin of stylolites were quite hypothetical and had little evidence in their support. Most of them are today entirely rejected; a few have a slight following. The following is a grouping of the theories, with their principal advocates, which today are regarded as unestablished:

a. Organism Theory
- Eaton, 1824
- Klöden, 1828
- Leube, 1850
- Quenstedt

b. Crystallization Theory
- Bonnycastle, 1831
- Vanuxem, 1838, 1842
- Emmons, 1842
- Hall, 1843
- Rossmässler and Cotta, 1846
- Meyer, 1862
- Hunt, 1863

c. Erosion Theory
Plieninger, 1852
Quenstedt, 1853
Weiss, 1868
Hopkins, 1897
Rinne, 1905

d. Gas Theory
Zelger, 1870
Potonié, 1910

e. Bitumen Theory
Alberti, 1858

ORGANISM THEORY. Among the earliest observers to propose an organic origin for stylolites was Eaton (1824, p. 134), who believed the columns to be fossil corals, and proposed for them the name "lignilites". Klöden (1828, p. 28), in observing the structures in the Muschelkalk at Rüdersdorf, regarded the feature as a fossil, and, altho in doubt as to the nature of the animal, proposed for it the name "Stylolithes sulcatus". In 1834 Klöden discussed their origin in more detail but found few followers. Leube (1850, p. 141) described stylolites as an animal with "kopfähnlicher Formation und anhängenden Saugorganen".

Of the many early investigators of stylolites, Quenstedt was one who changed his ideas several times. He at first suggested that the structures were due to the filling up of hollow spaces, or holes, made in the soft slime by the upward movement of mussel shells. Plieninger, in 1852, strongly refuted this theory.

CRYSTALLIZATION THEORY. This theory had its principal support among American investigators. The first to suggest the origin of stylolites as resulting from mineral crystallization was Bonnycastle (1831, p. 74). Basing his theory upon observations in the Niagaran and Trenton limestones, he regarded the structures as a "new mineral due to infiltration" and suggested that the "yellowish coating" was probably "a new variety of shale, in which there is a good deal of iron".

Vanuxem (1838, p. 271; 1842, pp. 107-109) claimed to have solved the mystery of stylolites and suggested that they were due to the crystallization of sulfate of magnesia in soft sediment at the time the rocks were deposited. The salts, after having been subsequently removed by solution, left their

moulds in the sediments to be filled in by the succeeding layer. In his 1842 report Vanuxem states

> As their origin is due to sulfate of magnesia, for the sake of brevity they might be termed *epsomites*. The carbon which usually lines the cavities shows that the liquid which held the salt in solution contained bituminous matter.

Emmons (1842, p. 111) accepted the crystallization theory of Bonnycastle and Vanuxem, but suggested that, in some instances, strontium sulfate might have been the crystallizing agent. Hall (1843, p. 96) accepted the theory with modifications and suggested that the crystallization might in some cases have been due to carbonate of lime. Meyer (1862, p. 590), in support of the theory, proposed that gypsum might have been the agent of crystallization. He had detected columns coated with this substance.

Rossmässler and Cotta (1846, p. 128) compared stylolites with ice crystals (Eisstängeln) that form in the soil in winter and suggested a similar origin for both.

Hunt (1863, pp. 631-634), in describing the stylolites of the Trenton and Niagaran rocks, spoke of them as "crystallites" and proposed that in many cases sulfate of soda might have been crystallized instead of magnesium sulfate, as advocated by Vanuxem. He described examples "in which crystallites penetrate a mass of chert imbedded in the limestone" (Hunt, 1863, p. 633, Figs. 437 and 438).

EROSION THEORY. Plieninger (1852, p. 78) proposed an elaborate explanation of stylolites which, for some time, had quite a few followers. He suggested that the surface of the soft limestone ooze was first raised above water and, upon drying, was separated into blocks by shrinkage-cracks. Thru the action of rain, columns, protected by shells and other foreign substances, would result. After subsidence and further deposition of lime ooze, the whole would gradually become compact limestone with the enclosed stylolitic feature.

> The fact that rain, under certain circumstances, may produce columns very similar in form to Stylolites had already been noticed, and this was doubtless one reason why Plieninger's theory gained so many adherents (Marsh, 1867, p. 137).

Quenstedt (1853, p. 71), aided by Fallati, proposed a theory similar to the one of Plieninger in which he likened

stylolites to "earth pyramids" which owe their columnar structure to a small stone or shell protecting the underlying soil, while the surrounding earth is washed away (Hopkins and Siebenthal, 1897, p. 306). This idea of Quenstedt was accepted by Weiss (1868, p. 728), and received its most recent support by Rinne (1905, p. 186).

In making a study of the Salem limestone of Indiana, Hopkins (Hopkins and Siebenthal, 1897, pp. 305-308) concluded that in all cases stylolite-seams mark bedding or stratification planes in the rock. He suggested that quite probably all are not due to the same cause.

> Some look as though they were formed by cracks in the drying of the limestone mud, and others look like a rain or spray washed surface . . . and possibly the escape of gases, as advocated by Zelger, may have acted in some places.

GAS THEORY. The idea that escaping gases may have been a factor in the formation of stylolites was first suggested by Zelger (1870, p. 833). He considered the structures as due to "the escape of compressed gases through the soft plastic mass, and the later filling in of the passageways" (Hopkins and Siebenthal, 1897, pp. 306-307).

Zelger's theory had but few followers, one of whom was Potonié, who, in 1910, proposed that the organic substance of the slime, by further decomposition, created gas bubbles. If the gas would collect under a mussel shell in the lime ooze, then the shell would be shoved upward, and the cavity thus formed would be filled in from below, taking the form of a stylolite.

BITUMEN THEORY. Another and entirely different hypothesis as to the origin of stylolites was suggested by Alberti (1858, p. 292). Having observed the stylolites covered with a dark substance which he regarded as bitumen, he suggested that the columns were formed by drops of petroleum pushing their way upward in the rock which was yet in a soft, viscous state. The hardened petroleum would then serve as asphalt caps.

2. Two Principal Theories under Controversy

Two theories of the origin of stylolites have today a divided following among geologists. The first, the "Pressure Theory"—that stylolites are a result of the differential com-

pression of sediments while in the soft plastic state—has been offered several times with various modifications. The second, the "Solution Theory"—that stylolites are a result of differential chemical solution under pressure in hard rock—is the most recent explanation and today is generally held as most plausible, especially by recent German investigators. Because of lack of sufficient evidence in support of them, however, neither of these theories has received definite acceptance by American workers. The following is a grouping of the principal advocates of the two theories:

a. Pressure Theory
Quenstedt, 1837, 1861
Thurmann, 1857
Marsh, 1867
Gümbel, 1882, 1888
Rothpletz, 1900

b. Solution Theory
Fuchs, 1894
Reis, 1901, 1902
Wagner, 1913

PRESSURE THEORY. Quenstedt is the originator of the pressure theory, suggesting for the first time, in 1837, that stylolites may have resulted from compression of plastic sediment. After having changed his views in 1853, when he proposed a theory similar to the one of Plieninger, he went back to his original pressure idea, in 1861, and offered a rather elaborate explanation. He took the view that two beds of lime ooze overlying one another, separated by a layer of shells and a layer of clay, would be so compressed into one another that stylolites would result. The two beds, at the time of compression, would have different hardness because of the different times of their deposition (Quenstedt, 1861, p. 200).

Thurmann launched his pressure theory in 1857. He advocated the view that two lime layers lying one above the other, in a plastic state, would be differentially compressed into one another regardless of whether or not there were a clay layer between them. He also explained the "Gerölleindrücke" of the Nagelfluh (Tertiary) as a result of pressure while the pebbles were in a plastic state.

Pressure Theory of Marsh. Probably the most commonly accepted theory in America is that of Marsh (1867,

pp. 135-143), who advocated the view that stylolites were caused by a "slipping through vertical pressure of a part capped by a fossil against an adjoining part not so capped" while the rock was still in a plastic state. Marsh's theory is accepted by both Dana and Geikie in their textbooks.

Marsh made a study of the Niagaran limestones of New York, and published the most exhaustive work that has been done in America on the phenomenon. He presented the geologic conditions essential for stylolitic formation as follows:

> Let us first suppose a quantity of fine carbonate of lime . . . slowly deposited under water, and, while still soft, shells and other organic substances scattered over it, and the whole then covered with a very thin layer of argillaceous mud. If, after this, the deposition of calcareous matter proceeds, gradually forming a second bed, its increasing weight will slowly condense the bed below. The shells beneath the clay layer will offer more resistance to vertical pressure than the material around them, and hence the latter will be carried down more rapidly, thus leaving columns projected into the bed above, each protected by its covering, and taking its exact shape from its outline. . . .
>
> If the shell, instead of lying horizontal, as in the above instances, has an oblique position, curved columns will generally be formed, the curvature being towards the upper edge of the shell and its amount depending upon the degree of elevation. Where the rock is not homogeneous, bent or even broken columns often occur, evidently caused by meeting with impediments, just as a nail is turned from its course when driven against an obstacle. . . .
>
> The comparatively few stylolites extending from the upper layer of limestone into the lower are evidently formed essentially in the same way as those already described, though under somewhat different circumstances. Where the shape has been determined by a fossil, it will generally be found that this was deposited above the argillaceous layer rather than below it.

Important conclusions given by Marsh may be summarized as follows: (1) Stylolitic displacement took place in the rock before consolidation was completed. (2) Nearly all of the separate columns have on their summits a fossil shell which has accurately determined their shape. (3) When the columns stand at right angles to the stratification, they have been produced by vertical pressure resulting from the weight of the superincumbent strata. The comparatively few stylolite-seams which have different positions are due to lateral pressure. (4) The columns start from the junction of two beds of limestone, separated by a thin seam of argillaceous

shale, which, when later broken up, comes to rest as the clay caps at the ends of the stylolites. (5) The longer columns usually have the convex side of the shell uppermost; and the shorter ones, the reverse. When the shell lies obliquely on the column, the latter will, in most cases, be found curved, the degree of obliquity of the shell determining the amount of curvature.

Experiment of Gümbel. Believing, as did Quenstedt and Marsh, that stylolites are due to differential compression of sediments before consolidation, Gümbel (1882, p. 642) tried to prove his theory experimentally. In his explanation of stylolites, he placed the emphasis on the always-present clay cap at the ends of the columns. He suggested that they are always formed at the horizon of a clay or marl layer between two lime layers. By the drying out of this clay, cracks would be formed and the layer would be broken up. Pressure of the above, yet-plastic, lime ooze would force a portion of the broken clay parts to settle down into the underlying bed of plastic sediment, while another portion would be projected into the overlying bed.

In his experiment, Gümbel took a mass of plastic ooze, covered by a thin layer of clay, and placed over this a metal plate in which various shaped holes had been cut. Exertion of pressure upon this plate resulted in columns of the underlying plastic substance being pushed up thru the artificial holes of the plate. Continuing his experiment to prove his theory, Gümbel repeated the conditions; but, before exerting the pressure, covered the plate with another layer of plastic material. Upon application of pressure, columns of the mass below the plate were forced up into the overlying mass, and thus the figure of stylolites resulted.

Gümbel's experiment met strenuous objections from Rothpletz, Fuchs, Reis, and Wagner, who conclusively pointed out that it was insufficient to explain the origin of stylolites. Rothpletz showed that the physical basis of the experiment was not sound; that the clay cap took a rôle which it could not possibly play; that the clay layer, instead of being torn apart, would be compressed together by the weight of the superimposed layer. Gümbel's experiment and theory failed to explain the occurrence of horizontal stylolites and other complexities.

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Fuchs pointed out that the conditions of Gümbel's experiment were by no means similar to those of nature; that they were merely mechanical conditions; and that the power of the pressure was that of the experimentor, a thing external from that occurring in nature, and the experiment was thus not a result of a natural reaction. Fuchs raised the questions: "By what in nature would the all-important, stiff, metal plate be represented?" and "By what in nature would the necessary extra force of pressure be supplied?" He also insisted that had Gümbel, after placing the metal plate between the two layers of plastic material, left the experiment to itself, no columnar projections would have resulted, and the experiment, thus, would have been a failure.

Pressure Theory of Rothpletz. The most plausible pressure theory is the one offered by Rothpletz (1900, pp. 3-32), who suggested that the necessary differential compression of sediments to produce stylolites resulted from a differential and irregular hardening of the plastic mass brought about by the introduction of a cementing medium, at first unevenly distributed. Rothpletz's principal points may be summarized as follows:

1. Stylolites give no indications pointing to any sort of essential chemical activity. The fossils which often crown the columns are constantly preserved whole, as are those found in other portions of the limestone. There was no case observed (by Rothpletz) where the larger fossils of the stylolite-bands were considerably corroded.

2. The lime must have been spongy and plastic, and the lime grains must have been not entirely cemented. The formation of stylolites in compact, completely hardened lime is not possible.

3. If the mass of plastic material were of uniform hardness, and it were compressed together, the result of the compression would not be differential. However, if a hardening of portions of the lime ooze were brought about by the secretion of a cementing medium, then compression of the overlying mass would little affect these hardened (cemented) parts, and they would stand projected as columns, or pegs, into the above, yet-soft mass. The overlying sediment would sink down between the hardened portions, and the sides would be fluted, or striated, by the grains (of the cemented

columns), in the direction of the pressure. If a cemented portion, while being compressed into the above soft mass, should strike another partially consolidated part, then this compression would be lessened, thus explaining the differing lengths of stylolites of the same seam.

4. Since it is possible to have pressure exerted in directions other than vertical, stylolites may also form in an oblique, or even horizontal, direction. The clay and fossil caps, however, seem to be lacking in these types of stylolites.

Theoretically, Rothpletz's explanation sounds plausible. However, field observations furnish an abundance of evidence against it. This has been conclusively shown by Reis and Wagner, and is discussed later in this paper. Were one to accept his assumption that "stylolites give no indications pointing in any way to any essential chemical activity" his theory would stand with less objection. His statement that oblique and horizontal stylolites bear no clay caps is also at fault.

SOLUTION THEORY. The solution theory was first suggested by Fuchs (1894, pp. 673-688). It was more thoroly established by Reis, 1901-1902, and extensively reviewed and studied by Wagner, in 1913.

Investigations of Fuchs. After a careful study of stylolites, Fuchs came to the conclusion that (1) they are formed in hard rock by chemical solution, under pressure, along a crack or crevice; the differential ability of the rock to resist solution accounting for the interteething of the strata along the line of solution; (2) the clay cap is the non-soluble residue of the dissolved rock substance; (3) the polished and striated sides of the columns are a result of the movement which has taken place.

The first part of Fuchs' paper is devoted to a discussion of the pressure theory and the experiment of Gümbel (see p. 27). The most important conclusions from Fuchs' investigations may be summarized as follows:

1. Stylolites never appear singly, but always occur collectively, running in lines, forming the so-called "Stylolithenbänder".

2. Contrary to the former assumption that stylolites depend upon planes of stratification (all theories which were formerly postulated proceeded from this supposition which

was regarded, to a certain extent, as self-evident), it is found that stylolites are not confined to stratification planes, but are nothing more than a "highly modified form of crevice". Fuchs came to this conclusion after having observed stylolites which ran obliquely, and even horizontally, and stylolite-lines which even crossed one another at right angles.

3. Stylolites are not formed in soft, plastic sediment, but in already hardened stone.

4. The so-called "Drucksuturen", described by Rothpletz, are similar in all fundamental points to stylolite-seams and are only a special form of them.

5. If the limestone is fossiliferous, one can notice that fossils which border on to "Drucksuturen" appear broken off from them; and on the other side of the suture one will find no continuation. These missing portions of fossils have been actually removed by solution.

6. The clay coverings of the columns consist of the residue of the dissolved substance. The formation of the striated surfaces has resulted from the movement which has taken place.

7. From the study of the analogous phenomenon of "Gerölleindrücke", it appears that a

chemical solution process, which wears away the contact surfaces of certain substances, attacks only the one side and leaves the other apparently untouched.

8. In explaining the changing of a straight, smooth crevice into a jagged, intertoothed suture, by chemical solution, one should picture a crevice in a rock stratum, with the rock substance on each side divided into a number of parts; and assume that along this line one part above will be attacked at one place, and at another place, a part below will be attacked. Noticeable interteething must then take place, and a stylolite-band will result.

Investigations of Reis. In addition to corroborating the evidence given by Fuchs, Reis (1901, p. 62; 1902, p. 157), after an investigation of the stylolites of the Muschelkalk, contributed the following additional evidence in support of the solution theory:

1. The actual removal of the hard stone, into which the columns of the opposite side have penetrated, is evidenced especially by a study of the fossils and oölites associated with

stylolites. The fact that there occur fossils which have been partially dissolved away, or entirely cut thru by stylolite columns, without any evidence pointing to their having been mechanically disturbed from their original positions, is sufficient proof of this.

2. Horizontal and oblique stylolites possess the same marked characteristics as the common vertical ones; namely the presence of clay caps, and striations on the sides.

3. The clay cap, formed as a residue and coming to rest at the end of the undissolved portion, would serve as a further protection to the unattacked part. This clay cap is always present and should be considered a part of the stylolite. Fossils, which crown the columns as a result of having been more resistant to solution than the opposite rock, often determine the shape of the stylolites.

The work of Reis is considered difficult to understand because of the unusual amount of detail. It is given a partial review by Wagner (1913, pp. 110-111).

Investigations of Wagner. The work of Wagner (1913, pp. 101-128) on "Stylolithen und Drucksuturen" is the most exhaustive and conclusive that has been done on the origin of stylolitic phenomena. Wagner's investigations were made, for the most part, in the Muschelkalk. He described and discussed, in detail, numerous complexities of structure; such as horizontal and oblique stylolites; curved stylolites; stylolite-bands crossing one another, even at right angles; and parallel stylolite-bands intersecting, or "boring" into one another. His paper is accompanied by several plates and figures.

After reviewing some of the theories of the origin of stylolites, Wagner took up a critical discussion of the differences between "Drucksuturen" and "Stylolithen" and arrived at the conclusion that the primary distinction between the phenomena is only a matter of size and form; that no sharp distinction can be made between the two, since all sorts of transition forms are found; that typically jagged lines of the "Drucksuturen" variety grade into typical stylolite-seams. Various transition forms have been described by Freiesleben, Klöden, Quenstedt, Hall, Suess, Fuchs, Reis, and Bittner. Rothpletz described only the extreme forms and thus arrived at his conclusion that they were of different origin.

In support of the solution theory, Wagner corroborated

the points presented by Fuchs and Reis, and gave an abundance of additional evidence. He stated that the strength of the solution theory lies in the unmistakable evidence of the actual removal (not compression) of the material of the one part, which has been penetrated by the column of the opposite part. Wagner's most important contribution to the solution theory was in presenting evidence obtained from a study of fossils associated with stylolites. Especially numerous in the Upper Muschelkalk at Ottendorf were examples found where stylolites had penetrated, and had even completely pierced, mussel shells (see Fig. 29). There was no evidence of mechanical disturbance of the fossils. The absent materials, Wagner pointed out, had been actually removed by chemical solution.

Wagner emphasized the view that the principles of Henry and Rieke—that at the places of strongest pressure greatest solution occurs—are primary considerations in the physico-chemical basis of the solution theory.

Additional important evidence given by Wagner will be presented later in this paper. Wagner summarized his conclusions as follows (Wagner, 1913, p. 126):

1. The pressure theory is not experimentally confirmed. The experiment of Gümbel involved conditions which are not found in nature.

2. "Stylolithen", "Drucksuturen", and "Gerölleindrücke" occur as a result of chemical solution, under pressure, in hard rock. The differing resistance to chemical solution, of different portions of the rock, accounts for the interteething of the parts.

3. From the principles of Henry and Rieke it follows that in places of strongest pressure, greatest solution takes place; that in places of lessened pressure, on the contrary, even a pause in solution can set in. The solution zone is, for that reason, continually at right angles to the direction of pressure, and is therefore over the ends of the stylolites. The side-surfaces remain unattacked because of being parallel to the direction of pressure, and become smoothed and striated thru movement.

4. The clay cap is the solution residue of the rock mass.

5. Fossils may crown the stylolites. They always show traces of corrosion. They even show interpenetrated, small

stylolites. Mussel and brachiopod shells, and oölitic grains show all stages of solution.

6. Above the stylolite-seam, and parallel with it, the rock is in an entirely undisturbed stratified position.

7. Younger stylolites penetrate thru older ones and may even eradicate them. Bent, or curved, stylolites often occur. Horizontal stylolites show no essential differences from vertical ones.

8. Single stylolites are not found.

9. The size and form of stylolites depends upon the nature of the rock.

10. Direct connection between stylolites and disturbed strata is observed.

11. "Drucksuturen" are young stylolites, or are stylolites forming under changing irregular pressure. Both are forming and "growing" today in rock strata.

12. For the pressure theory of Quenstedt, Gümbel, and Rothpletz, there appears scarcely any proof. In most cases the evidence is directly opposite. The solution theory of Fuchs, which Reis elaborates, always gives a satisfactory explanation. It is experimentally confirmed.

Other Investigations. The first to suggest that stylolites may have formed in hardened rock was Cotta, in 1851. However, until Fuchs advanced his theory, it was generally accepted that they originated while the rock was in a plastic state. Bittner, in 1901, came to the conclusion, as did Fuchs and Reis, that the sharp distinction between stylolites and "Drucksuturen", which Rothpletz made, was a faulty one.

Grabau (1913, pp. 786-788) accepted the solution theory as the most satisfactory, stating that

> ordinary pressure work has, however, not taken place here, for nowhere is there any evidence of deformation of the beds by crowding or compression above the columns, which project from one face of the suture into the hollows of the other.

Another recent investigator to suggest the solution theory as the one most plausible is Gordon (1918, Jour. Geol., pp. 561-569), who concluded that

> from a study of the hundreds of examples in the Tennessee marble, the writer is convinced that in the main they represent fracture planes. Convincing proof of this appears in their irregularity and frequent tendency to cut across the sedimentation planes obliquely or even at

right angles. Wagner, who described them as occurring along fractures, stresses this point when he says that, whereas under the pressure theory the sutures must follow the planes of stratification, in the solution theory they may intersect the stone in any direction.

Conclusions. Altho the various theories of the origin of stylolites have had a scattered following among scientists in the past, no one theory has received definite acceptance because of insufficient proof. Conclusive evidence in support of the solution theory was revealed by the writer's field investigation of stylolites. Not only were the observations and conclusions of Fuchs, Reis, and Wagner corroborated, for the most part, but an abundance of new and further convincing evidence was obtained. The writer presents an explanation of stylolites by the solution theory, and the complete evidence in support of it, in the following chapter (see p. 46).

Part III. A Study of the Stylolites of the Indiana Limestones and the Conclusive Evidence of Their Origin by Chemical Solution

THE field investigations of the writer have been confined, for the most part, to the rocks of southern Indiana. A few observations, however, have been made also in the Niagaran and Onondaga limestones of New York, in the Monroe and Columbus limestones of Ohio, and in the Tennessee marbles.

GEOLOGIC DISTRIBUTION OF STYLOLITES IN INDIANA

In Indiana, the stylolites of special significance are found in the thick Middle Mississippian limestones of three ages: namely, the Harrodsburg, Salem (otherwise known as the Spergen, and commercially known as the Bedford, or Indiana Oölitic), and Mitchell. Brief descriptions of these three formations follow:

Harrodsburg Limestone

This is the lowest of the three above-mentioned formations and lies between the Knobstone (a series of alternating arenaceous shales, and sandstones) below, and the Salem limestone above. The formation varies in thickness from 60 to 90 feet. It is generally impure; and in places, is dolomitic. In its lower part, it is a very coarse crinoidal limestone; near the central part, it becomes finer. Here the crinoids, large brachiopods, and pelecypods are replaced principally by bryozoans. Near the top, the limestone assumes very much the character of the overlying Salem.[1]

Salem Limestone

No limestone in the United States is better known nor more valuable for ornamental and building purposes than the Salem limestone.[2] It occurs in massive beds varying in thick-

[1] For a complete description of the Harrodsburg limestone, reference should be made to: Beede, J.W., 1915, pp. 194-203.

[2] For the latest full discussion of the Salem limestone, reference should be made to: Blatchley, R.S., 1908, pp. 299-460.

ness from 25 to nearly 100 feet. It is a granular limestone in which both the grains and cement are carbonate of lime. The grains are made up, for the most part, of Foraminifera, Ostracoda, and bryozoan remains, mingled with fragments of other forms, some of which have not been identified. The texture of the stone varies in coarseness in different localities. The great mass of the stone, however, is made up of the millions of minute, in places almost microscopic, shells which are fairly uniform in size; but in some localities the coarse stone is abundant, as a result of the predominance of many larger shells, such as gastropods and brachiopods. This latter variety of stone is less valuable from the commercial point of view.

The Salem limestone is quite massive, showing very few bedding planes. Cross-bedded lamination is a frequent feature. The formation, in most places, carries two systems of vertical joints, running approximately at right angles with each other. The joints are rarely abundant, generally 20 to 40 feet apart.

The variety in color of the Salem limestone proves to be a feature of considerable importance in the investigation of the origin of stylolites. The stone is of two shades of color, known commercially as "buff" and "blue". (The blue variety is more of a gray, and in places is so light that it is almost white.) The difference in the color of the stone is claimed to be the result of a chemical change in the small amount of iron compounds present, and an oxidation of the carbon content. Originally all of the stone was blue and the iron present was in the form of ferrous compounds. The oxidation of the iron into ferric compounds resulted in the original blue shade being turned into a light brown, giving a buff color to the stone. According to Hopkins (Hopkins and Siebenthal, 1897, p. 309; 1908, p. 314)

> The oxidation is a continuous process, not yet complete, carried on mainly by the oxygen in solution in the meteoric water, the circulation of which is accelerated or retarded by a variety of causes.

The line of separation of the buff and blue stone is usually very irregular. Consequently, there are blocks quarried in which both colors are present.[3]

[3] For a full discussion of the color of the Salem limestone, reference should be made to: Mance, G.C., 1917, p. 117; Hopkins, T.C. and Siebenthal, C.E., 1897, pp. 309-310; 1908, pp. 314-316.

The Salem limestone is especially pure, the percentage of calcium carbonate running very high—from 92 to 98 per cent, usually above 95 per cent. The percentage of insoluble constituents, organic matter, silicates, etc., is very low. The percentage of magnesium carbonate, when present, is always very low. A general conception of the composition of the Salem limestone can be gained from the following analysis of a sample taken from the quarry of the Perry Stone Company, Ellettsville district, Monroe County:

Calcium carbonate ($CaCO_3$)	97.27 per cent
Magnesium carbonate ($MgCO_3$)	.89
Alumina (Al_2O_3)	.33
Ferric oxide (Fe_2O_3)	.59
Silica (SiO_2)	1.00
	100.08

(Analysis made by Illinois Steel Co.)[4]

The quarrying of the Salem limestone in Indiana is confined mainly to two counties, Monroe and Lawrence. These two counties are conveniently divided into the following quarrying districts:[5]

Monroe County—
- *a.* Stinesville district.
- *b.* Ellettsville district.
- *c.* Hunter Valley district.
- *d.* Bloomington district.
- *e.* Sanders district.
- *f.* Belt district, between Clear Creek and Harrodsburg.

Lawrence County—
- *a.* Peerless district.
- *b.* Buff Ridge district.
- *c.* Reed Station district.
- *d.* Dark Hollow district.
- *e.* Bedford and vicinity.

Mitchell Limestone

Overlying the Salem limestone is a series of limestones of varying texture, appearance, and geologic age, called the Mitchell. In thickness it varies from 200 to 400 feet. Difficulty is found in separating the lithologic formation into its

[4] For tables of chemical analyses of the Salem limestone, reference should be made to: Blatchley, R.S., 1908, pp. 315, 329, 358, 366, 376, 382, 415.

[5] For the latest detailed description and maps of the quarrying districts, reference should be made to: Blatchley, R.S., 1908, pp. 356-451.

integral parts. The texture of the stone varies from the exceedingly fine-grained lithographic form, thru a typical oölite, to brecciated limestone, ending with an edgewise conglomerate. Thin shale and sandstone partings are to be found.[6]

GENERAL DESCRIPTION OF INDIANA STYLOLITES

The Indiana limestones afford abundant opportunity for a study of stylolites and stylolite-seams of various sizes, types, and complexities. The largest stylolites observed by the writer are 13 inches in length (see Fig. 12); some are so small as to be seen distinctly only under a hand-lens. The length of the seams is in proportion to the size of the stylolites—the larger stylolites constituting partings of greater extent than small stylolites. All stylolite-seams, instead of ending abruptly, grade into smaller and smaller sutures, and finally disappear as a barely noticeable line.

In what might be called the most perfect, but not the most common stylolite-seams, the interlocked parts are more or less columnar in shape, the downward and upward projections alternately interpenetrating with much regularity. The assumption, suggested by Marsh, Gümbel, and Rothpletz—that few stylolites extend from the upper layer into the lower—will not hold for the Indiana limestones. If one considers the upward-penetrating columns as stylolites, then the adjacent downward-pointing parts must be considered as reciprocal stylolites. In the larger sutures are often found these most perfectly column-shaped stylolites. They are especially sharply defined in the Salem limestone of the Dark Hollow district (see Figs. 2 and 11). The side-surfaces are often parallel; are always well striated, often having a polished or slickensided appearance, especially if there is a thin deposit of calcite on them; and are often covered with a very thin coating of clay, drawn from the clay cap to the base of the column. The ends of these columns are convex, fitting closely into the concave openings of the penetrated rock, and separated from them by the caps of clay.

Many common variations from this above-described, ideal type of stylolite are found. In their more common and typical development, the interpenetrating parts occur with less regu-

[6] For a description of the Mitchell limestone, reference should be made to: Beede, J.W., 1915, pp. 206-212.

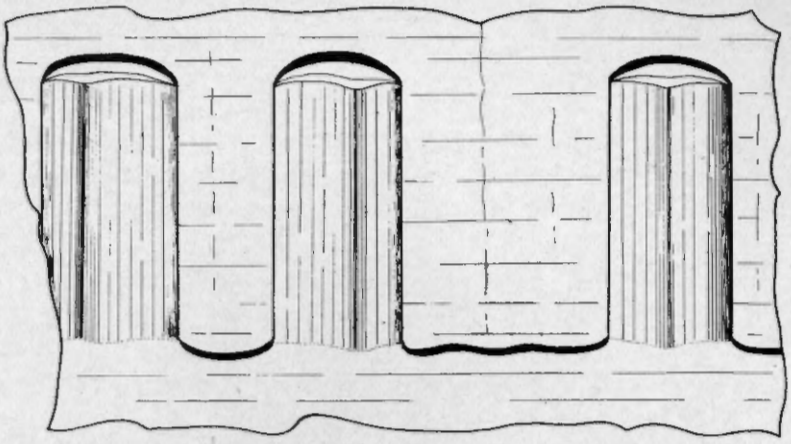

FIG. 11.—Diagrammatic sketch of the large, perfectly formed stylolites of the Salem limestone, such as are found in the Dark Hollow district, Lawrence County, Ind. In this specimen the block has been broken along the side-surfaces of the upward-penetrating columns, showing the striations; and thru the downward-pointing columns, exposing the lamination and texture of the rock. One-fourth natural size.

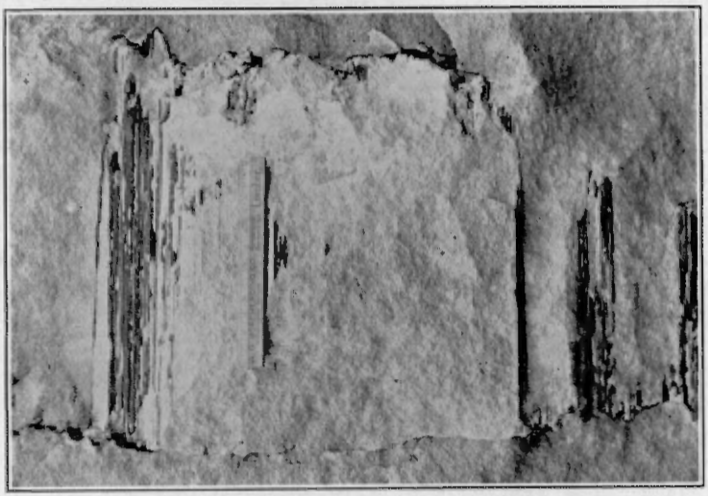

FIG. 12.—Thirteen-inch stylolite in the buff Salem limestone. From a quarry of the Consolidated Stone Company, Dark Hollow district, Lawrence County, Ind.

larity, are more or less irregular in shape and size, and present an extremely jagged suture (see Figs. 3, 13, 14, and 15). The parting is often just an undulating seam with only occasional interpenetrating perfect columns. A few extensive partings, with only a slight stylolitic structure, are to be found. The length and shape of the penetrations are quite variable. Short columns, between longer ones, are frequent. Some columns are very broad, compared with their length, and have flat or undulating ends. The ends of others show a subordinate interpenetration of minor columns (see Fig. 24). The sides of the interpenetrating parts, instead of being parallel, frequently converge towards the end, sometimes coming to a sharp point. This is especially true of smaller penetrations. Along a fractured surface of a block of stone, the jaggedness of the stylolite-seams is often exaggerated because of the irregularity of the fracture (see Fig. 12). The true seam is to be seen on the face of a sawed block which has been cut parallel to the direction of the penetrating parts (see Fig. 15). Stylolite-surfaces, which have been exposed by the splitting of the strata along the suture, present a dark, irregular, pinnacled appearance (see Figs. 4, 5, and 6). The dark color is a result of the clay deposit.

In addition to the larger types of stylolite-partings, hundreds of small, sharply intertoothed sutures are found. They are sometimes so small as to present a barely noticeable line (see Fig. 16). These correspond to the so-called "Drucksuturen" of the German investigators. That no distinction can be made between these and the larger stylolite-partings is unquestionable, since the latter always grade into this small type of seam, and finally disappear as a barely noticeable crevice. These small sutures have all of the fundamental characteristics of the larger ones. The interpenetrating parts are irregular and are usually more or less conically pointed. In some, however, the penetrations are minutely columnar in shape and occur with marked regularity. These are especially noticeable in a fairly fine, even-grained limestone. Occasionally are found two or three closely parallel small partings which abruptly join and continue as one larger seam (see Figs. 16 and 35), the combined amount of penetration of the smaller seams being equivalent to that of the larger one.

Regardless of the size and the character of the stylolite-seam, the striated sides of the penetrations and the clay part-

ing are ever-present features. The clay comes to rest as a thin cap at the end of the columns. Its thickness is as variable as the size of the stylolite. In the smallest sutures, the clay

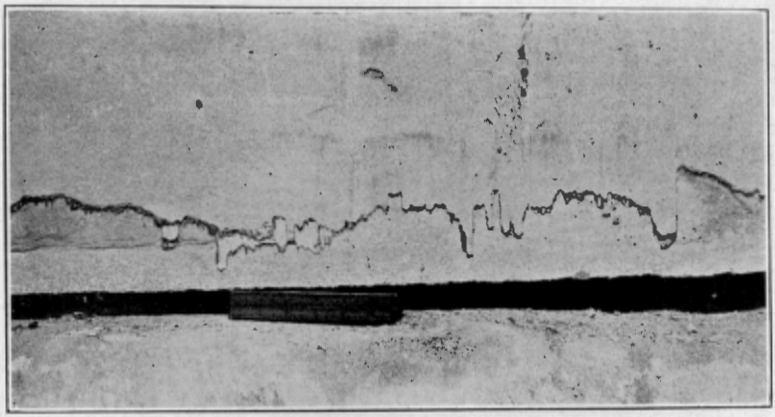

FIG. 13.—Complex stylolite-seam of the Salem limestone. From a quarry of W. McMillan and Son, Peerless district, Lawrence County, Ind.

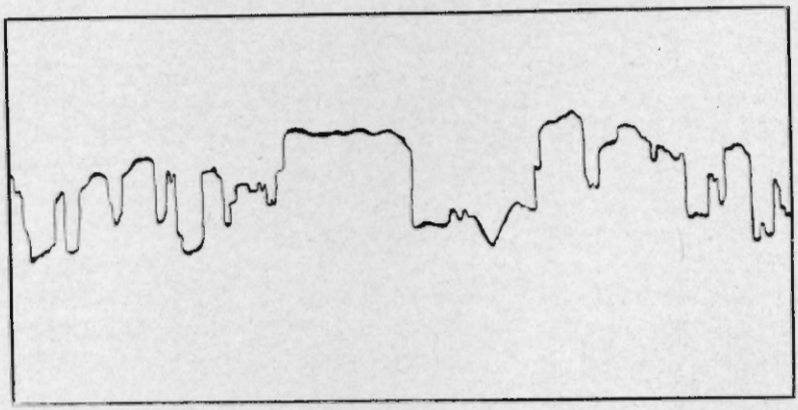

FIG. 14.—Diagram of a small, jagged stylolite-seam of the lower Harrodsburg limestone. Note the variety of shapes of the interpenetrating parts. Natural size.

is only microscopically visible, but, nevertheless, is present. In the largest sutures, it is sometimes as much as an inch in thickness. Shorter stylolites between longer ones bear caps

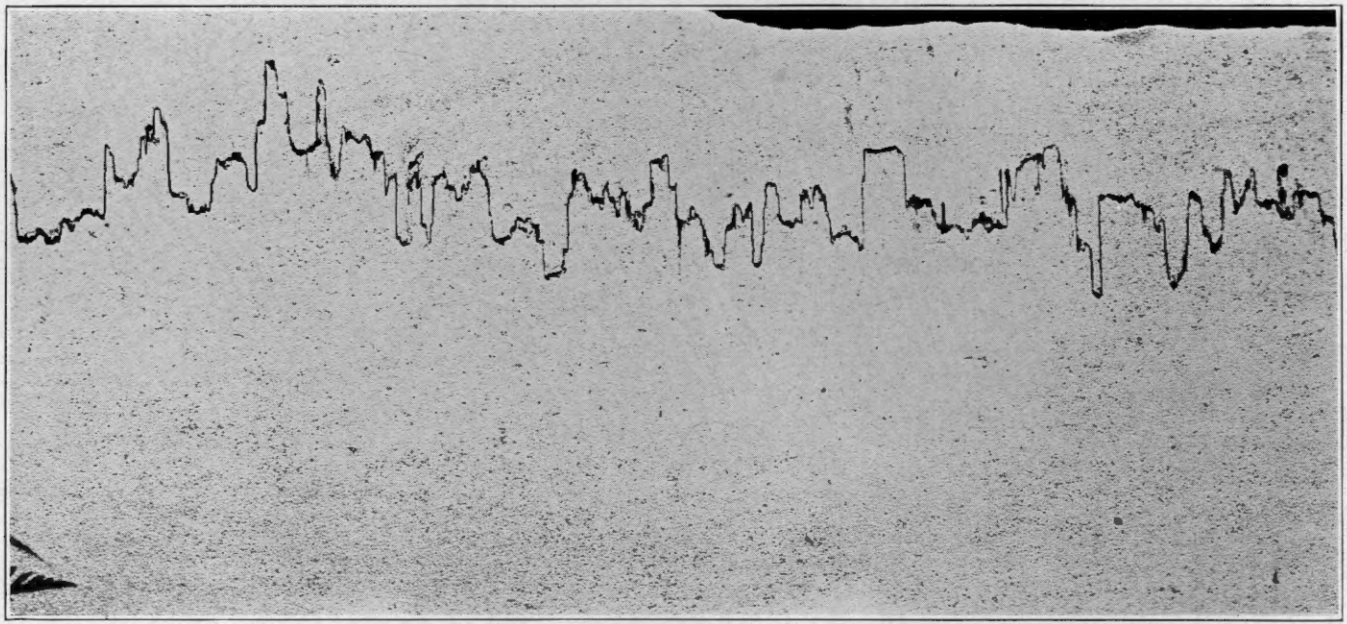

FIG. 15.—Typical stylolite-seam as it appears on a sawed surface of the Salem limestone. Note the irregularity in size and shape of the interpenetrating parts. About one-half natural size.

of the same thickness as the adjacent longer ones (see Fig. 26). A very thin coating of clay covers the striated side-surfaces of the penetrations, and diminishes in thickness from the end to the base. The color of the clay varies with the color of the stone. Stylolites of the "buff" stone bear brown caps; those of the "blue" stone, black caps. Gradations between these are also found. The clay caps often present a compact, laminated appearance. Their line of contact with the end of the column is usually sharp, altho in some instances, the caps appear to grade slightly into the limestone of the column.

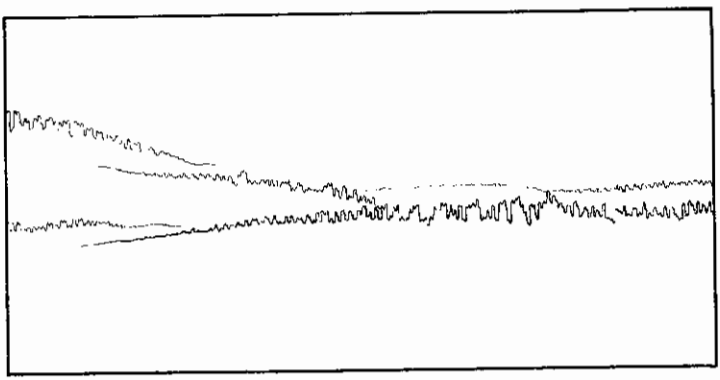

FIG. 16.—Diagram of the small, finely toothed type of stylolite-seams. The sutures end in a fine, barely noticeable line. Note the resemblance to the sutures of the human skull. Such a seam represents the "Drucksuturen" of the German investigators. This specimen is from the Mitchell limestone. Three-fourths natural size.

Distinct fossils are lacking in the clay, altho corroded fragments are often found. Chemical analyses of the clay caps show them to be similar to the residual clays of limestones (see pp. 67-83).

Relation to Stratification

The stylolite-seams of the Harrodsburg, Salem, and Mitchell limestones of Indiana are, in general, horizontal, and parallel with the lines of stratification, usually running along the bedding planes or lamination of the rock. The larger stylolite-seams, especially, often mark stratification planes; and are traceable, with no sharp break, into the common bed-

ding planes having no evidence of stylolites. They are very common at the junction of cross-bedded and horizontally bedded strata in the Salem limestone. They often sharply mark the parting between beds of distinctly different lithologic characteristics. Contrary, however, to the observations of Hopkins (Hopkins and Siebenthal, 1897, p. 307), that they never run across the grain, the writer has observed cases where even large seams leave the bedding planes and cut across the lamination (see Fig. 17). In one instance, an ap-

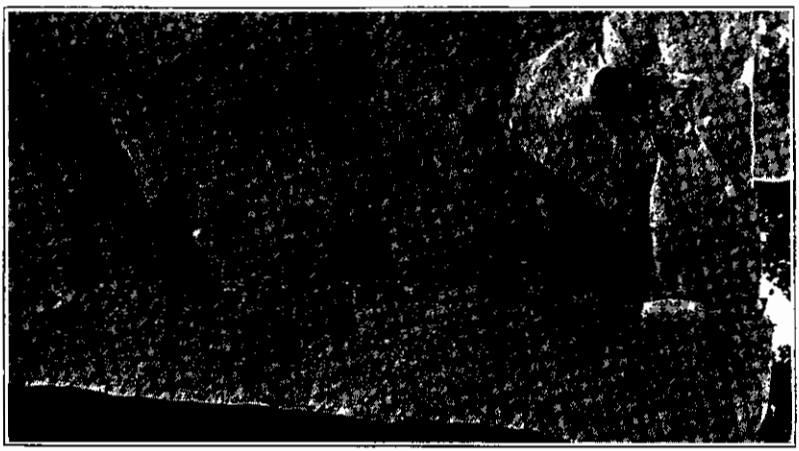

FIG. 17.—Stylolite-seam which leaves the bedding plane and cuts across the lamination of the upper stratum at an angle of about 20 degrees. From a quarry of the Consolidated Stone Company, Hunter Valley district, Monroe County, Ind.

parent fault-surface, cutting the bedding at an angle of about 60°, has developed a slightly stylolitic nature.

The many minute, sharply-toothed sutures, varying from an almost microscopic width up to a fraction of an inch or so, usually follow the lamination, but occasionally cut across the laminae at a small angle (see Fig. 16). Their general direction, however, as in the case of larger stylolite-seams, is horizontal. In some instances they follow the laminae of a false-bedded stratum.

The frequency of occurrence of stylolite-partings is quite variable in different geologic horizons, and in different locali-

ties. The structures are probably most numerous in the semi-lithographic strata of the Mitchell limestone, where several

FIG. 18.—Pile of waste stone, a result, for the most part, of stylolite-seams. The Consolidated Stone Company, Dark Hollow district, Lawrence County, Ind.

small partings occur only a few inches apart. Some of the Salem limestone quarries are almost devoid of the phenomenon; others reveal numerous examples. In some instances,

overlying, parallel seams are so close together as to penetrate, or even partially eradicate, one another (see p. 64).

The stylolite-partings of the Salem limestone attract much popular attention because they necessitate a considerable amount of waste stone which is not generally utilized for commercial purposes (see Fig. 18).

PHYSICO-CHEMICAL BASIS OF THE SOLUTION THEORY

Statement of the Theory

That the writer's investigations of stylolitic phenomena revealed conclusive evidence in support of the solution theory, and in direct opposition to the pressure theory, has already been stated. Briefly, the writer wishes to present the theory as follows: Stylolitic phenomena result from the differential chemical solution of hardened rock, under pressure, on the two sides of a bedding plane, lamination plane, or crevice, the undissolved portions of the one side fitting into the dissolved-out parts of the opposite, the interfitting taking place slowly and gradually as solution continues. Stylolites are limited to carbonate rocks. The explanation of their origin is taken up in detail on page 49. A discussion of the solution theory first necessitates the consideration of a few physico-chemical factors.

Effect of Carbon Dioxide upon Solution

Of the various constituents absorbed by water, which are especially effective in chemical changes in rocks, carbon dioxide is one of the most important. That nearly all minerals are more or less attacked even by pure water, and that their solubility is markedly increased in water containing dissolved carbon dioxide (carbonic acid), are well-known facts which need no further discussion.

Effect of Pressure upon the Solution of Gases in Liquids

From the law of Henry it follows that increase of pressure upon a liquid increases the weight of gas going into solution, the increase being proportional to the amount of pressure. Thus, an increase in pressure results in a proportional increase in the amount of carbon dioxide which water dissolves, which in turn increases the dissolving strength of carbonic acid upon the minerals attacked.

Effect of Temperature upon the Solution of Solids in Liquids

Altho the solvent action of water, especially if charged with carbon dioxide, is marked at ordinary or even low temperatures, there is no doubt that the action is increased by heat. That, as a rule, solids are more soluble in warm than in cold solvents is an established fact.

Effect of Pressure upon the Solution of Solids in Liquids

That the effect of pressure must be recognized as important in increasing the solubility of certain solids in liquids, is a factor of special significance in considering the origin of stylolites. From this principle it follows that, at the places of increased pressure, increased solution takes place. Van Hise states that

> In the common case in which the volume of the solution is less than that of the solvent and solid, pressure increases solubility; for in that case solution tends to bring the molecules together and works in conjunction with the pressure. . . . It is well known that the solubility of calcium carbonate is increased by pressure (Van Hise, 1904, pp. 77-78).

This principle has also been recognized and emphasized by Geikie (1903, pp. 411, 419). It has been thoroly established by E. Rieke, Sorby, and others, and experimentally confirmed by F. Becke and Daubrée. Upon this principle is based the theory of the origin of the solution type of impressions in pebbles (see p. 18). Here is a case of a mass of pebbles in a conglomerate where, of course, the pressure exerted upon each other is at the point of contact, and where the solution of the one takes place at the point of contact with the other.

Result of Supersaturation of a Solution

Since increased pressure or temperature, or both, may result in a supernormal amount of a solid being dissolved by a solvent, a decrease in the pressure or temperature may give rise to a supersaturated solution, and a consequent crystallizing out of the excess solute. Release of pressure gives a similar result in the solution of gases in liquids. For example, water under pressure is capable of dissolving an excess of carbon dioxide, and consequently of carrying an excess of mineral matter in solution. Release of pressure upon the solvent effects an escape of some of the carbon dioxide and a

precipitation of the excess mineral matter which can no longer be held in solution because of the weakening of the carbonic acid.

Solubility of Limestone

It is well established that calcium carbonate is nearly insoluble in pure water, but that it is readily attacked by carbonic acid (H_2CO_3) and converted into calcium bicarbonate, $H_2Ca(CO_3)_2$, which is quite soluble in water. Thus, since limestone is made up, for the most part, of calcium carbonate, it may be almost entirely removed by solution, leaving a residual

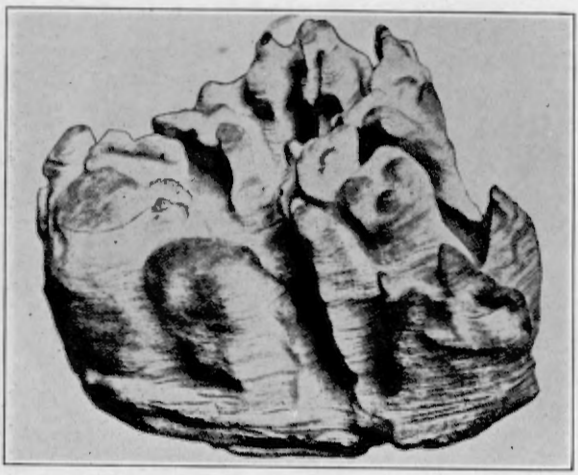

FIG. 19.—Limestone bowlder channeled by water containing carbon dioxide, illustrating the occurrence of differential solution similar to that required in the development of stylolitic phenomena. (From Cleland's Geology.)

clay composed of the less soluble, minor constituents of the rock—principally silica, alumina, oxides of iron, with small quantities of soda, potash, magnesium carbonate, and calcium carbonate which have not been completely dissolved. In the case of limestone, instead of there being a gradual transition from fully-formed residual clay into the parent rock, the passage from the clay to bed rock is sudden. The reason is that the clay is left as a residue from solution, and not from a gradual chemical breaking down and change of the minerals of the rock, as in the case of granites, etc. Thus a small thick-

ness of residual limestone clay is a product of the solution of a much greater thickness of parent rock, the proportion depending upon the purity of the limestone.

The differential weathering of limestone is often quite striking. Since the ability of limestone to resist solution is quite variable, even thruout a single stratum, a solution surface often presents an undulating and irregular appearance (see Fig. 19).

EXPLANATION OF STYLOLITIC PHENOMENA UNDER THE SOLUTION THEORY

Of the above-discussed factors, the writer wishes to emphasize the following two as the most important in the explanation of stylolites:

1. The effect of pressure upon the solution of solids.
2. The differential solubility of limestones, and other carbonate rocks.

Stylolites originate in carbonate rocks—varieties of limestones, dolomites, and marbles—along a bedding plane, lamination plane, or crevice, where the circulation of ground waters, charged with carbon dioxide, is most free. Here, then, solution begins. If the ability of the rock to resist solution is slightly variable on one side of the crevice or the other, the carbonic acid would, of course, attack the less resistant parts. If these more soluble portions are distributed first on one side of the crevice, and then on the other, a slightly undulating line would develop, with the undulations becoming more marked after further solution, the outstanding resistant parts of the one side fitting into the dissolved-out portions of the opposite. After the development of this undulating line, pressure (in most cases static pressure, resulting from the weight of the superincumbent strata) plays its rôle. Most of the weight of the overlying sediment is concentrated along the axis (the top and bottom surfaces) of each of these undulations. This results in an increased amount of solution at the points of increased pressure. The sloping sides of the undulations, which are freer from pressure than the tops and bottoms, are proportionately less attacked by the solvent. Increased solution of the weaker rock opposite the ends of the undulations results in (*a*) a

deepening of the interpenetrating parts, (*b*) a decrease in the pressure and consequent decrease in the solution of the sides of the undulations, and (*c*) a final development of vertical columns, with practically a complete concentration of the pressure and consequent solution at the ends. The sides of the columns, being free from pressure, usually are unattacked by solution. Continued solution at the ends results in a further deepening and lengthening of the interpenetrating columns. Striation of the side-surfaces results from the slow movement of the columns past one another. The non-soluble constituents of the dissolved rock come to rest as a clay residue at the end of each column, and serve as a further protection from solution of the resistant part. Increase in the length of the stylolites results in a proportional thickening of the residual clay. The length of the columns serves as a fair measure of the amount of solution which has taken place, providing the ends of the columns themselves have not been subjected to solution. On the sides of the stylolites, which are free from pressure and practically unattacked by solution, are often found deposits of mineral matter precipitated there from the supersaturated solvent resulting from the increased pressure and amount of solution opposite the ends. Such coatings of mineral matter are often slickensided as a result of further growth and interpenetration of the columns. The length of the stylolites depends upon three principal factors: (*a*) the length of time solution has gone on, (*b*) the solubility of the stone, and (*c*) whether or not solution has attacked the ends of the stylolites.

Thus it is seen that the principal factors in the development of stylolites are: (*a*) the presence of a crevice in the rock which permits a concentration of carbonated water; (*b*) the fact that carbonate rocks (limestones, dolomites, and marbles) exhibit a differential solubility; and (*c*) the physicochemical principle that an increase in pressure effects an increase in the solubility of a solid, as shown by Rieke, Sorby, Geikie, Van Hise, and others, and experimentally confirmed by Becke and Daubrée.

Wagner (1913, pp. 122-123) stressed the point, from the law of Henry, that an increase in pressure upon the solvent at the ends of the columns would permit an increase in the amount of carbon dioxide dissolved, which in turn would increase the amount of solution at these places. Reis pointed

out that slight tremblings within the rock might cause friction, thus creating heat, which in turn would increase the dissolving powers of the solvents. The writer believes this latter conclusion to be unimportant in explaining the development of such an intertoothed phenomenon as stylolites.

From the solution theory it can be seen that a vast number of variations in size, shape, distribution, and character of stylolites is to be expected, principally from (*a*) variations in the composition and lithologic nature of the rock, (*b*) the erratic distribution of varying soluble portions of the stone, (*c*) variations in the direction of pressure exerted upon the rock, and (*d*) the length of time solution has continued.

The spacing of the alternating, less resistant portions of the stone on the two sides of the crevice may occasionally be quite regular. This, however, would be an exception. In most cases the distribution would be very erratic, so that the resulting columns would be of varying widths. In the beginning, stylolite-seams are the small, finely serrated type. A little further solution might, because of differential solubility of the rock on opposite sides, develop a slightly undulating stylolite-seam, each of these undulations bearing smaller penetrations in varying numbers. A continuation of the process upon these compound major undulations might result in the development of larger, major columns, whose ends might be marked with the smaller, original penetrations, such as are often observed (see Fig. 24), and still further continuation of solution might bring about a complete, or almost complete, eradication of these original, smaller, intertoothed parts. All sorts of gradations between the beginning, barely noticeable, undulating line, and the large, major stylolite-seams are to be observed in the field.

If, in the gradual interpenetration of the stylolites, the less resistant portion on the one side, which is being dissolved out opposite the end of the column, changes in resistance so that it is as resistant as, or more resistant than, the penetrating part, solution might then take place in the rock on both sides, or change to the end of the column. Such variations in the chemical resistance to solution therefore often produce quite a diversity in the length and shape of the interpenetrating parts (see Figs. 15 and 26). It explains the occurrence of shorter stylolites between longer ones. If the rock on each side of a solution crevice were of uniform re-

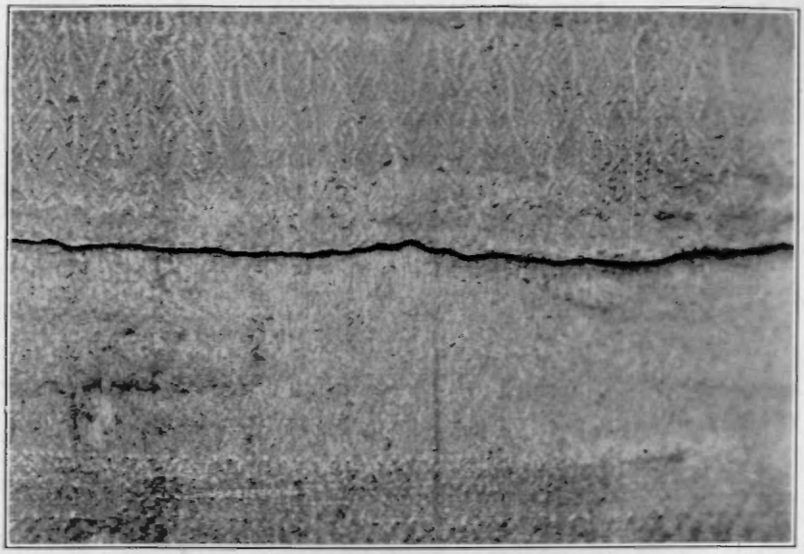

FIG. 20.—Undulating solution seam, containing three-eighths of an inch of black residual clay. This seam, within a short distance to both the left and right, becomes highly stylolitic. See Fig. 21. From a quarry of the Consolidated Stone Company, Dark Hollow district, Lawrence County, Ind.

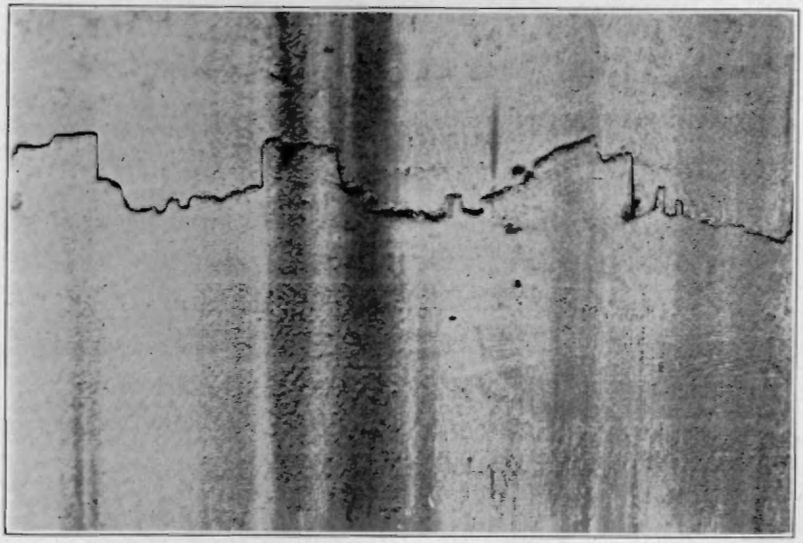

FIG. 21.—Stylolitic portion of the seam shown in Fig. 20.

sistance, stylolitic interteething would not result. Continued solution would give only a slightly undulating seam, with a residual clay parting (see Fig. 20). Such seams are found. They sometimes continue for several yards, with perhaps an occasional, sharply protruding column (perhaps several inches in length), or a series of columns, where the rock offered sufficient differential resistance to solution to produce such (see Fig. 21).

Converging and pointed penetrations might result where the difference in resistance to solution on the two sides of the crevice is little and is less than that in the case of columns with parallel sides. Altho most of the solution is confined to the ends of the columns where the pressure is greatest, the side-surfaces might be more or less attacked. Since the end represents the first and oldest portion of the columns, the portions nearer the end, because of their longer existence, would be longer exposed to the attack of whatever solution might take place on the sides, and would thus become gradually narrowed, giving converging or pointed columns. Dynamic, lateral pressure upon the rock would promote further solution of the sides. Wagner emphasized this point in explaining pointed penetrations.

The writer would explain curved, or bent, stylolites as a result of the columns, during their growth, striking an especially resistant part at an angle (the resistance being sufficient to overcome the effect of the overlying pressure upon vertical solution) and consequently being deflected to one side, following the line of least resistance. The occurrence of such is an exception among Indiana stylolites. The writer observed a few cases where the bending of the column had been sufficient to fracture it. Wagner explained curved stylolites as resulting from "complicated pressure and solution factors" and gave examples where the fractures on the concave sides had been filled with gypsum (Wagner, 1913, p. 118).

With the exception of the few cases of curved stylolites, the direction of penetration is parallel with the direction of pressure, and the plane of solution is usually at right angles to it. In undisturbed strata, void of lateral, dynamic pressure, the pressure is static, resulting from the weight of the overlying sediments; the stylolites are vertical, and the stylolite-seams, horizontal. Such is the usual case in the Indiana

limestones. In strata where folding has occurred, stylolite-seams are sometimes found along the inclined bedding planes with the individual columns themselves vertical instead of at right angles to the bedding planes. Evidently the stylolites developed after the lateral compressive forces ceased, their development being in response merely to the vertical static pressure due to the weight of the superincumbent rock—the inclined bedding plane providing an avenue for ground water circulation. Examples of such are noticeable in the steeply

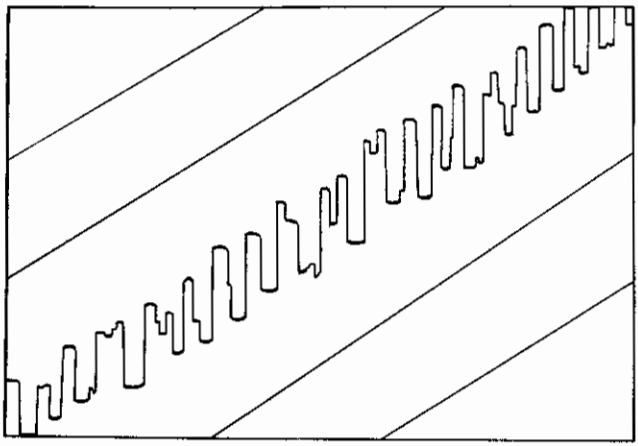

FIG. 22.—Diagram of stylolite-seam along an inclined bedding plane, where the position of the individual columns is vertical, instead of at right angles to the plane of stratification. Observed in the steeply inclined strata of the "Niagara domes" of northern Indiana by Professor E. R. Cumings.

inclined strata of the so-called "Niagara domes" of Northern Indiana (see Fig. 22). Where lateral pressure exists, horizontal and angular columns may develop along vertical and angular crevices, the direction of penetration of the columns depending upon the direction of the pressure. The occurrence of such is described by Fuchs, Reis, Wagner, Gordon, and others.

The above discussion shows that a great number of stylolitic variations and complexities are to be expected, and can be explained by the solution theory. A discussion of the

various phases of the phenomenon which have special bearing upon the solution theory, in opposition to the pressure theory, follows.

CONCLUSIVE EVIDENCE WHICH ESTABLISHES THE SOLUTION THEORY OF THE ORIGIN OF STYLOLITES, AND OPPOSES THE PRESSURE THEORY

The solution theory and the pressure theory are very strikingly opposed to each other. The first attributes to stylolites an origin in hardened rock; the second, an origin resulting from the differential compression of sediments in the soft, plastic state. Thus, a great amount of the evidence supporting the one theory stands in direct contradiction to the other. With this in view, the writer wishes to present three principal lines of evidence establishing the solution theory; namely: (1) evidence that stylolitic phenomena originate not in plastic rock, but in consolidated, hardened rock, the penetrations of the one stratum fitting into the cavities of the opposite which have been formed by the actual removal (not compression) of rock material; (2) evidence that the clay caps of the penetrations are the solution residue of the dissolved limestone; (3) stratigraphic evidence which precludes the pressure theory and supports the solution theory. The writer believes that proving these points alone is sufficient to establish conclusively the solution theory. However, additional evidence along other lines will also be presented.

1. Evidence that Stylolites Originate in Hardened Rock with the Actual Removal of Rock Material

RELATION OF STYLOLITES TO THE LAMINATION OF THE ROCK. The Indiana limestones afford unusual opportunity for a study of the relation of stylolitic structures to sedimentary conditions. Field studies of stylolites reveal the conclusive fact that all penetrations bear the same lithologic characteristics as the strata from which they protrude. Especially striking is this observation where a stylolite-seam occurs along a disconformity or a bedding plane between two distinctly lithologically different strata, such as a coarsely fossiliferous bed and a fine-grained oölitic, or semi-lithographic one, etc. In such cases, adjacent columns exhibit a sharp contrast. This observation is yet more striking where a stylolite-

seam marks the line between a distinctly laminated stratum and one showing little lamination. This is best understood from a study of Fig. 23. Here the horizontal lamination of the upper stratum is distinctly continued into the downward-penetrating columns. The laminae are sharply cut off at the edges of a column, but are continued in the next downward-pointing one. There is no evidence of distortion or disturbance of the lamination, either within the columns, or above them. At the ends of the upward-pointing columns, the laminae, instead of bending around the convex ends, retain

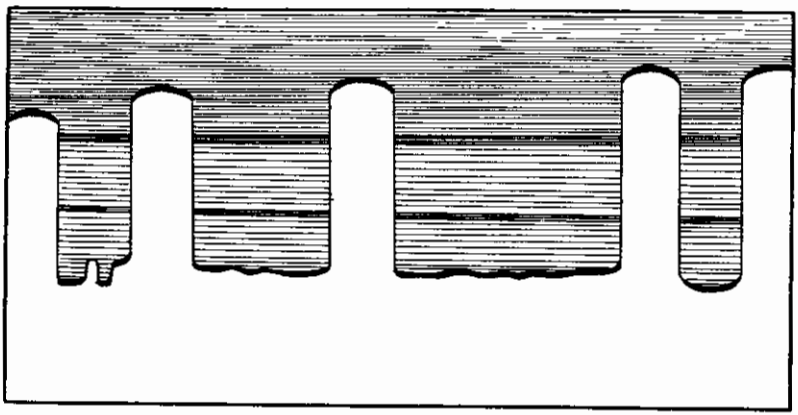

FIG. 23.—Semi-diagrammatic sketch, showing the relation of stylolites to the lamination of the rock. Note that the distinct laminae of the upper layer are undisturbed, both above the upward-penetrating columns, and within the downward-pointing ones. The laminae are not bent around the ends of the columns, but are actually hollowed out. Note the darker laminae.

undisturbed their parallel, horizontal position, the rock having been actually hollowed out.

More striking yet is this observation of undisturbed lamination as seen where a stylolite-parting occurs between a cross-bedded and a horizontally bedded stratum. The most distinct example was observed by the writer at a quarry of J. Hoadley and Sons Co., Stinesville district (see Fig. 24). Here the overlying bed is distinctly cross-bedded, and the lower one clearly horizontally laminated. Very pronounced is the continuation of the angular lamination from the upper

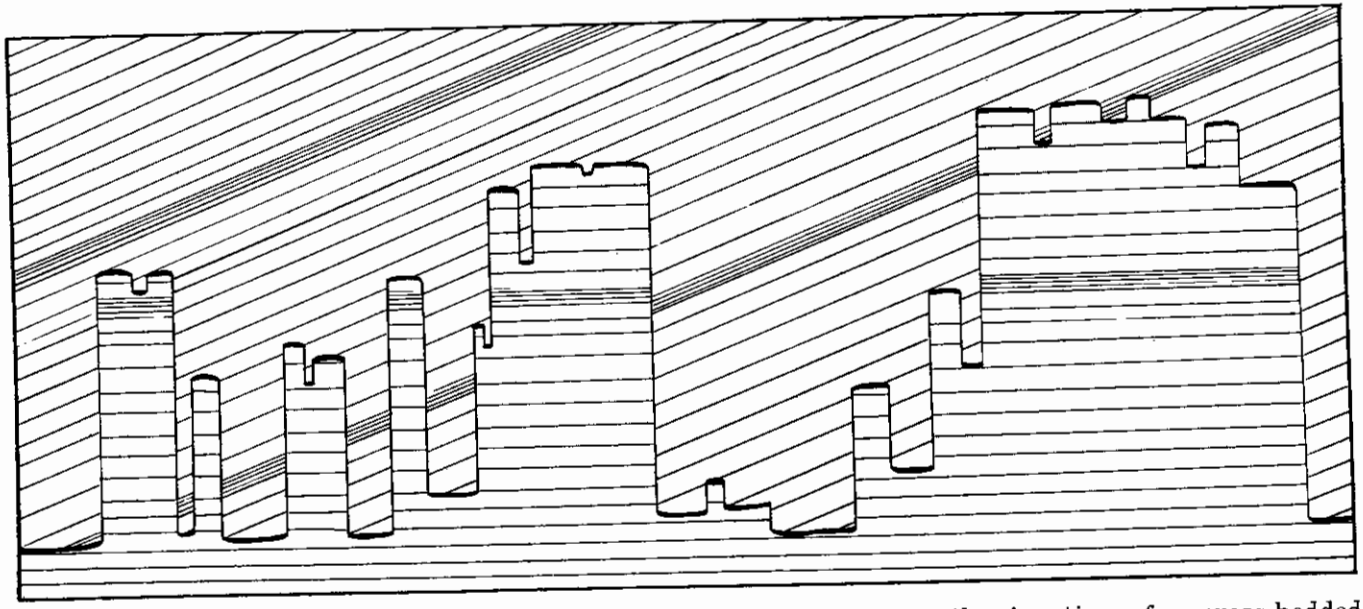

FIG. 24.—Semi-diagrammatic sketch of a stylolite-seam occurring at the junction of a cross-bedded stratum and a horizontally laminated one. Note that the angular lamination of the above layer is continued into the downward-pointing columns, and the horizontal lamination of the lower stratum is continued into the upward-pointing penetrations. Note, also, the presence of smaller inter-toothed columns at the ends of the large, major penetrations. One-fourth natural size. From a quarry of J. Hoadley and Sons, Stinesville district, Monroe County, Ind.

stratum into the downward-pointing penetrations, and the presence of horizontal lamination in the adjacent, upward-projecting columns.

Often dark laminae stand out very clearly in the stratification. Where penetrated by stylolites, they are missing (see Figs. 23 and 24). Under the pressure theory one should expect to find them displaced above or below the ends of the penetrating columns. Such is not the case. How could the various, above-described laminated conditions have been retained, had the sediments been "differentially compressed in a plastic state"? The rock materials have been actually re-

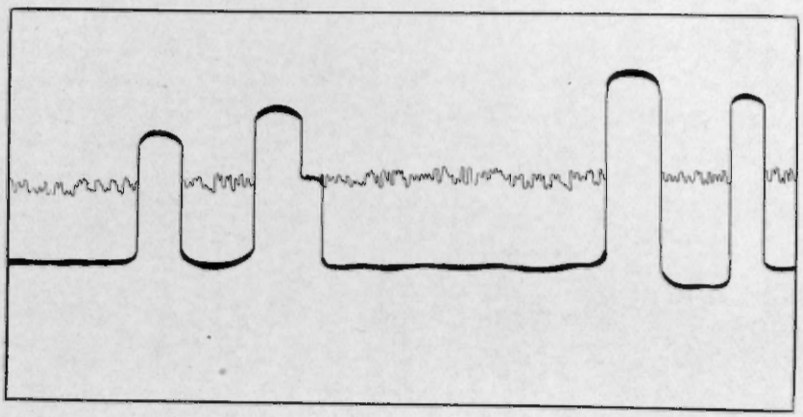

FIG. 25.—Diagram of a small stylolite-seam partially eradicated by the penetration of upward-pointing columns of a large stylolite-seam. Mitchell limestone. One-third natural size.

moved, and the two beds have been "dovetailed" into each other.

Analogous to this observation of the removal of the laminae of the one bed into which the columns of the opposite have penetrated, are numerous examples of small stylolite-seams which have been penetrated and removed by larger stylolites. Figure 25 is a case where a small, once-continuous stylolitic suture, following the lamination of the rock, occurs now only in the downward-projecting columns, being sharply cut off and absent in the rock of the upward-pointing parts. Under the pressure theory, should not one expect to find it displaced in the rock above the columns?

Since the solution theory requires an actual removal of rock material to an amount at least equal to the length of the stylolites—sometimes as much as a foot, which would mean that the rock strata had been reduced in thickness that amount—one might expect a sag of the overlying rock strata towards the center of the stylolite-parting, where solution reaches its maximum. The occurrence of such a sag is rare since stylolite-seams are so numerous and so distributed that the amount of displacement of one seam is compensated by that of an adjacent, underlying one. Such a phenomenon, however, was noticed by the writer, especially in one locality, a quarry of W. McMillan and Son, Reed Station district. Here, the occurrence of stylolite-seams is less common than usual. At the time of the writer's observation, a quarry face exposed an entire stylolite-seam, grading at both ends into a hardly noticeable line, and reaching a maximum thickness of eight inches in the middle. A sag in the seam and the well-laminated bed above it, equivalent to about eight inches (the maximum amount of penetration), was distinctly noticeable.

RELATION OF STYLOLITES TO THE COLOR OF THE ROCK. The difference in color of the Salem limestone presents some peculiarly interesting relationships in the study of stylolites. The sutures are frequently found at the contact of beds of the blue and buff varieties of stone, in which case the columns pointing in one direction will stand out in color contrast with the adjacent ones (see Fig. 26). An interesting case is represented in Fig. 27 in which the blue and buff contact presents quite an irregular outline. Here, the irregular blue parts of the upward-pointing columns are not continued into the adjacent downward-penetrating buff columns. This phenomenon involves a consideration of the origin of the two colors of the stone. If the rock were all originally blue, according to the generally accepted theory, the question arises as to whether or not the irregular color change of the above-figured example took place before, or after, the development of the stylolites. It would appear that the stylolitic development was subsequent to the color change—that the blue parts of the underlying stratum have been actually removed and are now occupied by the downward-projecting buff columns of the overlying layer. If this was the case, the phenomenon furnishes additional evidence that the stylolitic structures

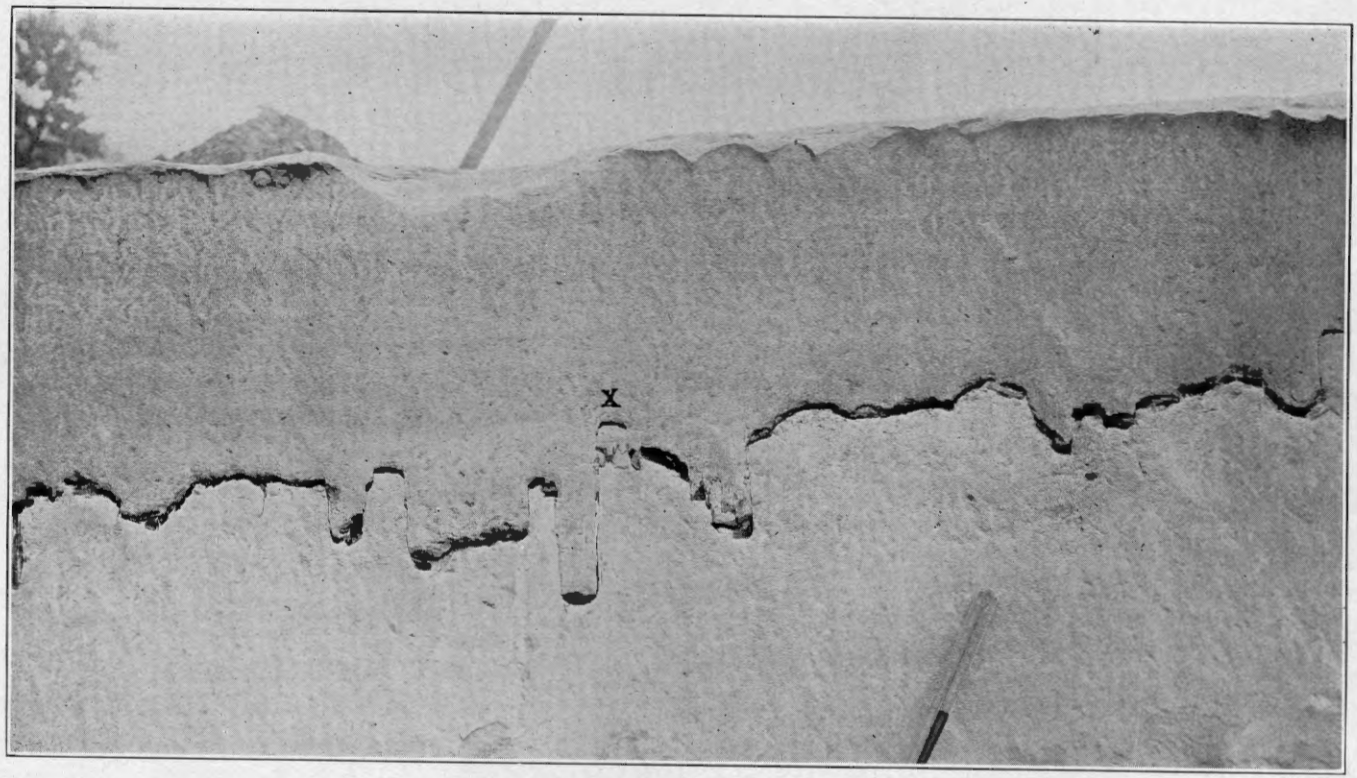

FIG. 26.—A typical, large stylolite-seam in the Salem limestone of the Dark Hollow district, Lawrence County, Ind. Note the irregularity in length and width of the interpenetrating parts. The darker, upper stratum is blue stone; and the lower, buff. Note the small, minor stylolite-seam running across the column below X. The clay parting is plainly visible. The upper and lower strata are distinctly lithologically different. The longest column is about 9 inches.

were formed after the hardening of the rock, since the alteration of the buff stone from the blue is in itself (according to the theory) a feature which occurred since the consolidation of the rock. Observations of the above nature are not uncommon in the Salem limestone. It has been suggested, however, that the above-described color changes of alternating columns could have occurred since the development of the stylolites, altho evidence appears to be against it.

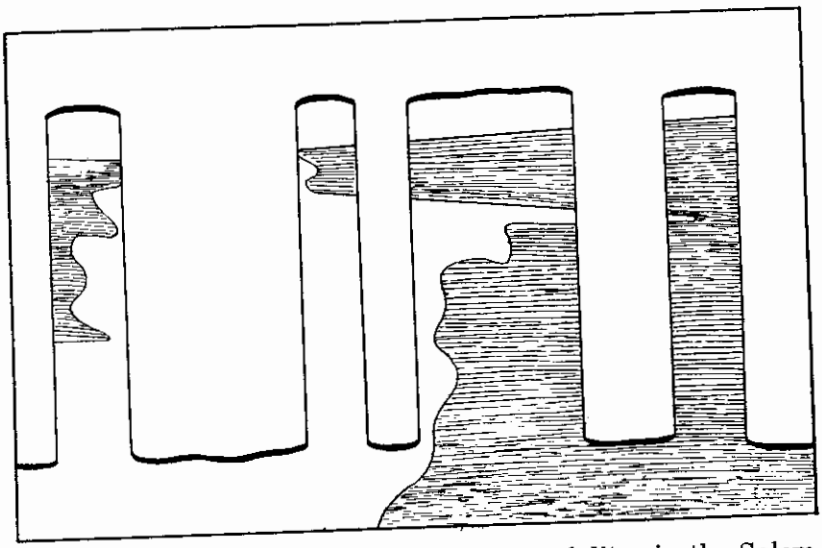

FIG. 27.—Semi-diagrammatic sketch of stylolites in the Salem limestone, showing blue (shaded) portions of the lower stratum penetrated by buff columns of the upper layer. One-third natural size.

RELATION OF STYLOLITES TO FOSSILS. Careful observations of Indiana stylolites show the presence of fossil caps to be an exception. This fact alone precludes Marsh's theory in which the fossil caps were an essential feature. The former assumption that each column has a shell at its end was no doubt a prejudiced one. Stylolitic phenomena are just as numerous in the non-fossiliferous, even lithographic, strata as in the highly fossiliferous ones. Only a few cases have been observed by the writer where the outline of the stylolite was determined by the presence of a fossil covering. Frequently, however, the stylolite ends are partially covered

by a shell. The presence of a shell covering might, no doubt, favor the formation of the columns, the shell often being more resistant to solution than the opposite rock mass. Shell coverings, when present, often show distinct signs of corrosion—a distinct evidence in support of the solution theory. Wagner's investigations of the Muschelkalk stylolites revealed the frequent occurrence of fossil coverings which determined the shape of the columns. The fossils of the Muschelkalk, however, are much larger than those of the Indiana limestones. Wagner treats of the subject in much detail (Wagner, 1913, pp. 119-121).

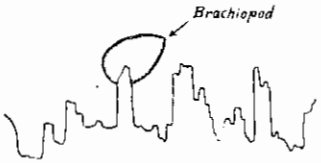

FIG. 28.—Example of a brachiopod shell partially penetrated by a column of a small stylolite-seam. Mitchell limestone. Two times natural size.

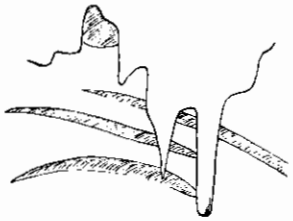

FIG. 29.—Mussel shells pierced by stylolites. (After Wagner.)

The smoothness and sharpness with which the edges of stylolites are cut is striking. Close inspection of the columns shows that the hundreds of fossils, oölitic grains, mineral crystals, etc., have been sharply smoothed off at the contact of the sides of the penetrations. The missing remains are not to be found. The lower, coarsely fossiliferous portion of the Harrodsburg limestone reveals many examples of this, and microscopic examination of the fine-grained Salem limestone gives an abundance of distinct evidence. Above or below the stylolite-seams are often found remains of brachiopods, gastropods, bryozoans, etc., which have been pierced, or

partially penetrated, by small columns (see Figs. 28 and 29). Polished surfaces of the Tennessee marble often offer splendid examples of this (see Fig. 30). Many specimens of fossils which have been penetrated by stylolites are found in the Columbus limestone of Ohio. One of the most striking ex-

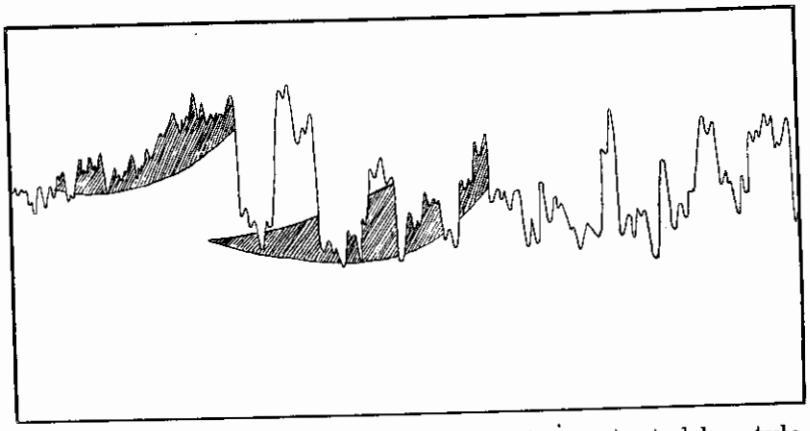

FIG. 30.—Large shells (shaded portions) penetrated by stylolites. Specimen is from a polished slab of Tennessee marble in the Monroe County State Bank, Bloomington, Ind. Three-fourths natural size.

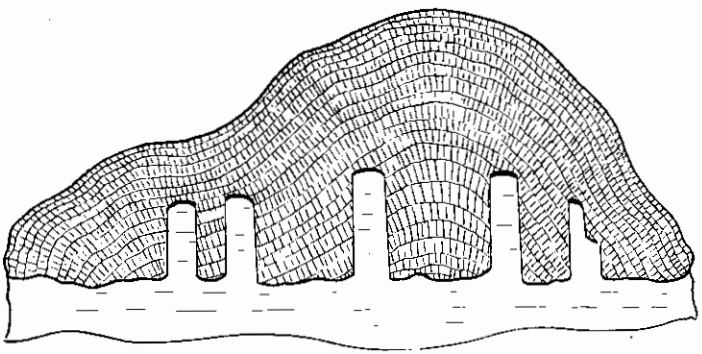

FIG. 31.—Diagram of a stromatoporoid into which a series of stylolites have penetrated. Note that the fossil structure has been actually removed where the upward-pointing columns occur. From a specimen in the Geological Museum, Ohio State University. About one-third natural size.

amples, observed by the writer, is that of a stromatoporoid into which a series of columns of considerable size have penetrated (see Fig. 31). Here is a conclusive case of part of the fossil structure having been actually removed, and occupied by the upward-pointing columns of the rock below. The residual clay is found in its place at the end of the columns.

These numerous, partially cut fossil shells, mineral grains, etc., mentioned above, show no evidence of compression or disturbance from their original positions. They have been cut after the rock material was firmly hardened and cemented together. These observations alone preclude all other theories of the origin of stylolites.

PENETRATION OF ONE STYLOLITE-SEAM BY ANOTHER ADJACENT PARALLEL SEAM. The vertical distance between stylolite-seams is quite variable. It is sometimes as small as a few inches. Sometimes the seams are so close as to touch, penetrate, or pierce one another. In all cases, parallel stylolite-seams, as they grow, become closer together by a distance dependent upon the amount of solution which takes place. Thus, two parallel seams, which in their beginning were separated by a very thin layer, might, after sufficient solution and growth, become so close as to touch one another (see Fig. 32). Continued solution would result in the interpenetration of the two, and still further growth would cause a partial, or complete, eradication of one or the other. These various stages are observed in the Indiana limestones. The above-mentioned Fig. 25 is an example where a large, major stylolite-seam has partially destroyed a small, minor one. Individual stylolite-columns of various sizes, which bear a partially penetrated column of an overlying or underlying seam, have been observed. Wagner (1913, p. 118) cites the example of an older curved stylolite which has been pierced by a younger vertical one (see Fig. 33). All this evidence is decisive proof of the actual removal of rock material, and presents a phase of the problem which can be explained by no other theory than solution.

STRIATED AND SLICKENSIDED FACES OF STYLOLITES. The ever-present striations on the side-surfaces of stylolites, running parallel with the direction of penetration, present a problem hard to explain by the pressure, and other theories.

FIG. 32.—Two parallel stylolite-seams of the Salem limestone, which, in places, touch and partially penetrate one another.

Still more difficult to account for by the pressure theory are the numerous polished and slickensided mineral deposits—usually calcite—on the sides of the columns (see pp. 50 and 88). There can be no question but that this mineral matter was deposited there after the rock had become hardened. Further movement of the columns past one another then resulted in the polishing of such deposits. That striations and slickensides were developed while the rock was yet in a soft plastic state appears to be a physical impossibility. They result from the slow slipping of the face of one column along that of the adjacent one, in hardened rock, such as takes place along a fault surface. Striations of stylolites of coarse-grained stone are deeper and coarser than those of finer-grained rock.

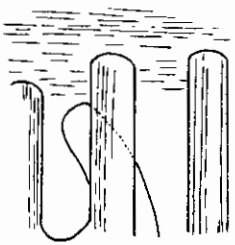

FIG. 33.—Example of an older, curved stylolite pierced by a younger, vertical one. (After Wagner.)

If stylolites were formed in soft, plastic sediment, as explained by the pressure theory, should not one expect the sides of the alternating columns to be intercemented at the time of the hardening and cementation of the entire rock mass? Such is not the case.

DIRECTION OF STYLOLITES AND STYLOLITE-SEAMS. The pressure theory would require that stylolite-seams be developed along bedding or lamination planes where a film of clay has been deposited. Differential compression of the plastic, or semi-plastic, mass would thus produce vertical columns at right angles to the bedding planes. However, stylolite-seams are developed along inclined bedding planes with the columns not at right angles to them (see p. 54). Such stylolites have been formed subsequent to the folding and tilting of the strata. Folding obviously either occurred after

the rock had become consolidated, or was responsible for the consolidation. That the pressure theory fails to explain such an occurrence of stylolites is evident.

The pressure theory also fails to explain the origin of stylolite-seams which cut across the stratification at various angles (see Fig. 17). If adherents of the pressure theory would have the seam developed along an angular crevice, it would fall upon them to explain the origin and existence of such a crack in plastic rock. Equally difficult would it be to explain the occurrence of a clay layer along such a crevice (see p. 86).

2. Evidence that the Clay Partings Are the Solution Residue of the Dissolved Limestone

The general assumption of most investigators of stylolitic phenomena, with the exception of the exponents of the solution theory, is that the ever-present clay partings of stylolite-seams represent original, once-continuous, thin layers of clay material laid down in the seas with the lime sediments. The solution theory holds that the clays are the residue of the dissolved rock, altho advocates of the theory, however, have never given conclusive proof of this. The writer wishes to present several lines of evidence showing that the clays are a solution residue.

CHEMICAL RELATIONS BETWEEN THE CLAY CAPS AND THE ASSOCIATED LIMESTONE. No investigator has attempted an analysis of the ever-present clays of stylolites to show the chemical relations between them and the associated limestone (or dolomite or marble). If the clay caps are the solution residue of the dissolved limestone, one should expect a definite relationship between their chemical constituents and those of the limestone from which they were derived. The clay should consist, in the main, of the least soluble components of the parent limestone, with probably a subordinate amount of the soluble substances which have not yet been completely dissolved; since, in the solution of limestone, only the calcium carbonate is removed in appreciable quantities. The clay, if a solution residue, should be nothing more than a concentration of the less soluble constituents of the rock from which it was derived. It should contain these substances in a proportion dependent primarily upon the amount dissolved and carried away during the weathering of the parent rock.

The writer wishes to consider (*a*) the decomposition of limestones in general, showing the relationship between their chemical constituents and those of their residual clays; and (*b*) the chemical relations between the clay partings of stylolite-seams and the associated limestones, showing that the clays fulfil the requirements of a residual product of the limestones in which they are found.

It has already been pointed out that since limestones are composed, for the most part, of calcium carbonate, their decomposition is effected primarily by solution—especially in humid climates (see p. 48). In the alteration of limestone to residual clay, the soluble constituents of the parent rock are leached out (in varying proportions, depending upon the solubility) and the less soluble constituents are concentrated in the form of a clay residue. By comparing the chemical composition of an original rock with the composition of its decomposed equivalent, one is able to obtain an approximate idea of the loss of the various elements. In order to understand best the changes which take place in limestones, reference should here be made to Tables No. 1, 2, and 3. In these tables, column I is the analysis of the fresh limestone, while column II is that of the residual product. Columns III, IV, and V are calculated from I and II.[7] Column IV shows the percentage of each constituent saved, assuming a certain substance to be constant (silica or alumina), while column V gives the percentage of each constituent lost. Column III, the percentage of loss for the entire rock, is derived by multiplying I by V. The supposition, however, that any element is fixed in amount is erroneous, since the most resistant materials are attacked, to a limited extent, by carbonated waters (Van Hise, 1904, p. 514). In making calculations, the method has been to choose the constituent in which the loss has been least, and by this to gauge the loss of the other substances. A study of the decomposition of limestone shows calcium carbonate to be removed in most appreciable quantities, while

[7] The formula employed in these calculations is as follows: $\frac{A}{B \times C} = x$; and $100 - x = y$, in which A = the percentage of any constituent in the residual material; B = the percentage of the same constituent in the fresh rock; and C = the quotient obtained by dividing the percentage of alumina (or silica, whichever is taken as a constant factor) of the residual material by that in the fresh rock, the final quotient being multiplied by 100. Then x equals the percentage of the original constituent saved, in the residue, and y the percentage of the same constituent lost. (Merrill, G.P., 1921, p. 188, footnote 2.)

TABLE No. 1

Analyses of Fresh Limestone and Its Residual Clay, Batesville, Ark. From: MERRILL, G. P. 1921. Rocks, Rock-Weathering and Soils, p. 217.

CONSTITUENTS	I Fresh Limestone	II Residual Clay	III Percentage of Loss for Entire Rock	IV Percentage of Each Constituent Saved	V Percentage of Each Constituent Lost
	Per cent	Per cent	Per cent	Per cent	Per cent
Silica (SiO_2)	4.13	33.69	0.00	100.00*	0.00
Alumina (Al_2O_3)	4.19	30.30	0.47	88.65	11.35
Ferric oxide (Fe_2O_3)	2.35	1.99	2.11	10.44	89.56
Manganic oxide (MnO)	4.33	14.98	2.49	42.41	57.59
Lime (CaO)	44.79	3.91	44.32	1.07	98.93
Magnesia (MgO)	0.30	0.26	0.27	10.62	89.38
Potash (K_2O)	0.35	0.96	0.23	33.63	66.37
Soda (Na_2O)	0.16	0.61	0.085	46.74	53.26
Water (H_2O)	2.26	10.76	0.95	58.37	41.63
Carbon dioxide (CO_2)	34.10	0.00	34.10	0.00	100.00
Phosphoric acid (P_2O_5)	3.04	2.54	2.73	10.24	89.76
Total	100.00	100.00	87.755	.....	.....

*Silica taken as constant.

TABLE No. 2

Analyses of Fresh Limestone and Its Residual Clay, Staunton, Va. From: MERRILL, G. P. 1921. Rocks, Rock-Weathering and Soils, p. 219.

CONSTITUENTS	I Fresh Limestone	II Residual Clay	III Percentage of Loss for Entire Rock	IV Percentage of Each Constituent Saved	V Percentage of Each Constituent Lost
	Per cent	Per cent	Per cent	Per cent	Per cent
Silica (SiO_2) Titanium dioxide (TiO_2)	7.41	57.57	2.03	72.61	27.39
Alumina (Al_2O_3)	1.91	20.44	0.00	100.00*	0.00
Ferric oxide (Fe_2O_3)	0.98	7.93	0.29	75.11	24.89
Lime (CaO)	28.29	0.51	28.24	0.17	99.83
Magnesia (MgO)	18.17	1.21	18.06	0.62	99.38
Potash (K_2O)	1.08	4.91	0.62	42.51	57.49
Soda (Na_2O)	0.09	0.23	0.07	23.96	76.04
Carbon dioxide (CO_2)	41.57	0.38	41.53	0.85	99.15
Phosphoric acid (P_2O_5)	0.03	0.10	0.02	31.22	69.78
Water (H_2O)	0.57	6.69	0.55	Gain	Gain
Total	100.00	100.00	90.86		

*Alumina taken as constant.

TABLE No. 3

Analyses of Fresh Limestone and Its Residual Clays (Collected from Two Horizons), Campus of Mississippi Agricultural and Mechanical College. From: LOGAN, W. N. 1907. Mississippi Geological Survey, Bull. 2, Part I, p. 222.

	I	II	III	IV	V	VI	VII	VIII	IX
CONSTITUENTS	Fresh Limestone	Residual Clay	Percentage of Loss for Entire Rock	Percentage of Each Constituent Saved	Percentage of Each Constituent Lost	Residual Clay	Percentage of Loss for Entire Rock	Percentage of Each Constituent Saved	Percentage of Each Constituent Lost
Moisture (H_2O)	0.81	4.06	0.00	Gain	Gain	2.95	0.00	Gain	Gain
Volatile matter (CO_2, etc.)	28.61	8.60	24.75	13.48	86.52	10.90	23.72	17.09	82.91
Silica (SiO_2)	27.05	60.43	0.00	*100.00	0.00	56.97	1.55	*94.27	5.73
Ferric oxide (Fe_2O_3)	5.45	10.05	0.94	82.70	17.30	10.40	0.78	85.59	14.41
Alumina (Al_2O_3)	6.45	13.15	0.55	91.40	8.60	15.09	Gain	104.00	Gain
Lime (CaO)	30.21	2.13	29.26	3.16	96.84	1.00	29.76	1.48	98.52
Magnesia (MgO)	0.00	0.54	0.00	Gain	Gain	1.25	0.00	Gain	Gain
Sulphur trioxide (SO_3)	0.32	0.36	0.16	50.45	49.55	0.34	0.17	47.65	52.35
Total	98.90	99.32	55.66	.....	.....	98.90	55.98	.....	.....

*Silica in II taken as constant.

Column I. Fresh Selma limestone.
II. Residual clay of I, collected at bottom of deposit near contact with limestone.
III. Percentage of loss for entire rock.
IV. Percentage of each constituent saved.
V. Percentage of each constituent lost.
VI. Residual clay of I, collected in middle of deposit, above II.
VII. Percentage of loss for entire rock.
VIII. Percentage of each constituent saved.
IX. Percentage of each constituent lost.

Columns III, IV, V, VII, VIII, IX calculated by the writer.

silica and alumina are least attacked. The amount of lime retained in the residual clays is quite variable. Analyses often show an increase in the percentage of lime upon approaching the parent rock (see Table No. 3, columns II, IV, VI, and VIII). From the analyses of various limestones and their residual clays one learns that in some cases alumina is the most constant constituent, and in others, silica. If pyrite is present in the limestone, the alumina may be removed in part as aluminum sulfate. Where alkalies are almost wholly lacking in the fresh rock, it is believed that one is safe in saying that little or no silica is lost thru the action of alkaline carbonates (Merrill, G.P., 1921, p. 217). As the Tables No. 1, 2, and 3 (column IV) show, most of the silica and alumina of the parent rock is saved, and one is safe in assuming that neither of these constituents is lost in appreciable quantities in the decomposition of limestone. Magnesium carbonate is generally more resistant than calcium carbonate, altho Van Hise points out that "in some instances more magnesia is dissolved than lime" (Van Hise, 1904, p. 516). A good portion of the potash and soda remains in the clay, these materials being less soluble than either magnesia or lime. C. H. Smyth, Jr. (1913, Jour. Geol., Vol. 21, pp. 105-120) shows that the solubility of potash is low as compared with that of calcium carbonate. The solubility of soda, however, is often fairly high, altho variable.

The amount of iron leached out varies greatly and irregularly (see Tables No. 1, 2, and 3; column V).

> Doubtless this variability is dependent upon the fact that iron occurs in both the ferrous and ferric forms—the former being more readily soluble. Where the iron is mainly ferrous, one would expect that a larger proportion would be dissolved; where ferric, a smaller proportion (Van Hise, 1904, p. 517).

In the complete decomposition of any rock, the ferrous oxide (which has not been leached out) is almost entirely oxidized to the ferric state. A striking characteristic of residual clays is the high percentage of ferric oxide as compared with the small amount of ferrous oxide (see analyses of residual clays: Clarke, F. W., 1916, pp. 507-508; Merrill, G.P., 1921, p. 294). In sedimentary clays and shales one usually finds a considerable portion of the iron as ferrous oxide. This is surprisingly well shown in a composite analysis of fifty-one Paleozoic

shales which show 2.90 per cent of FeO and 4.04 per cent of Fe_2O_3 (Clarke, F.W., 1916, p. 546). Clarke points out that

> In the shales the proportion of ferrous relatively to ferric oxide has increased; probably because of the reducing action of organic matter in the sediments as they were first laid down. Ferric oxide has been evidently reduced, and organic substances furnish the most obvious reagents for producing such an alteration.

That most of the parent limestone is lost in its decomposition is well shown in Tables No. 1 and 2, column III. In the first, 87.75 per cent of the original rock was lost, while in the second, 90.86 per cent. The amount of loss of the parent rock is dependent, of course, upon the quantity of soluble materials. The order of loss of the various constituents is somewhat variable in different cases, but commonly occurs as follows:

a. Lime—removed in most appreciable quantities, usually 90-100 per cent.
b. Magnesia—usually more resistant than lime, altho in some instances it is dissolved more rapidly than the lime.
c. Soda—solubility often fairly high, altho variable.
d. Potash—solubility low as compared with lime.
e. Iron oxide—solubility quite variable, depending upon whether it exists as ferrous or ferric oxide, the former being more readily dissolved. Most of the iron of the residual clay occurs as ferric oxide.
f. Alumina—practically insoluble. It may be removed in part, however, as aluminum sulfate, if the limestone contains pyrite.
g. Silica—practically insoluble. It may also be partially leached out if the rock contains alkalies in appreciable quantities.

The writer wishes to present three tables of analyses—Tables No. 4, 5, and 6—to show the chemical relationship between the clay partings of stylolite-seams and the associated limestones. Each table gives the analysis of the fresh limestone (column I); the analysis of the clay of the stylolite-seam (column II); the percentage of loss of the entire rock (column III); the percentage of each constituent saved (column IV); and the percentage of each constituent lost (column V). Columns III, IV, and V were calculated on the

assumption that the clays are residual, in view of determining whether or not they fulfil the requirements of a solution residue of the limestone in which they are found.

In selecting material for the analyses one must take precautions that the samples are properly related—the limestone must be the nearest possible to that from which the clay was supposedly derived. Thus, the limestone directly above an upward-penetrating stylolite would probably be a fair test of the stone from which the clay cap was derived, unless there had been also some solution of the column itself. The limestone of the adjacent downward-penetrating stylolite would also furnish a fair test of the material which had been removed next to it. Since the clays are so thin, difficulty is experienced in collecting material which is entirely free from particles of the adjacent country rock. At the best, one can hardly expect to procure a sample which would give an errorless analysis of the missing dissolved limestone. The following analyses, however, show surprising results:

TABLE No. 4

Analyses of Salem Limestone (Blue) and Residual Clay of Associated Stylolite-Seam, from Quarry of Consolidated Stone Company, Dark Hollow District, Lawrence County, Ind.

Constituents	I		II		III	IV	V
	Fresh Limestone		Residual Clay		Percentage of Loss for Entire Rock	Percentage of Each Constituent Saved	Percentage of Each Constituent Lost
Silica (SiO_2)	0.84		29.64		0.10	88.30	11.70
Alumina (Al_2O_3)	0.18		7.16		0.00	100.00*	0.00
Ferric oxide (Fe_2O_3)	0.04		8.22		0.56	28.30	71.70
Ferrous oxide (FeO)	0.76		0.84				
Ferrous carbonate ($FeCO_3$)		0.55					
Lime (CaO)	54.04		14.80		51.40	6.80	93.20
Calcium carbonate ($CaCO_3$)		96.50					
Magnesia (MgO)	0.08		0.44		0.07	13.80	86.20
Magnesium carbonate ($MgCO_3$)		0.17					
Potash (K_2O)	0.15		3.58		0.06	59.60	41.40
Soda (Na_2O)							
Total silicates and oxides not combined with CO_2		1.63		49.44			
Carbon dioxide (CO_2)	42.76		12.10		39.72	7.10	92.90
Volatile and combustible matter, less CO_2	0.60	0.60	19.14	19.14	0.12	79.80	20.20
Total	99.45	99.45	95.92		91.50		

*Alumina taken as constant.

Column I. Fresh Salem limestone (blue variety).
II. Black residual clay of stylolite-seam associated with I.
Analyses by Kenneth W. Ray, Indiana University, 1921.
Columns III, IV, V calculated by the writer.

TABLE No. 5

Analyses of Salem Limestone (Buff) and Residual Clay of Associated Stylolite-Seam, from Quarry of Consolidated Stone Company, Dark Hollow District, Lawrence County, Ind.

Constituents	I		II		III	IV	V
	Fresh Limestone		Residual Clay		Percentage of Loss for Entire Rock	Percentage of Each Constituent Saved	Percentage of Each Constituent Lost
Silica (SiO_2)	0.89	.....	39.92	.....	0.00	100.00*	0.0
Alumina (Al_2O_3)	0.20	.....	8.76	.....	0.005	97.30	2.7
Ferric oxide(Fe_2O_3)	0.04	.....	14.41	.....	0.11	76.10	23.9
Ferrous oxide(FeO)	0.41	.....	1.01	.....			
Ferrous carbonate ($FeCO_3$)	.....	0.47	.....	.....	.....	.....	.....
Lime (CaO)	53.28	.....	15.68	.....	49.80	6.60	93.4
Calcium carbonate ($CaCO_3$)	.....	95.14	.....	.....	.....	.....	.....
Magnesia (MgO)	0.54	.....	0.08	.....	0.52	3.30	96.7
Magnesium carbonate ($MgCO_3$)	.....	1.13	.....	.....	.....	.....	.....
Potash (K_2O) Soda (Na_2O)	0.07	.....	1.56	.....	0.036	49.50	51.5
Total silicates and oxides not combined with CO_2	.....	1.32	.....	65.74	.....	.....	.....
Carbon dioxide (CO_2)	42.63	.....	9.52	.....	40.40	4.90	95.1
Volatile and combustible matter, less CO_2	0.43	0.43	7.94	7.94	0.26	39.00	61.0
Total	98.49	98.49	98.88	.....	91.135	.....	.....

*Silica taken as constant.

Column I. Fresh Salem limestone (buff variety).

II. Brown residual clay of stylolite-seam associated with I.

Analyses by Kenneth W. Ray, Indiana University, 1921.

Columns III, IV, V calculated by the writer.

TABLE No. 6

Analyses of Harrodsburg Limestone and Residual Clay of Associated Stylolite-Seam, from Quarry Two Miles Northeast of Bloomington, Ind.

Constituents	I		II		III	IV	V
	Fresh Limestone		Residual Clay		Percentage of Loss for Entire Rock	Percentage of Each Constituent Saved	Percentage of Each Constituent Lost
Silica (SiO_2)	9.58	.....	33.68	.....	0.00	100.00*	0.0
Alumina (Al_2O_3)	3.39	.....	10.78	.....	0.31	90.9	9.1
Ferric oxide (Fe_2O_3)	2.18	.....	6.56	.....	0.22	88.9	11.1
Lime (CaO)	41.74	.....	17.94	.....	36.60	12.3	87.7
Calcium carbonate ($CaCO_3$)	.....	74.49	.....	.....	.....	.....	.....
Magnesia (MgO)	3.97	.....	1.89	.....	3.43	13.6	86.4
Magnesium carbonate ($MgCO_3$)	.....	8.30	.....	.....	.....	.....	.....
Total silicates and oxides not combined with CO_2	.....	15.15	.....	51.02	.....	.....	.....
Carbon dioxide (CO_2)	37.08	.....	16.14	.....	32.44	12.5	87.5
Volatile and combustible matter, less CO_2	1.51	1.51	3.98	3.98	0.37	75.7	24.3
Total	99.45	99.45	90.97	.....	73.37	.....	.....

*Silica taken as constant.

Column I. Fresh Harrodsburg limestone.

II. Gray residual clay of stylolite-seam associated with I.

Analyses by J. C. Warner, Indiana University, 1920.

Determinations for FeO, $FeCO_3$, K_2O, and Na_2O were not made.

Columns III, IV, V calculated by the writer.

It has been shown that, in the transformation of limestone to residual clay, silica and alumina are two constituents which are retained with little or no loss. Therefore, one finds that practically the same ratio exists between the silica and alumina of a parent limestone and the silica and alumina of the derived clay (see Tables No. 1, 2, and 3; columns I and II). In the above analyses of limestones and stylolite-clays several relationships are striking and convincing. In Table No. 4 the fresh limestone contains 0.84 per cent silica and 0.18 per cent alumina—a ratio of about 4.6 to 1. In the clay there is 29.64 per cent silica and 7.16 per cent alumina—a ratio of 4.1 to 1. The limestone of Table No. 5 contains 0.89 per cent silica and 0.20 per cent alumina, the ratio being 4.45 to 1; the associated clay has 39.92 per cent silica and 8.76 per cent alumina, the proportion being about 4.5 to 1. In the limestone of Table No. 6 there is 9.58 per cent silica to 3.39 per cent alumina, while in the clay the amounts are 33.68 per cent and 10.78 per cent. In both analyses (limestone and associated clay) silica and alumina occur in approximately the same ratio, 3 to 1. Thus it is seen, in the three above sets of analyses, that, as far as the ratio between silica and alumina is concerned, the clays of the stylolite-seams fulfil the requirements of a residual limestone clay.

A study of the relationship of the iron oxide content of the fresh limestone to that of the stylolite-clay also reveals evidence that the clay is of residual origin. In the limestones (Tables No. 4 and 5; column I), one finds the iron oxide existing principally as ferrous oxide, with but a bare trace of ferric oxide; while in the clays (column II), the reverse is noted. An oxidation of ferrous to ferric oxide is normal in the decomposition of limestone to residual clay (see p. 72). If the clays of the stylolite-seams were of sedimentary origin —as exponents of the pressure theory would have them—one would expect to find a considerable portion of their iron as ferrous oxide. As the analyses show, however, the ferrous oxide is low compared to the ferric. It is seen also that in Table No. 4 there is a greater loss of iron oxide (column V) than in Table No. 5. Such is to be expected in view of the fact that in the limestone of the former the percentage of ferrous oxide is greater than in that of the latter. Where the iron is mainly ferrous, one may expect considerable proportions to be dissolved (see p. 72). Thus, from the analyses,

it is seen that the behavior of the iron content is as should be expected in the transformation of a limestone to its residual clay.

In considering the proportionate amount of lime, one finds that the greatest percentage of that of the parent rock has been lost—assuming, of course, that the clays are of residual origin. The analyses show a loss of 93.20 per cent, 93.40 per cent, and 87.70 per cent in Tables No. 4, 5, and 6 respectively (column V). This is hardly as great a loss of lime as usually is found in the decomposition of limestone, altho it compares very favorably with some analyses. The lime content of the clay can readily be accounted for by the occurrence of corroded fossil fragments which have not been completely dissolved (see p. 85), and also by the fact that difficulty is found in collecting clay which is entirely free from particles of the adjacent country rock. In the second place, one should hardly expect as thoro a leaching of the calcium carbonate of a stylolite clay seam as that of a residual limestone soil. Residual limestone clays are formed on top of the bed rock and are continually being acted upon by fresh meteoric waters; while stylolite-clays, which occur within the strata, are subjected to the action of waters which have passed thru the overlying bed rock and are already more or less saturated with calcium carbonate.

The analyses also show the expected loss of magnesia. In Tables No. 4 and 6 the amount of magnesia lost is somewhat less than that of lime, while in No. 5 it is slightly greater. The tables also show that most of the carbon dioxide was lost—92.90 per cent, 95.10 per cent, and 87.50 per cent in Tables No. 4, 5, and 6, respectively. The carbon dioxide content of a residual clay is dependent, principally, upon the amount of lime and magnesia with which it is united as carbonates. The analyses show further that the loss of potash and soda is as should be expected in the decomposition of a limestone. These two constituents, being less soluble than lime or magnesia, would normally be retained in greater quantities.

Table No. 7 is compiled for a comparison of the percentages of various constituents lost. The first three columns (taken from Tables No. 1, 2, and 3) show the percentages of the materials lost in the transformation of limestone to residual clay soil; while the last three columns (taken from

Tables No. 4, 5, and 6) show the loss in the formation of the clays of the stylolite-seams, assuming the clays to be of residual origin. One finds, in making a careful study of this comparison, that the loss of the various constituents in the stylolite-clays is in direct accord with that in the transformation of a limestone to its residual product. If the stylolite-clays were of sedimentary origin, one surely would not expect this relationship to exist.

TABLE No. 7

Table for a Comparison of the Percentages of Various Constituents Lost in the Transformation of Limestones to Their Residual Clays.

Compiled from Column V of the preceding analyses, Tables No. 1–6.

Constituents	Residual Limestone Clays			Clays of Stylolite—Seams		
	Table 1	Table 2	Table 3	Table 4	Table 5	Table 6
Silica (SiO_2)	0.00*	27.39	0.00*	11.70	0.00*	0.00*
Alumina (Al_2O_3)	11.35	0.00*	8.60	0.00*	2.70	9.10
Ferric oxide (Fe_2O_3) ... Ferrous oxide (FeO) ...	89.56	24.89	17.30	71.70	23.90	11.10
Lime (CaO)	98.93	99.83	96.84	93.20	93.40	87.70
Magnesia (MgO)	89.38	99.38	Gain	86.20	96.70	86.40
Potash (K_2O)	66.37	57.49	.....	41.40	51.50	.....
Soda (Na_2O)	53.26	76.04				
Carbon dioxide (CO_2) ...	100.00	99.15	86.52	92.90	95.10	87.50
Water (H_2O)	41.63	Gain	Gain	.....	.....	.....
Volatile and combustible matter, less CO_2	.....	.....	.....	20.20	61.00	24.30

*Taken as constant.

Since the per cent of soluble constituents in the limestones of Tables No. 4 and 5 is very high, one would expect a large proportion of the parent rock to be lost when decomposed. The calculations show a total loss for the entire rock of 91.50 per cent and 91.135 per cent (column III). These samples were collected from the same quarry, but from different stylolite-seams. Thus, the figures show that solution affected both limestones equally. Such would be expected. Since less than 9 per cent (by weight) of the limestone is saved, it is readily seen that a considerable amount of decomposed limestone would be necessary to produce a small deposit of residue.

The clay caps of the stylolites of the Salem limestone are always thin in comparison with the length of the stylolite (the length of the stylolite gives a fair measure of the amount of solution which has occurred). In the quarry from which the samples of Tables No. 4 and 5 were collected, stylolites about 1 foot in length bear well-compacted clay caps not over ⅜ to ½ inch in thickness. In no instance is the clay parting too thick to be explained by the solution theory. The samples in Table No. 6 were collected from an impure stratum of Harrodsburg limestone. In the decomposition of this limestone, less of the original rock, as compared with the Salem limestone, would be lost by solution and a greater proportion left to accumulate as residual clay. Calculations show 73.37 per cent loss (by weight) for the entire rock (column III). The stylolites of this formation bear clay caps of a proportionately greater thickness than those of the Salem limestone. Fairly short, massive stylolites have clay caps up to an inch or more in thickness.

From the foregoing study of the chemical relations between the clay partings of stylolite-seams and the associated limestones, one can realize the conclusive evidence that the stylolite-clays fulfil the requirements of a residual product of the limestones in which they are found.

The analyses show that the general assumption, made by Hopkins and other observers, that the black and brown stylolite clay partings are of a highly carbonaceous nature, is a faulty one, since the content of volatile and combustible matter (less CO_2) is less than 20 per cent (see Tables No. 4 and 5; column II). In all instances there has been a loss of the volatile and combustible matter of the original rock. This is due to the expected oxidation and volatilization of a portion of the carbon content.

It should be noted that the limestones of Tables No. 4 and 5 contain only a trace of ferric oxide (in each instance 0.04 per cent) and a much greater amount of ferrous oxide. The analyses reveal further that they contain 0.60 per cent and 0.43 per cent, respectively, of combustible matter (carbon). The limestone of Table No. 4 is the so-called "blue" variety, while that of No. 5 is the "buff" stone. The writer believes that the generally accepted theory that the buff stone

is derived from the original blue as a result, primarily, of the oxidation of the ferrous oxide to the ferric, and, secondarily, of the oxidation of the organic matter to some volatile form, furnishes a problem worthy of further consideration. The analyses, referred to above, do not support the theory in regard to the iron oxide, since each sample of stone contains the same amount. Thus, the quantity of Fe_2O_3 could not account for the difference in color of the two samples. However, the expected relation in organic matter is noted, the blue stone containing 0.60 per cent, and the buff, 0.43 per cent. With a view to determine the cause of the coloration, Hopkins submitted three sets of analyses, of the two varieties of Salem limestone, which were not as satisfactory as might be desired (Hopkins and Siebenthal, 1897, p. 309; 1908, p. 315). In all cases the amount of ferric oxide was very small, less than 0.20 per cent, and did not substantially support the theory with regard to the coloration. In two of the three sets of analyses, the buff stone showed a slightly higher percentage of Fe_2O_3; but in one case the blue stone contained the greater amount. Hopkins pointed out that "the percentages are so small that it is doubtful whether the differences are due to more than the possible errors incident to manipulation". The analyses showed further, however, that the organic matter in each case was only half as much in the buff as in the blue stone. It should be borne in mind that the difference in color of the blue and buff stone is not great, sometimes scarcely perceptible in a hand specimen, but is often quite distinct on a large block or quarry face. In face of the limited evidence, the writer is inclined to believe the slight difference in color is due, primarily, to variations in the amount of organic matter.

There is always a definite relationship between the color of the clay partings of stylolite-seams and that of the associated limestone. Stylolites of the blue stone bear black caps; those of the buff stone, brown caps. From the analyses (Tables No. 4 and 5), one finds that the black residual clay from the blue stone contains 19.14 per cent organic matter and 8.22 per cent ferric oxide; whereas the brown clay of the buff stone has but 7.94 per cent combustible matter, and 14.41 per cent ferric oxide. In either clay the ferric oxide exists in more than sufficient quantity to produce a reddish

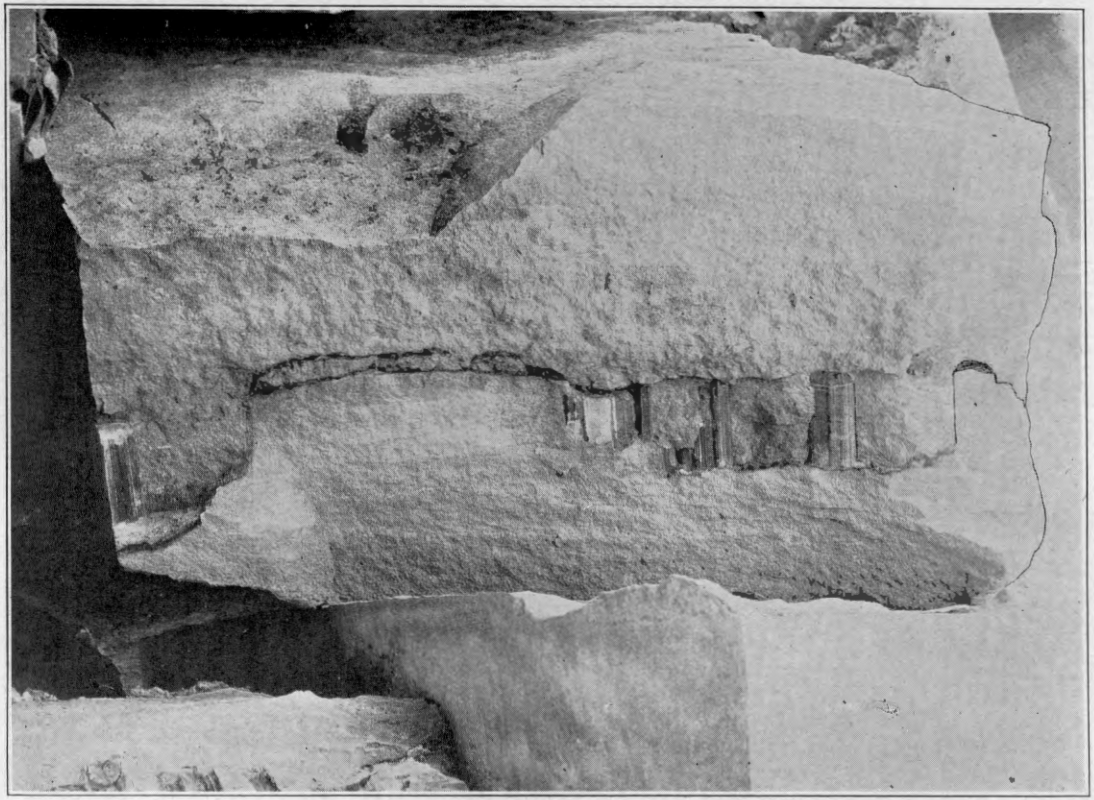

FIG. 34.—Stylolites of the Salem limestone, showing a double clay parting, separated by a thin layer of limestone, at the top of the wide column on the left. The other columns have single clay caps. Note the well-defined striations on the sides of the columns at the right. From a quarry of the Consolidated Stone Company, Dark Hollow district, Lawrence County, Ind.

show the Harrodsburg limestone to contain as much as six to eight times the amount of insoluble constituents as the Salem limestone (compare Table No. 5 with No. 6).

That the clay partings and the associated stylolites always show a definite chemical and physical relationship is certainly not a coincidence. It is conclusive proof that the clay is a residue from the solution of the limestone.

OCCURRENCE OF CORRODED FOSSIL FRAGMENTS IN THE CLAY RESIDUE. The presence of corroded fossil fragments in the clay caps speaks for itself. Altho often only microscopically visible, they are to be found. They are the partially dissolved remains of the original limestone, and make up a considerable portion of the subordinate calcium carbonate content of the residual clay.

SUBORDINATE FEATURES OF THE CLAY CAPS. Stylolite caps often present a compressed and semi-laminated appearance. Since the circulation of ground waters would be variable, one should not always expect a uniform, even rate of solution to take place. A retardation or pause in the solution would produce a consequent pause in the deposition of the residue and thus give a laminated appearance to the deposit. Altho the line of contact between the clay caps and the ends of the columns is usually sharply defined, a few examples were found which show a slight gradation resulting from a partial solution of the limestone column itself.

Occasionally, stylolites are found which have what might be termed a "double cap", where the end of the column is marked by two layers of clay separated by a thin layer of limestone (see Fig. 34). In such a case the solution has been divided between two crevices, and the combined thickness of the clay of the two partings of the one column is equal to that of the single cap of the adjacent column. Analogous to this, a stylolite frequently contains one or more small, subordinate stylolite-seams crossing it at right angles (usually near the end), while the surrounding columns show none. This is nothing more than subordinate solution which has taken place along crevices of this one major projection and has produced within it minor stylolite-seams (see Fig. 26).

3. Stratigraphic Evidence which Precludes the Pressure Theory and Supports the Solution Theory

OCCURRENCE OF STYLOLITES ONLY IN SOLUBLE ROCKS. Investigation of the geologic distribution of stylolites reveals indirect evidence that the phenomenon is one of solution. The fact that stylolites occur only in carbonate rocks—varieties of limestones, dolomites, and marbles—suggests solution as a factor, or otherwise they would not be limited to soluble rock strata (see p. 13). If the pressure theories of Marsh, Gümbel, Rothpletz, and others explain their origin, why should stylolites not be found in shales, sandstones, etc.? Could not Gümbel's experiment (see p. 27) be applied to rocks other than soluble ones?

OCCURRENCE OF ANGULAR STYLOLITE-SEAMS. It is interesting to note that in undisturbed strata, such as the southern Indiana limestones, the direction of stylolite penetrations is vertical (with but few exceptions), resulting from the static pressure of the overlying mass; and the direction of the stylolite-seams is usually horizontal, or nearly so, and parallel with the planes of stratification. However, in some instances, stylolites have developed along angular crevices which cut across the stratification (see Fig. 17). A normal fault surface, in one case, was stylolitic. In disturbed or metamorphic strata, where lateral pressure has been active, such as in the Muschelkalk of Germany and the Tennessee marble, stylolites run in all directions, the occurrence of vertical seams even being common. Stylolite-sutures which cross one another are observed. Since the pressure theory considers the clay caps of the columns as an original deposit of clay laid down in due order with the rest of the sediments, how can it explain the clay partings of angular to vertical stylolite-seams which cut across the stratification of the rock at various angles? These partings are undoubtedly not original deposits of clay, for they are by no means limited to the stratification planes of the stone (see pp. 44, 54, 67).

OCCURRENCE OF BRANCHING STYLOLITE-SEAMS. Commonly there are found two or more parallel stylolite-seams which converge and join into one larger seam, producing what might be called a "branching stylolite-seam" (see Figs. 35 and 36). This major, single seam sometimes continues some distance, and then branches again. The subordinate branches, after

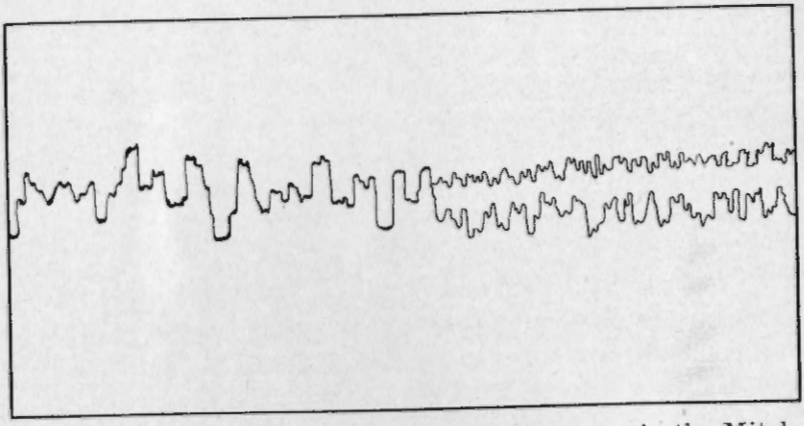

FIG. 35.—Diagram of a branching stylolite-seam in the Mitchell limestone. Note that the combined length of the columns of the two minor, branching seams is equivalent to that of the stylolites of the major, single seam. Three-fourths natural size.

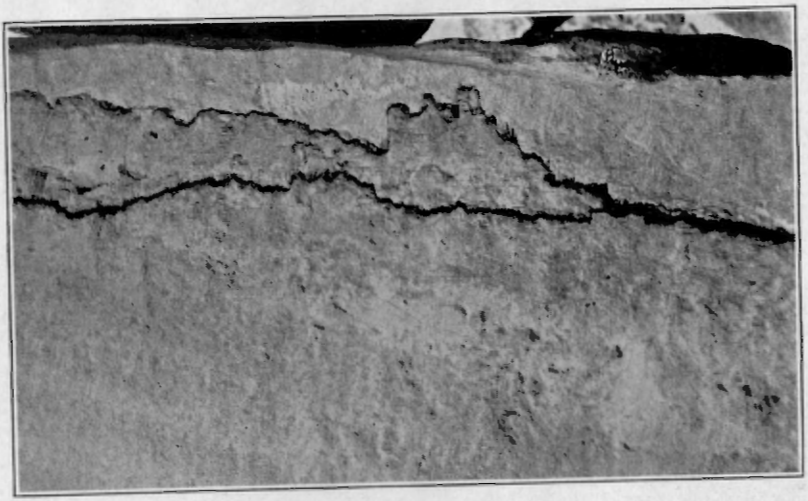

FIG. 36.—Branching stylolite-seam in the Salem limestone. Note that the combined thickness of the black clay of the two branching seams is equivalent to that of the major, single seam.

continuing parallel, often again converge into a single seam. In such cases, the combined thickness of the clay residue of the branching seams is equal to the thickness of that of the larger, single seam (see Fig. 36). At the places of branching, these subordinate seams cut across the lamination at a small angle. Such phenomena result from solution along a branching crevice. How could such a stratigraphic distribution of clay be explained by the pressure theory? The explanation of "double caps" (see p. 85) would also be very difficult by other theories than that of solution.

OCCURRENCE OF STYLOLITES ALONG DISCONFORMITIES. The occurrence of stylolites along the disconformable contact of two different geologic formations furnishes unusual evidence that the phenomena originated by the actual removal of hardened rock, rather than by the differential compression of plastic sediments. The writer has in mind, especially, the presence of stylolites along the undulating contact of the Monroe (Silurian) with the Columbus (Devonian) limestones of central Ohio[8], and along the disconformity between the Louisville (Silurian) and Geneva (Devonian) limestones of southern Indiana. The latter observation was made by the writer in the vicinity of North Vernon, Ind. Here, the unconformity represents a "lost interval" of several geologic ages, the Louisville limestone being Niagaran (Lockport) in age, while the Geneva limestone is correlated with the Onondaga. It is an absurdity, of course, to conceive the two formations as having existed as soft plastic rock at the same time, as would be necessary under the pressure theory.

4. Other Evidence which Supports the Solution Theory

DEPOSITS OF MINERAL MATTER. Since there is an excess amount of solution of mineral matter at the ends of stylolites, because of the increase in pressure there, the solvent might become supersaturated, in which case a precipitation of the excess mineral matter would take place in the cavities and crevices where the pressure is less or absent (see pp. 50 and 66). Abundant evidence of this is found in field investigations. The presence of mineral matter on the side-surfaces of the columns (where pressure is at a minimum) has long

[8] Observations at this horizon have been made by Professor J. Ernest Carman, in his studies of the Monroe formation of Ohio.

been known, and gave rise to the early suggestions of the crystallization theory (see p. 22). The occurrence of calcite, gypsum, magnesium sulfate, and strontium sulfate has been described by various writers. Deposits of calcite, with often a subordinate amount of pyrite, are the principal ones found in connection with Indiana stylolites. Coatings of calcite on the sides of the columns occur sometimes with a thickness of as much as 1/16 of an inch or more. The deposits are thicker, in many cases, nearer the end (the older part) than the base of a column. Such deposits have usually been slickensided by further growth and interpenetration. This feature is unexplained by all other theories. Since the sides of stylolites are free from pressure, the deposition of mineral matter there is to be expected.

Several examples are found where small joints in the stratum immediately underlying a stylolite-seam are infiltrated with calcite. This mineral matter was no doubt derived from the solution of the limestone along the stylolite-parting. Fractures on the convex side of curved stylolites are often filled with mineral matter. Wagner stresses this observation (Wagner, 1913, p. 118). Various minor evidences of the deposition of mineral matter in connection with stylolites are common.

ANALOGY OF THE ORIGIN OF STYLOLITES TO THAT OF IMPRESSED PEBBLES. The occurrence of the phenomenon of impressed pebbles (of the solution type—see p. 16) is in itself evidence in support of the solution theory of stylolites. In both phenomena—impressed pebbles and stylolites—the solution of the one part results at the point of pressure of the other. Rothpletz's observation of two impressed limestone pebbles whose contact was marked by a minute stylolite-suture (see p. 18, and Figs. 9 and 10) is an observation in direct support of the solution theory of the origin of stylolites. Here was a case of an impression in a pebble resulting from the actual removal of hardened rock material by solution, where the contact with the pressed-in pebble was slightly interteethed as a result of subordinate differential solution.

CONCLUSION

The abundance of evidence in support of the solution theory of the origin of stylolites establishes the conclusion that

the solution of limestone, under pressure, and the resulting production of residual material are geologic processes which may have considerable bearing upon the explanation of various stratigraphic features and peculiarities of limestones. One can readily see that the occurrence of stylolites, themselves, indicates a secondary change of no little importance in the parent limestone. Not only are the original limestone strata reduced in thickness (which may be considerable in a highly stylolitic formation), but a secondary clay, of residual origin, is introduced. The writer is firmly convinced that many of the thin clay partings in limestones—always heretofore referred to as sedimentary clays or shales—are of residual origin, produced by solution of the limestone along a bedding plane or lamination plane. Stylolites result where the limestone exhibits a *differential* resistance to solution. If the rock on each side of a solution crevice were of uniform resistance, stylolitic interteething would hardly result. Continued solution would give only a slightly undulating seam, with a residual clay parting (see p. 53; also Figs. 20 and 21). The possibilities of secondary modifications of limestone beds by solution, with the production of residual clays, should not be overlooked.

SUMMARY

Detailed field investigations of stylolites reveal many features and complexities which can be satisfactorily explained only by the solution theory—that stylolitic phenomena result from the differential chemical solution of hardened rock, under pressure, on the two sides of a bedding plane, lamination plane, or crevice, the undissolved portions of the one side fitting into the dissolved-out parts of the opposite, the interfitting taking place slowly and gradually as solution continues. The clay caps of the stylolites are a residual product of the limestone which has been dissolved.

A careful study of stylolitic structures discloses many features which are unexplained not only by the older unestablished theories, but by the gas theory of Zelger and Potonié, and the pressure theories of Quenstedt, Thurmann, Marsh, Gümbel, and Rothpletz. The writer wishes to present the following summary of the more important observations which conclusively establish the solution theory of the origin of stylolites and oppose the other theories:

1. Stylolites originate in *hardened,* and not plastic rock, with the actual removal of rock material. They do not result from a differential compression of soft sediment. Evidence in support of this:

a. The laminae of stylolites are sharply cut off at the edges of each column. There is no evidence of disturbance or compression of the lamination of the columns, or of the rock above and below the columns.

b. Small, once-continuous stylolite-seams appearing across every other column of a major stylolite-suture are found. The missing portions of the once-continuous, minor parting have been actually removed by the penetration of the larger columns of the major seam.

c. A slight sagging of stylolite-seams, equivalent to the amount of penetration of the columns, is occasionally observed.

d. Stylolites have the exact lithologic characteristics, and color, of the stratum from which they protrude.

e. Fossils, oölitic grains, and mineral crystals are sharply cut off, with no evidence of disturbance, at the contact of the sides of the interpenetrating columns. The missing parts are not to be found.

f. Large fossil shells are often completely pierced or partially penetrated by stylolites.

g. Adjacent, parallel stylolite-seams often partially penetrate one another.

h. The side-surfaces of stylolites are always striated, and mineral deposits on them are slickensided.

i. Stylolite-columns are not intercemented as should be expected if they were formed in plastic sediment before the cementation and hardening of the rock took place.

j. Stylolites are found along inclined bedding planes, with their direction of penetration vertical, instead of at right angles to the stratification as the pressure theory would require.

2. Stylolite-seams are always characterized by a parting of clay which rests as a thin cap at the end of each column. This clay is the solution residue of the dissolved lime-mass. The most important evidence in support of this:

a. There is a definite relationship between the chemical constituents of the clay and the constituents of the associ-

ated limestone. Chemical analyses show the constituents of the clays to fulfil all the requirements of a residual product of the limestone in which they are found. The insoluble substances exist in the same proportions in both the residual clay and the limestone from which the clay was derived.

b. The thickness of the clay caps varies in direct proportion to the length of the stylolites.

c. The thickness of the clay caps varies in inverse proportion to the purity of the limestone. Stylolites of the purest limestones have the thinnest caps.

d. There is always a definite relationship between the color of the stylolite-clays and the color of the associated limestone.

e. Corroded fossil fragments are found in the clay caps.

3. Certain geologic and stratigraphic relations suggest evidence which precludes all theories but the solution theory. The most important are:

a. The occurrence of stylolitic phenomena is limited to carbonate rocks—rocks which are soluble.

b. The pressure theory explains the clay partings as original deposits of clay laid down in due order with the other sediments. Therefore the direction of stylolite-seams would of necessity be parallel with the stratification of the rock. Field observations show numerous examples of stylolite-partings cutting across the lamination at various angles—in some cases at right angles.

c. Branching stylolite-seams are common.

d. Stylolites occur along disconformities between geologic formations.

4. Other evidence in support of the solution theory follows:

a. Various deposits of mineral matter are associated with stylolitic phenomena. They result from a supersaturation of the ground waters as a result of increased solution at the ends of the columns where the pressure is greatest.

b. The origin of stylolites is somewhat analogous to that of the solution type of impressed pebbles.

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