A STUDY OF STYLOLITE DEVELOPMENT

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A STUDY OF STYLOLITE DEVELOPMENT

By

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To My Parents

Abstract

A petrographic study of samples from the Lockport Formation, all having undergone stylolitization has shown two stages of stylolite development.

Stage One - The development of microstylolites and microstylolite swarms leads to the formation of a stylolite. Through the process of amalgamation, microstylolites in a swarm merge together to form an "adolescent" stylolite. Geometric changes of the solution seams are analagous to the principle of superposition of waves.

Stage Two - An "adolescent" stylolite grows into a "mature" stylolite as the result of discrete solution of the surface. The geometry of the stylolite becomes more sutured and interpenetrating as a result of pressure-solution.

The formation of a stylolite suggests an even greater volume loss than would be anticipated by the amplitude of the solution surface. Stylolite development is an active evolutionary process.

Acknowledgements

I am greatly indebted to Dr. P.M. Clifford for all his help, especially for his input to the development of this model. Thank you also to Frank Fueten who provided much insight and helped solve many problems. Len Zwicker deserves much recognition for preparing excellent thin-sections. I would also like to thank Andy Fyon for his instruction and guidance.

My friends have made this year very enjoyable for me. I just wish that it wasn't over so soon. Most of all, I would like to thank Ann, who, in one way or another, put up with me, and the long hours I kept.

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CHAPTER 1

1.1 Introduction

A stylolite, by definition, is a thin seam or surface, marked by an irregular and intersecting or mutual interpenetration of the two sides, the columns, pits, and teeth like projections on one side, fitting into their counterparts on the other (Amer. Geol. Inst. 1972).

The purpose of this study is to show that stylolite development is a two stage process. First, a stylolite "proper" is the result of an amalgamation of microstylolites. These in turn are amalgamations of sutured grain contacts. Secondly, continued dissolution around/in the neighbourhood of the stylolite increases the amplitude and changes the geometry of the seam.

The model that is proposed is based soley upon the interpretation of hand sample and thin-section observations. Several inferences can be drawn from these observations that substantiate the mechanism of stylolite development.

1.2 Previous Work

Since the turn of the century, several authors have hypothesized about stylolitization. Stockdale (1922, 1926) states that "stylolitic phenomena result from a differential solution of the consolidated rock,under some pressure, on the two sides of a parting "(1926,p401). This mechanism requires a bedding plane, or analogous parting, alternatingly differentially soluble on both sides. More soluble zones, attacked by a weakly acidic solution, would produce an undulatory parting. With time, pressure becomes significant, being greatest at the crests, and least on the sides, resulting in interpenetrating columns. Insoluble material concentrated by the solution process caps the ends of the columns, and lines the sides as a thin film.

While Stockdale's mechanism requires dissolution of a consolidated rock, Shaub models stylolite formation in a pre-consolidated sediment (Shaub,1939,1949). Initially, there is deposition of a lime mud with a clay layer on top of it. This layer acts as an impermeable barrier to escaping water. Another lime mud layer is deposited on top of this initial lime mud and clay layer. Because there is not an impermeable barrier on this second layer, it can dry out earlier than the underlying beds. Contractions of the upper bed sets up a built-in tension, with localized reduced-pressure zones in the underlying layer. Tension can be relieved by upward movement of portions of the underlying soft lime mud into the reduced-pressure zones. The clay will be carried with the lime mud, thus forming the clay layer of a stylolite, as the lower bed contemporaneously interpenetrates the upper bed.

Prokopovich (1952) has suggested that a freshly deposited lime mud be subjected to dissolution at the sediment-water interface. This will result in an etched or pitted surface, with insoluble materials left as a veneer over this irregular surface. Renewed deposition of another lime mud bed will form a stylolite, as a trapped layer of insoluble material.

Thus far, three theories of stylolite formation have been presented, the SOLUTION-PRESSURE theory (Stockdale, 1922,1943), the CONTRACTION-PRESSURE theory (Shaub, 1939,1949), and the SUBAQUEOUS-SOLUTION theory (Prokopovich,1952).

Of these three theories, that of Stockdale seems most likely to many workers. For example, relationships have been cited confirming Stockdales general theory that stylolites originate in hardened rock (Dunnington,1954).

> "Stylolites cutting initially indurated specifically; ooliths, fossils,pebbles.
>
> Stylolites cutting elements reckoned crystalline from time of origin; crystalline infillings of hollow fossils.

> Stylolites subsequent to secondary phenomena to which hardening is a pre-requisite; fracturing, brecciation, veination, coarse grade recrystallization, dolomitization, marmorization." (Dunnington,1954,p35)

In a critique of the three theories of stylolite origin, Dunnington vigorously dismisses Shaub's observations as being the result of the geometrical relationship of the cut slabs, relative to the stylolite plane. He argues that the structures seen by Shaub may very well be developed by pressure-solution in an indurated rock.

Dunnington's critique of the SUBAQUEOUS-SOLUTION theory is less vigorously dismissed. The analogies Prokopovich drew are strained, and do not offer a satisfactory explanation of normal stylolitic features. However, the suggestion that vertical seams may be due to solution in soft sediments is recognized. Dunnington believes that it may offer a "formidable alternative" to Stockdale's theory, only because it would be difficult to disprove.

Though in agreement with Stockdale that pressure-solution of hardened rock is the reason for stylolites, Dunnington disagrees about the process of origin. His impression is that minute serrations develop into microscopic columns, which in turn amalgamate into columns of macroscopic size.

More recently, Park and Schot (1968) have concluded that stylolite features are of "diagenetic pre-complete cementation" origin. Pressure solution starts early in diagenesis and is a major factor of rock induration by supplying cement through dissolution. This is also the belief of Bathhurst (1971). Park and Schot also believe that very thin, semi-parallel seams represent a cyclicity in time of pressure-solution, through-out the drawn-out process of diagenesis.

Bathhurst (1971) states that stylolites may begin in limestones which are only lightly cemented. Pressure-solution releases $CaCO_3$, and drives the cementation process to completion. The amount of $CaCO_3$ released is far too little to account for the entire cementation process, yet in a partially cemented sediment, it may be sufficient to complete it. Once cementation is complete, the permeability in the adjacent sediment is too low to transport solute ions away from the stylolite. This may be the end of stylolite growth.

1.3 Location

All specimens are from the Eramosa Member of the Lockport Formation (Middle Silurian). Collection was done at one location, a quarry 5 kilometers northwest of Dundas, on Highway 5.

Stylolites are abundant in this horizon, and excellent exposure can be seen in the quarry walls. An advantage of collecting all of the samples at one site is that one may assume regional stress, general lithology and composition of the pore fluids were essentially constant.

1.4 Nature of the Problem

The problem at hand is three-fold. How do stylolites originate, grow, and die off? Is their presence and location determined by the existance of a natural lithological parting (Stockdale, 1922); Or does the presence of clay minerals promote dissolution, and hence determine where solution surfaces originate (Weyl, 1959-Robin, 1979)?

Once a solution surface is established, what happens to it laterally and vertically? Three possibilities of growth exist; a) it grows vertically but not laterally, b) it extends laterally while the vertical dimensions remain constant, or c) it grows both vertically and laterally.

Of the three choices the last seems the most realistic.

Finally, what determines why a stylolite ceases to evolve? This can only be a matter for speculation. Unlike the origin and growth of a solution surface, there is no relevant petrographic evidence.

CHAPTER 2

2.1 Petrography

2.1.1 Hand Sample Description

The specimens are from a very fine grained, brown-buff, argillaceous dolomite. Stylolite and microstylolite features are abundant within the samples. Microstylolites occur in domains. They appear as groupings of very fine seams, whose cumulative thickness is less then three centimetres. Stylolites occur associated with these microstylolite domains, or by themselves. The amplitude of the stylolites is on a millimetre scale, normally two millimetres or less. Spacing of the stylolites is variable, ranging from two centimetres, to greater than twenty centimetres.

Bioclastic debris in the rock occurs as disseminated particles or in poorly defined horizons. Skeletal debris varies from well-preserved to poorly-preserved. Dolomitization of the particles appears to have obliterated any micro-structure that was present.

2.1.2 Transmitted Light Description

Petrographic analysis of the samples reveals that the rock is characterized by a xenotopic fabric. Grain size is consistently less than 0.25 millimetres. The distribution of grain sizes may be uniform to variable.

The only non-metallic crystalline material in the rock is dolomite. The absence of calcite has been confirmed by staining. Individual dolomite crystals show abundant inclusions of material. This gives the grains a dirty appearance.

Shukla and Friedman (1983) would describe these samples as a Type 2 dolomitization fabric (Table 1). Both bioclastic particles and groundmass are dolomitized. Dolomitized particles are of a much smaller grain size than the original dolomite crystals. Structure is not observable in these bioclastic relicts, only a vague outline of the original shape (figure 1). Quartz in not present in these samples.

2.1.3 Reflected Light Description

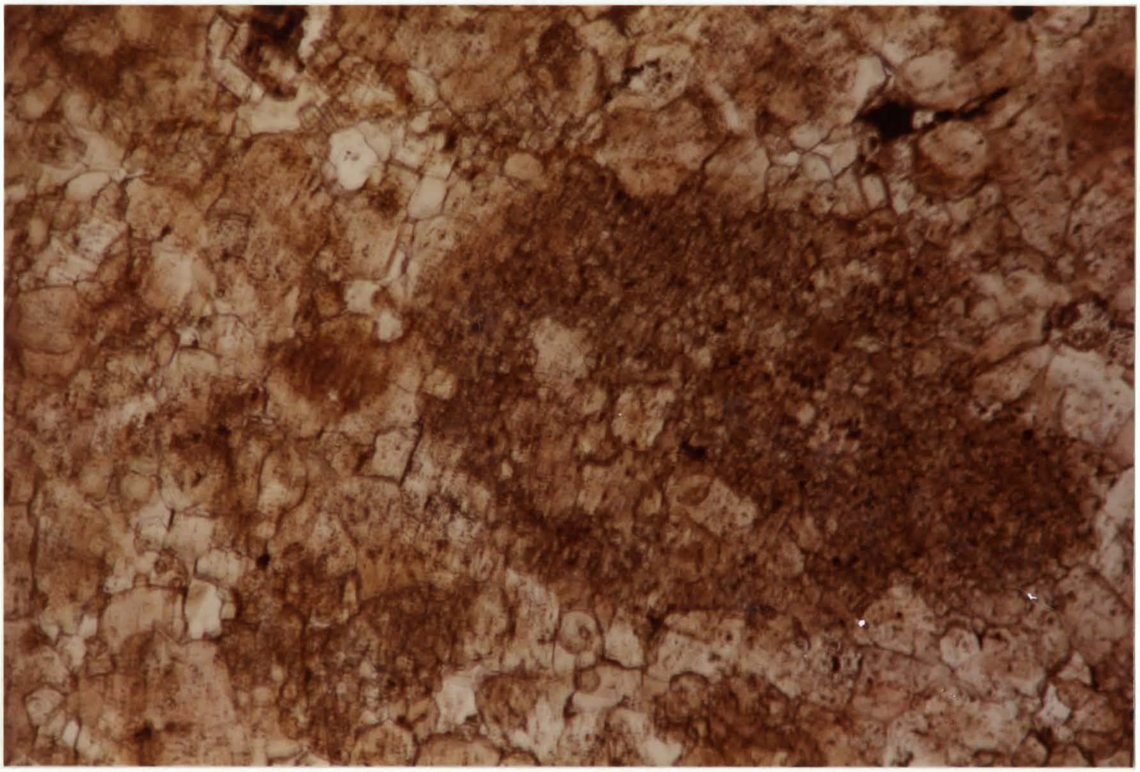
Under reflected light, one can distinguish microscopic pyrite grains, interstitial and within dolomite crystals. They are not abundant, and make up only a very minor constituent of the rock. Within the stylolite seam, these pyrite grains are much more abundant.

An interesting observation is that the crystals of dolomite in the tips of the stylolite columns appear to be

Table 1 Description of dolomitization fabrics found in Lockport Formation dolostones (after Shukla and Friedman, 1983).

FABRIC	DESCRIPTION
Type 1	-micrite groundmass of the limestone has been progressively replaced by dolomite
Type 2	-both particles and micrite groundmass are dolomitized -dolomitized particles are preserved with various degrees of clarity of shape and microstructure
Type 3	-mosaic of dolomite crystals which contain no clue regarding the identity of the precursor limestone/lime sediment

Figure 1 Photomicrograph of a dolomitized bioclastic particle. Structure is not observable, only an outline of the original shape. 63X



much "cleaner" than crystals in the socket. Outside the stylolite domain, the rock displays a mottled appearance of "dirty" and "clean" grains.

2.2 Micromorphology

2.2.1 Grain Contacts

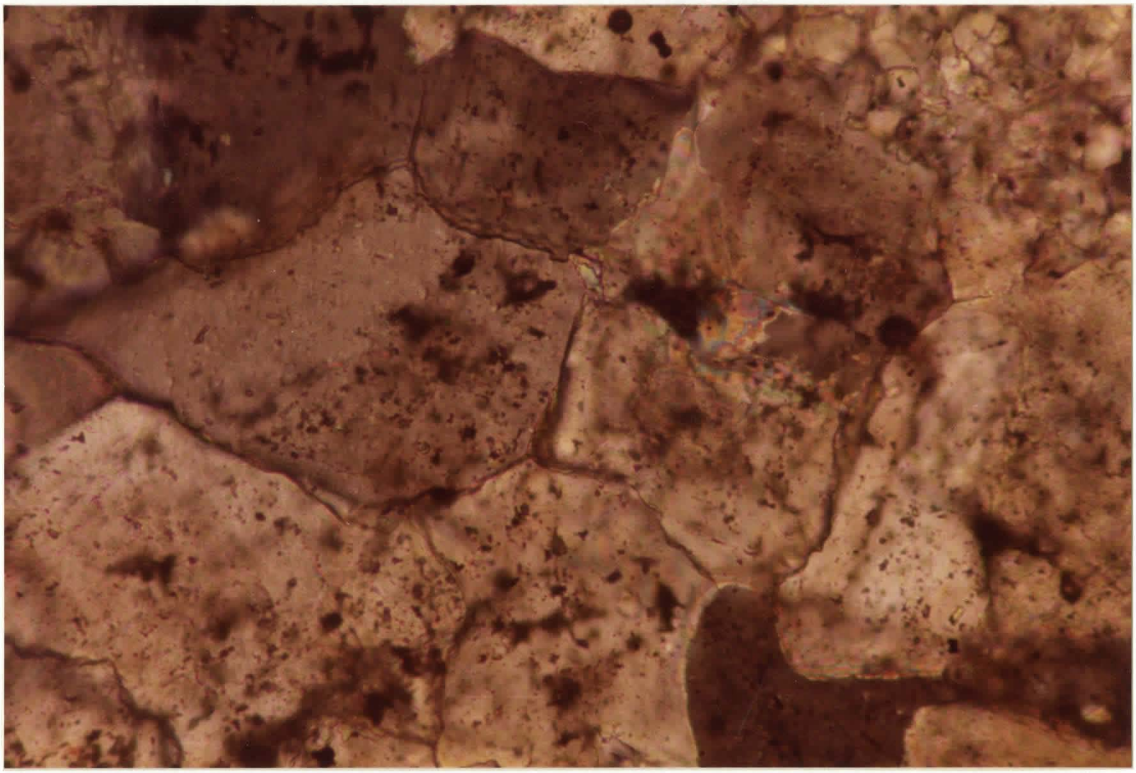
Varying degrees of suturing of the grain contacts are observed throughout the rock as a whole. When grain boundaries are approximately parallel to a solution seam, there is an evident sutured contact between any two grains. On the other-hand, grain contacts that are approximately normal to a seam are undulatory to planar. This conforms to an orientation of σ_1 normal to the mean orientation of stylolites or solution seams (figure 2).

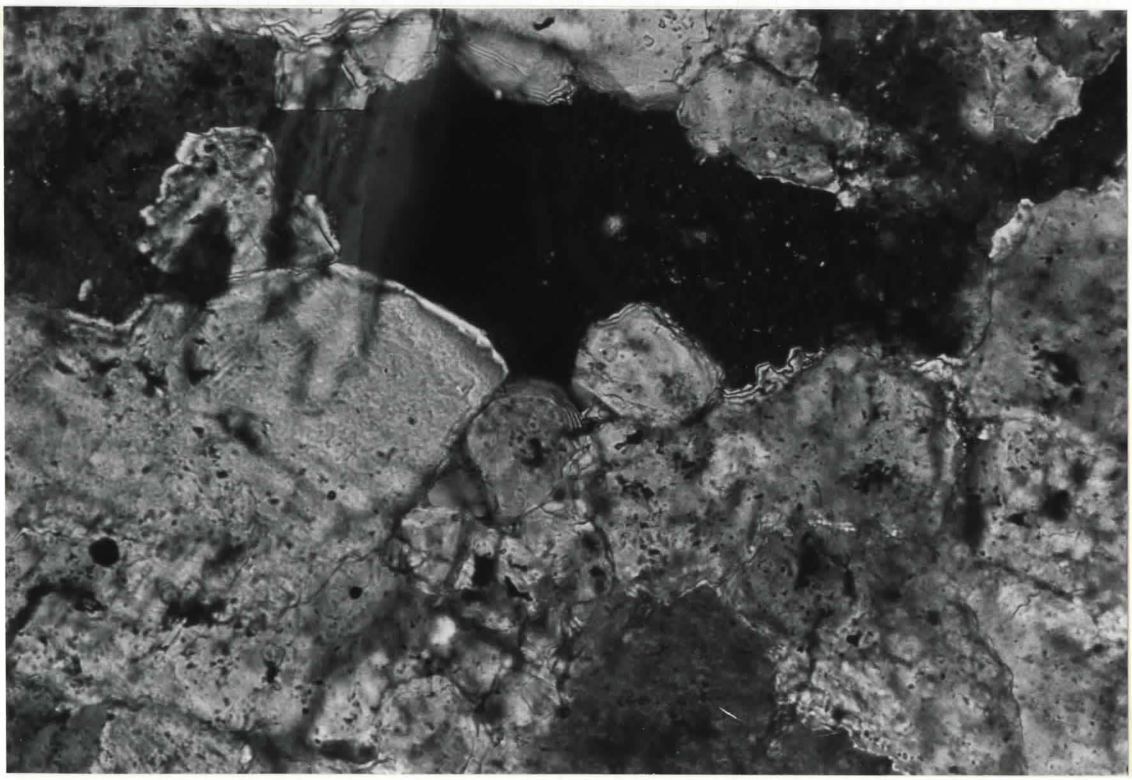
As one approaches a stylolitic domain, the degree of suturing intensifies, such that grains proximal to a stylolite are more sutured than grains several centimeters away. Suturing is intensified if a smaller grain is in contact with a large grain (figure 3).

Where small amounts of clay and organic material lie between grains, these contacts interpenetrate more than the contacts of adjacent "naked" grains. This observation appears to corroborate the proposal of Heald (1956) and Weyl (1959) that small amounts of clay enhance the rate of pressure-solution.

Figure 2 Polarized photomicrograph of sutured grain contacts that may be used to show the orientation of σ_1 . 250X

Figure 3 Polarized photomicrograph showing the interpenetration of a dolomite crystal by a smaller crystal. This type of grain contact is an intensified case of suturing. 250X





Overall, the degree of suturing of grain contacts is dependent upon the orientation of the grain face to the greatest principle stress, the proximity to a stylolitic zone, and the presence of small amounts of interstitial clays.

2.2.2 Individual Microstylolites

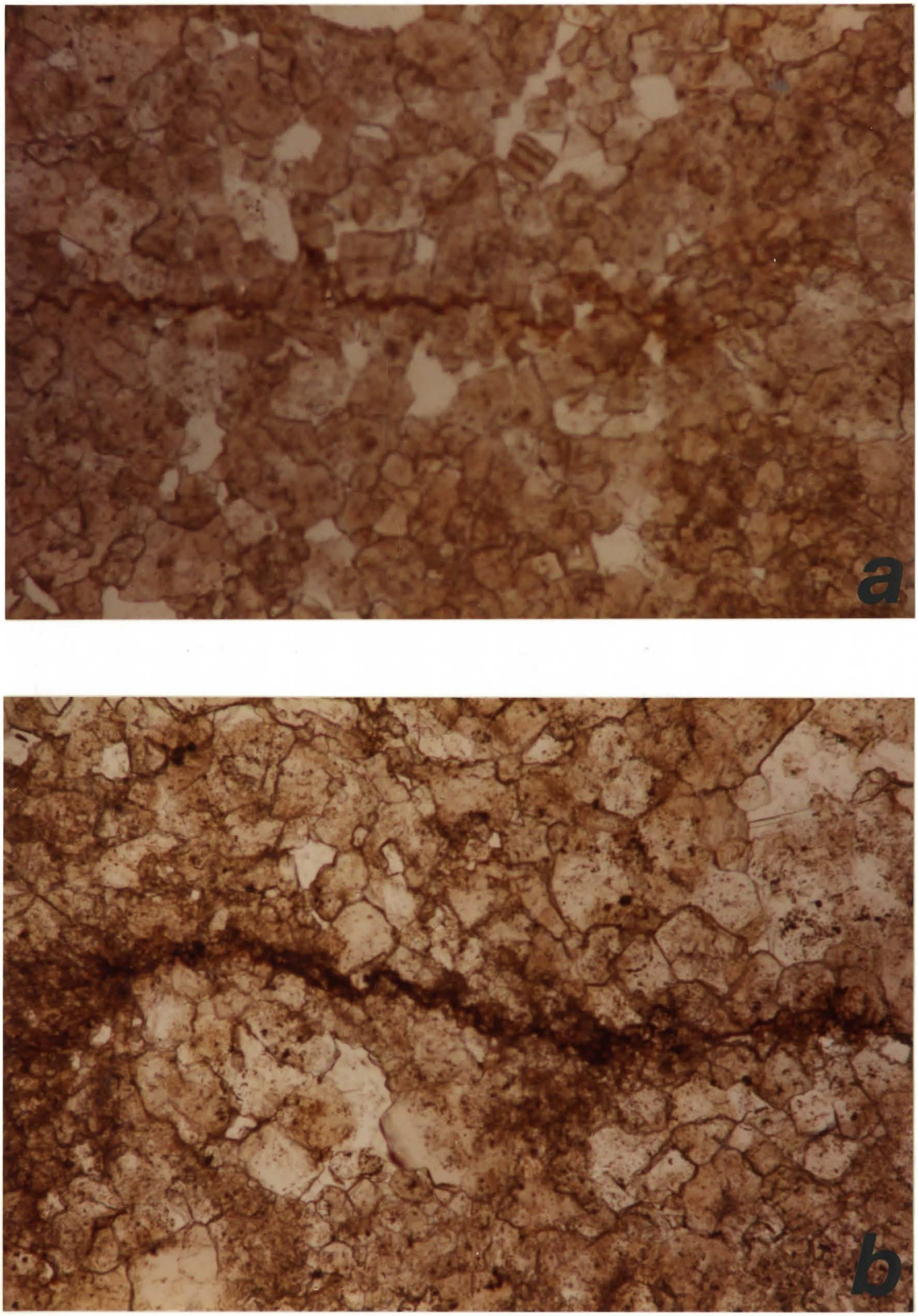
Individual microstylolites display three modes of occurrence (figure 4). They may occur isolated from a stylolitic domain, where the only associated pressure-solution features are sutured grain contacts. In this sense, the microstylolite appears to be an extension of a sutured contact, to two or more grains. There is a very thin accummulation of insoluble material which defines the feature. The aforementioned interstitial clay material is observed to prograde into the microstylolite form, oriented sub-parallel, or slightly oblique, to the nearest stylolitic zone.

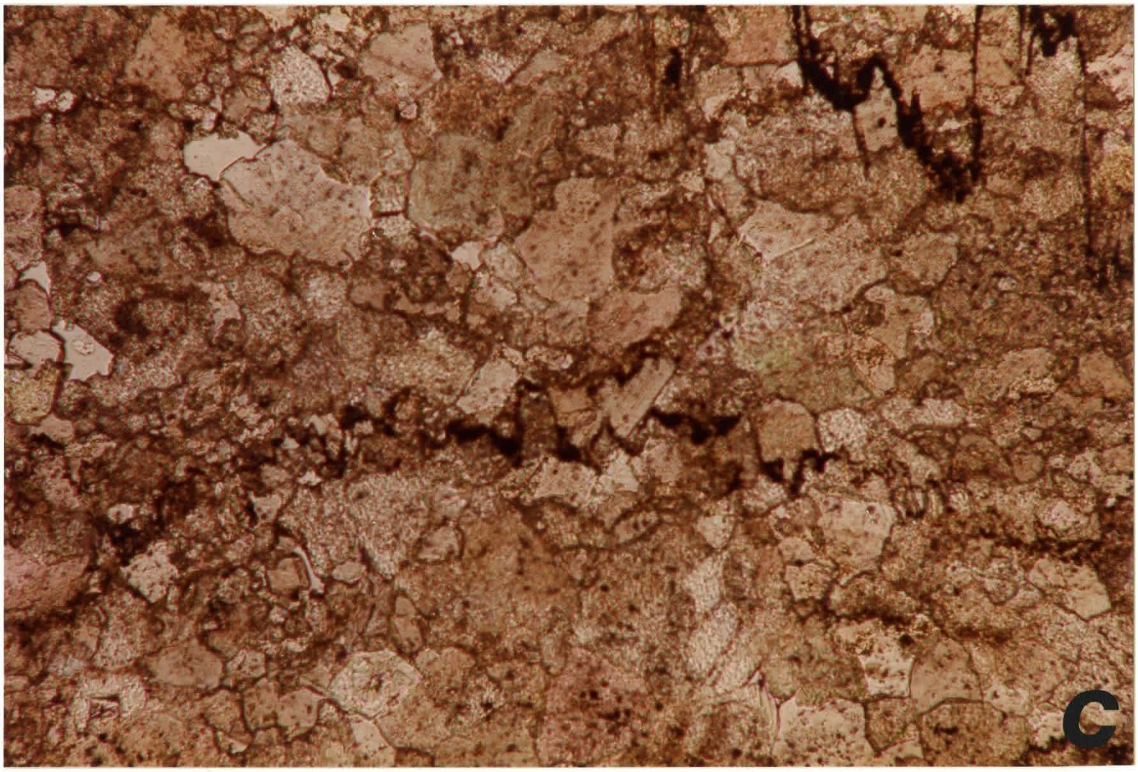
Secondly, individual microstylolites are observed distal to microstylolite swarms. These swarms may or may not have a stylolite within their domain. The concentrated insoluble material is thicker, and the individual microstylolites are generally sub-parallel to the swarm.

Lastly, individual microstylolites are proximal to a highly developed stylolite seam. In this occurrence, they are very like the second case, except that there is no microstylolite swarm present.

The individual microstylolite cannot be seen with

Figure 4 Photomicrographs showing individual microstylolites in their three modes of occurrence: a) a microsylolite that is only associated with sutured grain contacts, b) a microstylolite that occurs distal to a microstylolite swarm, and c) a microstylolite that occurs proximal to a well developed stylolite (shown). 63X


a
b


c

the naked eye. Its wavelength and amplitude appear to be equal to the grain size. The lateral extent of the feature increases with its proximity to a stylolitic domain, from about twice the grain size in the first mode, to more than ten times the grain size in the latter modes.

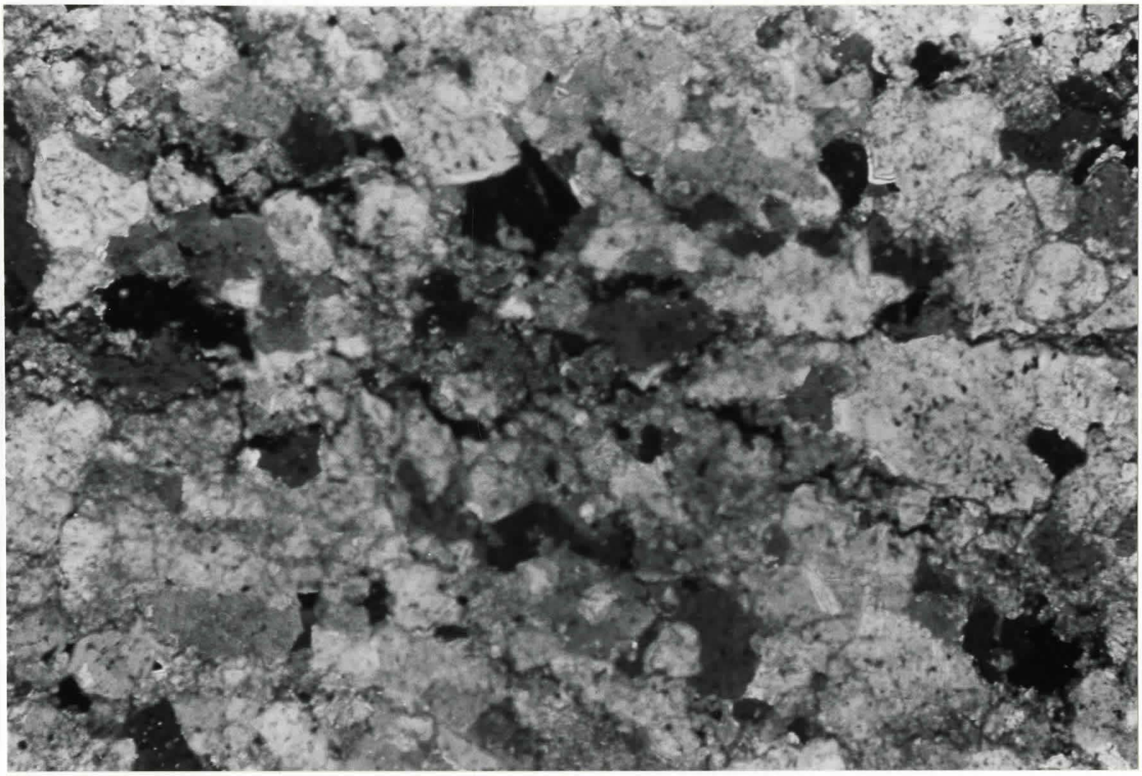
2.2.3 Microstylolite Swarms

Unlike individual microstylolites, these occur within a definable zone or domain. The domain has no specific characteristic. Its grain size may differ from, or be equal to, the neighbouring material. Nor is there any discernible difference in fabric inside and outside the domain.

The swarm itself is easily seen in cut slabs. It appears as a zone of abundant microstylolites which ranges in cumulative thickness from a few millimetres, to upwards of three centimetres. Spacing of the microstylolites is variable, normally less than 0.5 millimetres. They resemble a non-parallel inter-connecting network of very thin seams within the swarm (figure 5).

Each microstylolite in the swarm displays a greater accumulation of insoluble material compared to individual microstylolites observed outside the swarm. As well, the geometry of each microstylolite appears to be controlled by the size of the grains within the swarm domain. The lateral extent of each microstylolite differs within the swarm, but overall is greater than any microstylolite outside the swarm.

Figure 5 Photomicrograph of microstylolites in a swarm. They resemble a network of very thin seams. Note that the spacihg between the microstylolites is variable. 63X



2.2.4 Microstylolite Swarms and Stylolites

There is a relationship between microstylolite swarms and stylolites. Within a swarm, a dominant stylolite seam can be observed. This seam may be located centrally or at the periphery of the swarm. It may be rectiplanar or curviplanar, continuous or discontinuous, laterally within a swarm.

Microstylolites amalgamate by converging upon one another at point contacts. When this amalgamation results in a visible solution seam, microstylolites become a stylolite.

The stylolite is a simple wave-like feature, which is thicker and larger than any microstylolite in the swarm. The wavelength, amplitude, and frequency of the stylolite wave-form no longer appears to be controlled by grain size. Several grains are found in each column (figure 6).

Microstylolites become incorporated along the lateral extent of the stylolite. At column tips, across the tips, and along the limbs of each column, microstylolites are observed to merge into the stylolite (figure 7, 8). A branching network of these amalgamate at the end of stylolite.

Where the amplitude of the stylolite is greater than the simple wave-like form, it displays a more sutured character. There is a patchy or irregular distribution of seam material. Instead of being relatively uniform as in the microstylolites, the seam material is now "lumpy" (figure 6).

Figure 6 Photomicrograph of a simple wave-like stylolite that is present in a microstylolite swarm. The stylolite is much thicker and larger than the associated microstylolites. Note the patchiness of the seam material. 63X

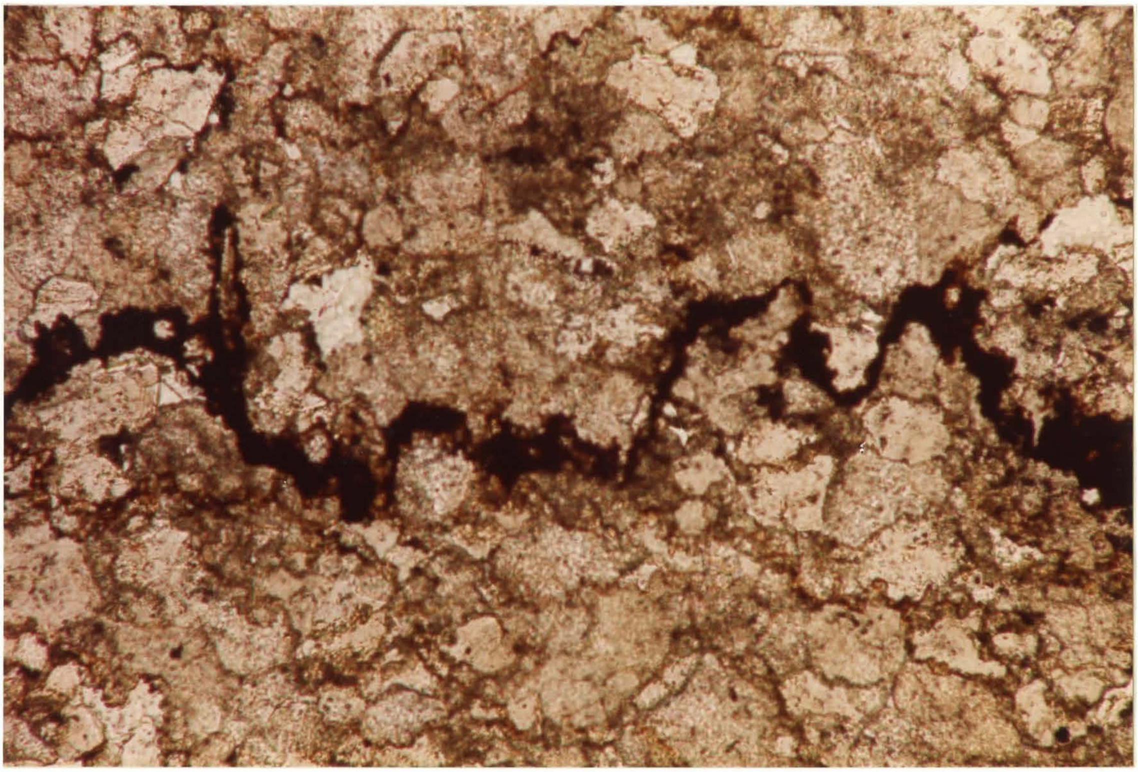
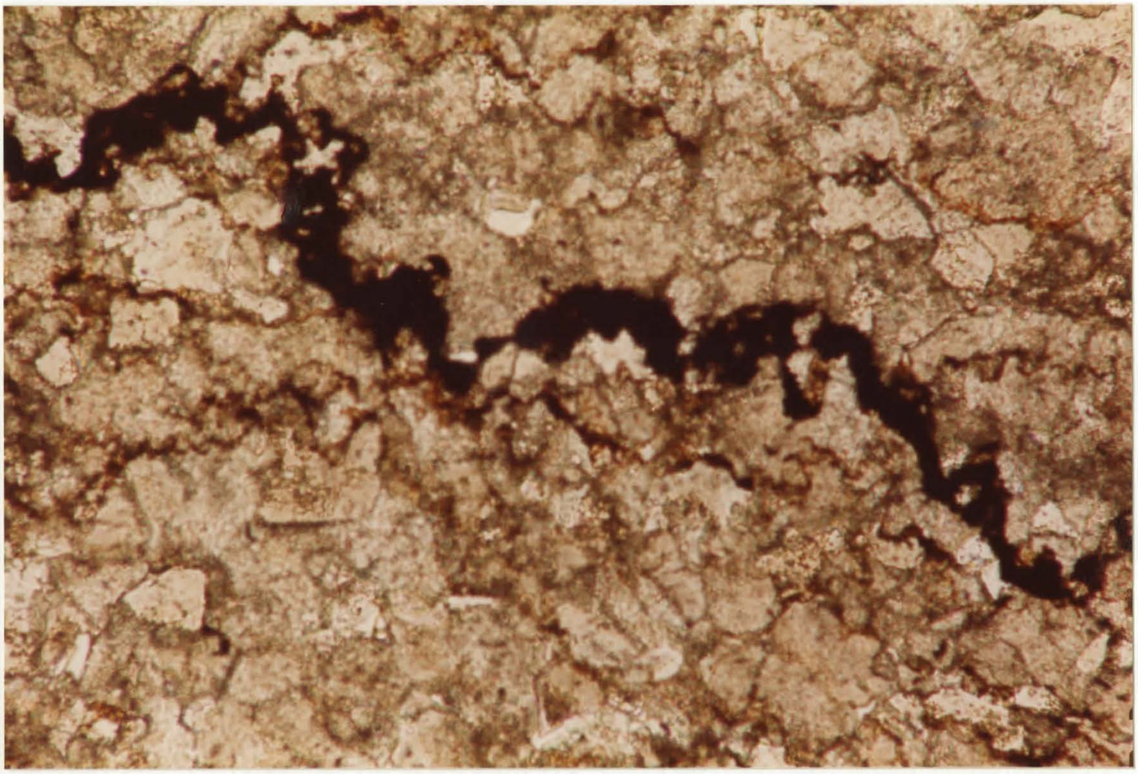
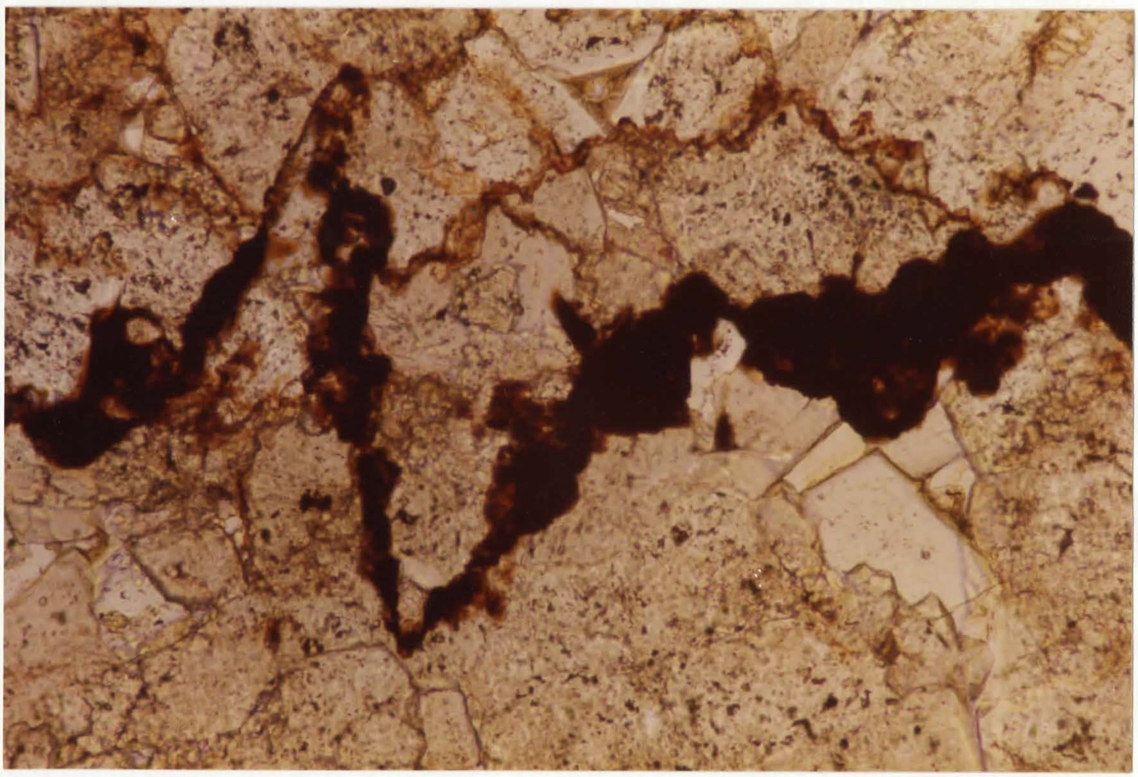


Figure 7 Photomicrograph of microstylolites being incorporated into a stylolite at the tips and across the tips of the columns. 63X

Figure 8 Photomicrograph of the incorporation of a microstylolite along the limb of a stylolite column. 160X





Within a given swarm where a stylolite can be traced laterally as its wave-form and thickness increase, the abundance of microstylolites decreases, as more microstylolites are incorporated into the seam.

2.2.5 Stylolites Without Swarms

Stylolites also occur in the absence of a microstylolite swarm. Some do show microstylolite associations, but there is not a swarm present. These stylolites are geometrically different from those associated with microstylolite swarms. They are strongly sutured to the point of having sharp peaks or sub-rectangular columns and greater amplitude (figure 9).

Several new characteristics are displayed in these stylolites. First, the seam material is thinner in this type. It appears to be drawn out along the limbs of a column, and caps the top of the column.

Secondly, striations show up for the first time. Deep interpenetrating columns have sharply cut grain boundaries on both sides of the contact. These contact surfaces are grooved in the direction of shortening (figure 10). Low amplitude, swarm-associated stylolites do not display such pronounced mutual interpenetration and striation.

Figure 9 Photomicrograph of a stylolite in the absence of a microstylolite swarm. The suturing of the seam resembles sharp peaks and sub-rectangular columns. 63X

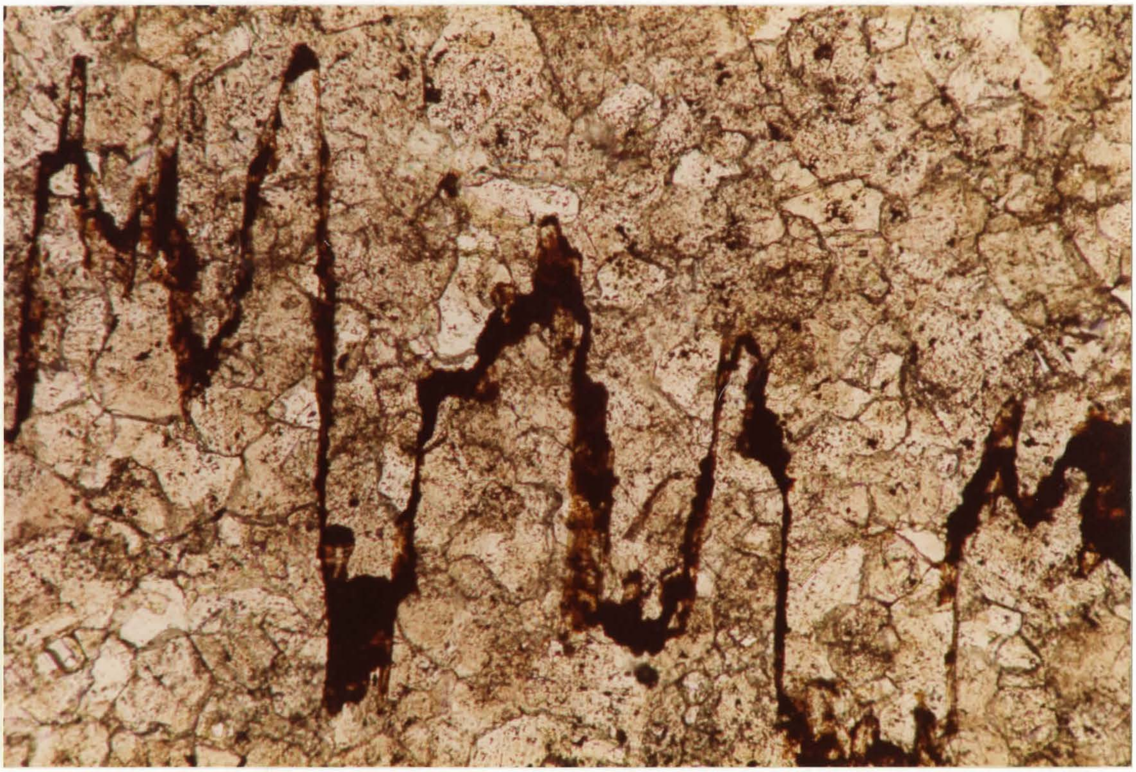
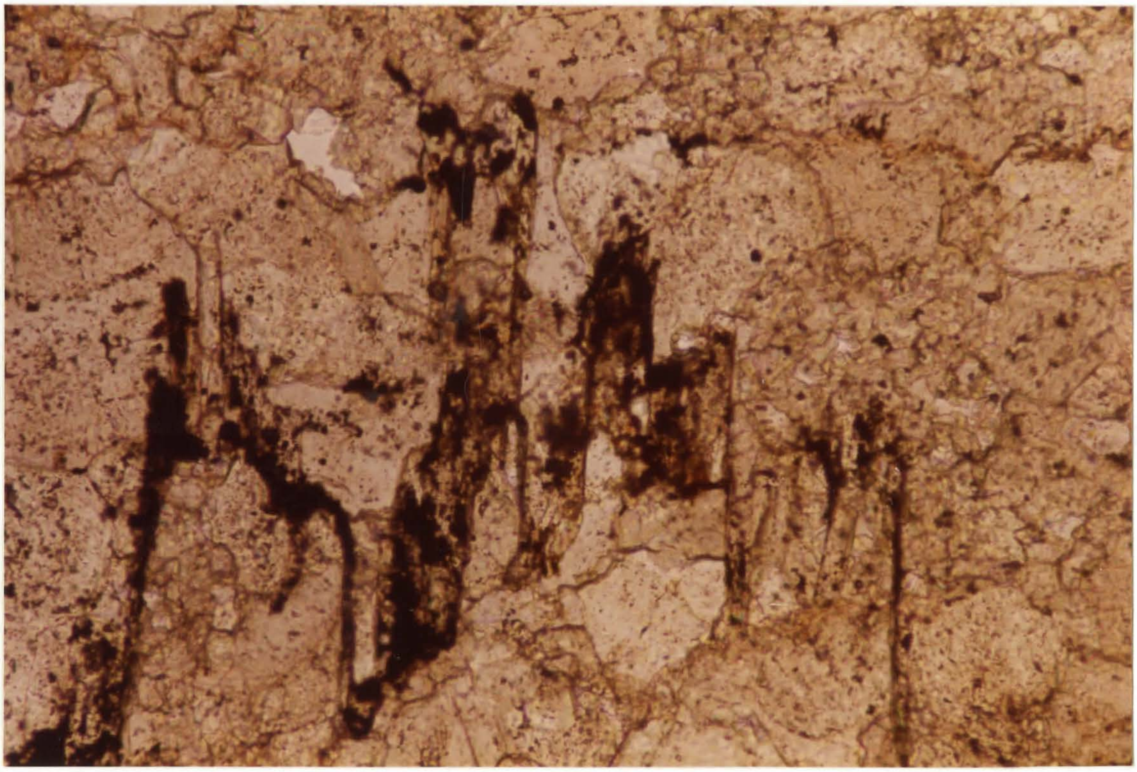


Figure 10 Photomicrograph of striations that may be found in a stylolite that occurs in the absence of a microstylolite swarm. 160X



2.2.6 Termination of a Stylolite

In hand sample, stylolites are observed to terminate abruptly or fan out into an array of microstylolites. When When it ends abruptly, the stylolite most often is not visibly sutured. If it is visibly sutured and/or associated with a swarm, it may fan out into an array of microstylolites. In both forms, the amplitude of the solution surface decreases towards its termination.

At microscopic scale, the termination of a stylolite always resembles a dendritic pattern of microstylolites. Small-scale seams are observed to bifurcate at their terminus, whereas large-scale seams branch along their trunk (figure 11, 12)

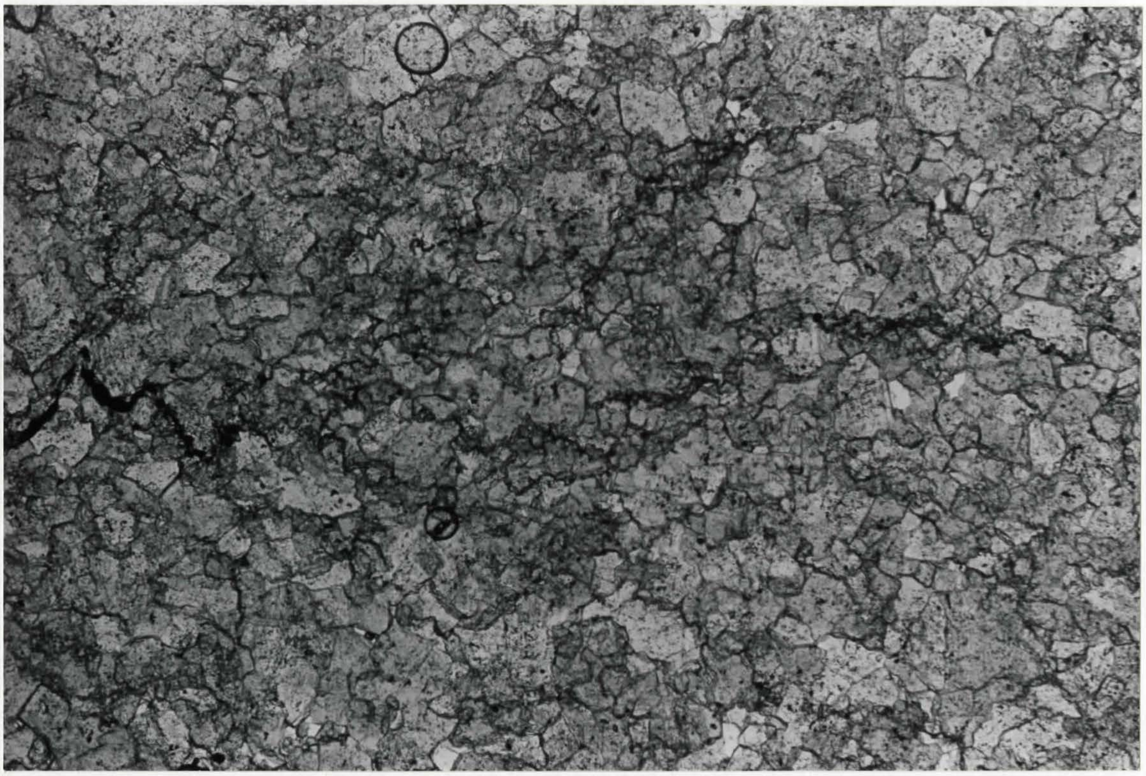
Each microstylolite can be assigned an order indicating its relative importance in the network. The lowest order seams are the most minor tributaries, and the highest order seam is the stylolite itself (Horton, 1945). Similar patterns are observed at a stylolite terminus when present in a microstylolite swarm.

2.2.7 Seam Thickness

For any one stylolite, the seam of insoluble material is thickest at the point in space when the microstylolites of a swarm coalesce. Through the stages of microstylolite, to microstylolite swarm, to microstylolite swarm and stylolite, to the disappearance of the swarm, the seam thickens steadily From this point onwards, the stylolite becomes thinner with increased suturing and greater amplitude.

Figure 11 Photomicrograph of a stylolite bifurcating at its terminus. 63X

Figure 12 Photomicrograph of a stylolite branching along its trunk, near its terminus. 63X



2.2.8 Seam Material

The study of the stylolite seam reveals two interesting features. In slab form, when viewed under reflected light, the seam material appears black, minutely fibrous, and has a greasy lustre when scratched. This may imply a bituminous composition of the seam material.

Examination of polished thin sections reveals that there are minute pyrite grains in the dolomite and within the seam itself. Pyrite is more abundant in the seam material, by a factor of two to ten times. This abundance becomes greater with increased thickness of the seam and amplitude.

2.3 Geometric Transitions

Visible stylolites were classified according to their geometry as seen in cut slabs. The classification scheme of Park and Schot (1968) provides a useful tool to describe the two-dimensional geometry of the stylolite (figure 13).

Three classification types were recognized; a) the simple or primitive wave-like type, class 1, b) the suture type, class 2, and c) the sharp-peak type, class 5. In the two modes of occurrence of stylolites, a transition between geometries exists (figure 14).

Stylolites that are swarm associated display class 1 and class 2 geometries. Class 1 wave-forms are lower amplitude, smaller wavelength, and are thicker than class 2 wave-forms.

Figure 13 The classification scheme of stylolites based upon their two-dimensional geometry. Classes: 1. Simple or primitive wave-like type; 2. Sutured type; 3. Up-peak type (Rectangular type); 4. Down-peak type (Rectangular type); 5. Sharp-peak type (tapered and pointed); 6."Seismogram" type,(after Park and Schot, 1968)

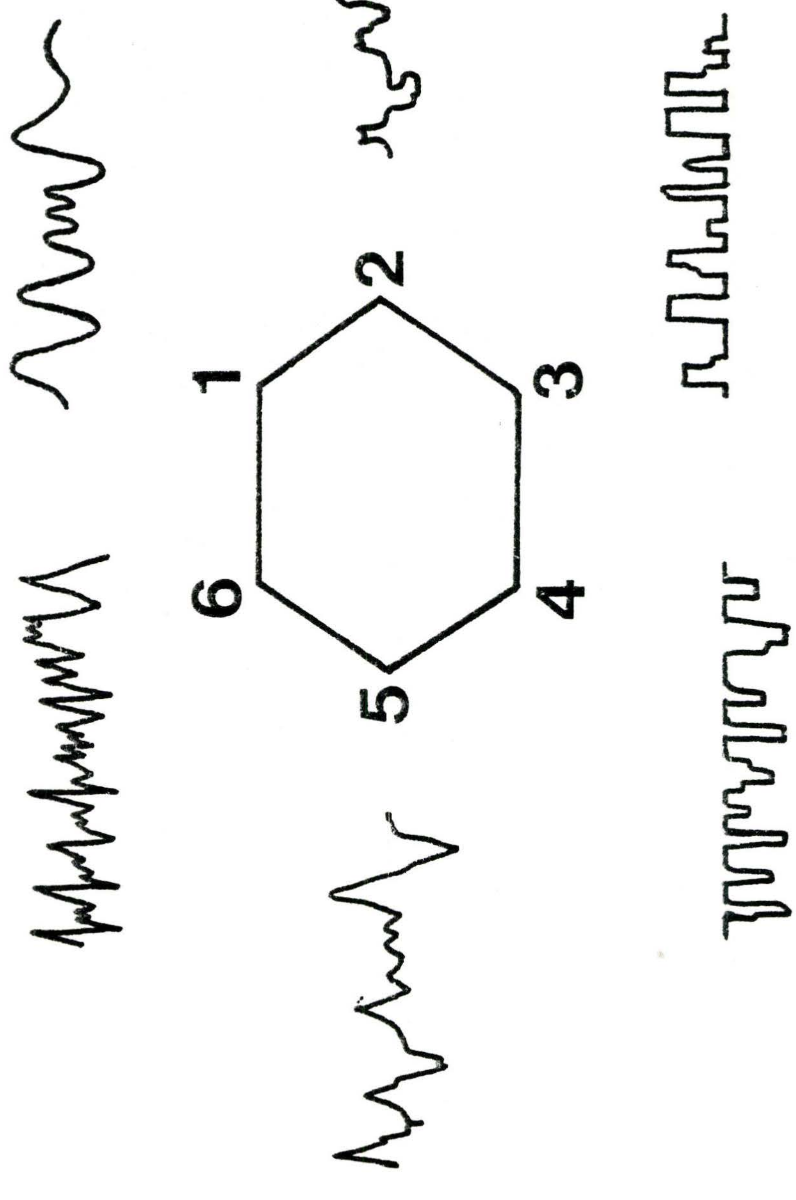
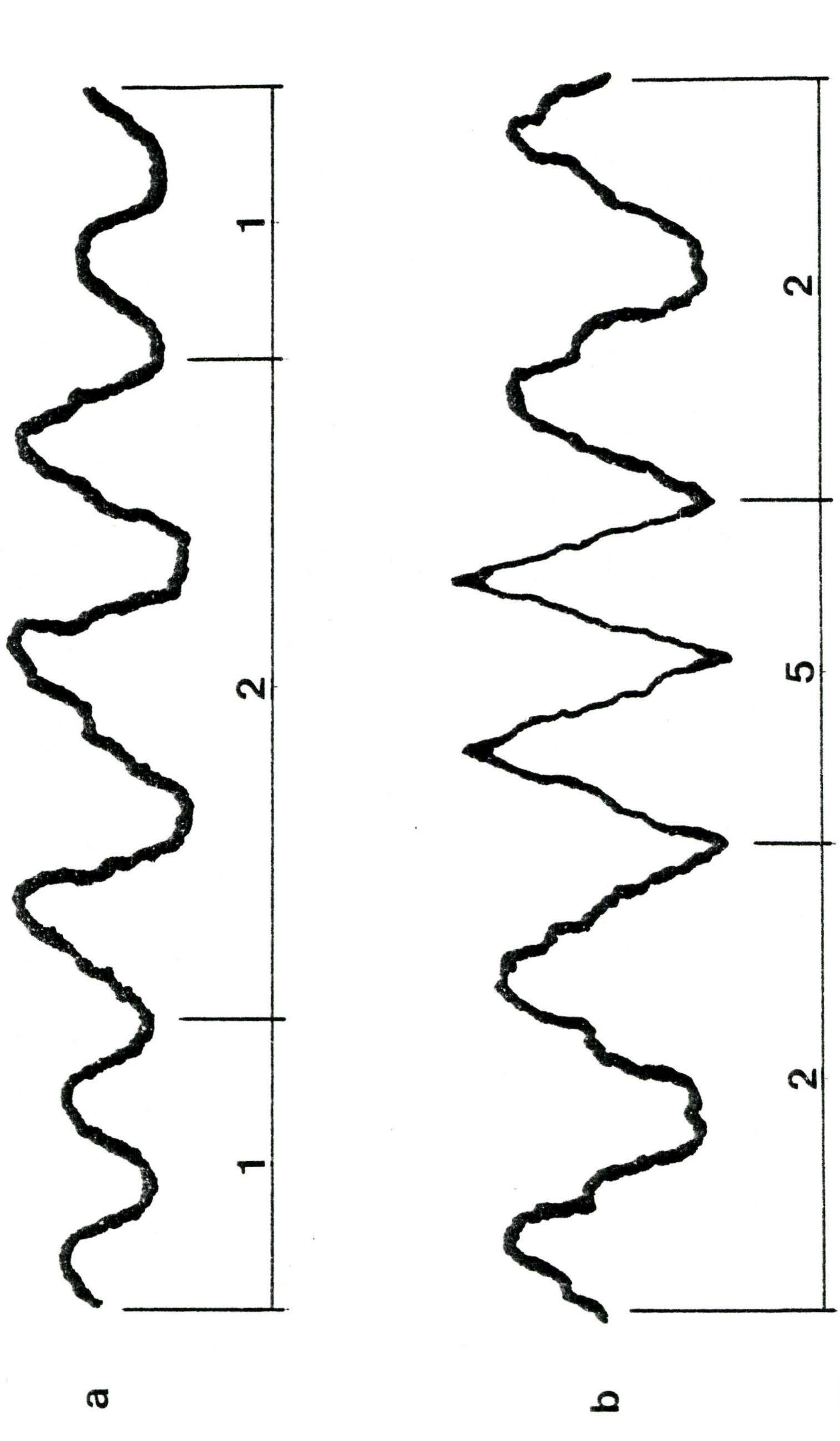

1
2
3
4
5
6

Figure 14 The geometric transitions found in the two modes of stylolite occurrence: a) class 1 and class 2 transitions in a swarm-associated stylolite, and b) class 2 and class 5 transitions in a stylolite where no swarms occur.


1
2
1
2
5
2
a
b

The sutured form is generally located only in the body of a stylolite, whereas the simple wave-form occurs throughout the solution surface.

Stylolites which exist independently without an associated swarm have a different geometry. Class 2 and class 5 are the dominant geometries. Class 5 wave-forms are of greater amplitude, may have a smaller wavelength, and may be thinner than class 2 wave-forms. Towards the terminations of a seam, the geometry gives way to a relatively simple wave-form.

CHAPTER 3

Interpretation of the morphological and transitional trends described earlier (Chapter 2) has lead to the development of a model for the growth of a stylolite, from its embryonic stage, through to maturity.

Simple assumptions have been made based upon the various observations. These are;

a) that the thickness of the solution seam is an indicator of maturity. This only applies to microstylolites and swarm-associated stylolites.

b) that increasing amplitude is associated with increasing development i.e. the longer the process continues, the greater the amplitude becomes, all other things being equal.

It is important to understand that the growth of a stylolite is an active evolutionary process. It can be subdivided into two stages. Stage one requires birth and amalgamation of "neonatal" microstylolites. These evolve into the "adolescent" stylolite. The second stage of growth is the maturing of the "adolescent" into a full-fledged, interpenetrating solution seam.

3.1 Formation of a Stylolite

Based upon observations of where a stylolite occurs, it seems that the solution surface need not originate at a natural lithological parting, as is suggested by Stockdale (1922). All of the solution features observed are within the limits of a bed.

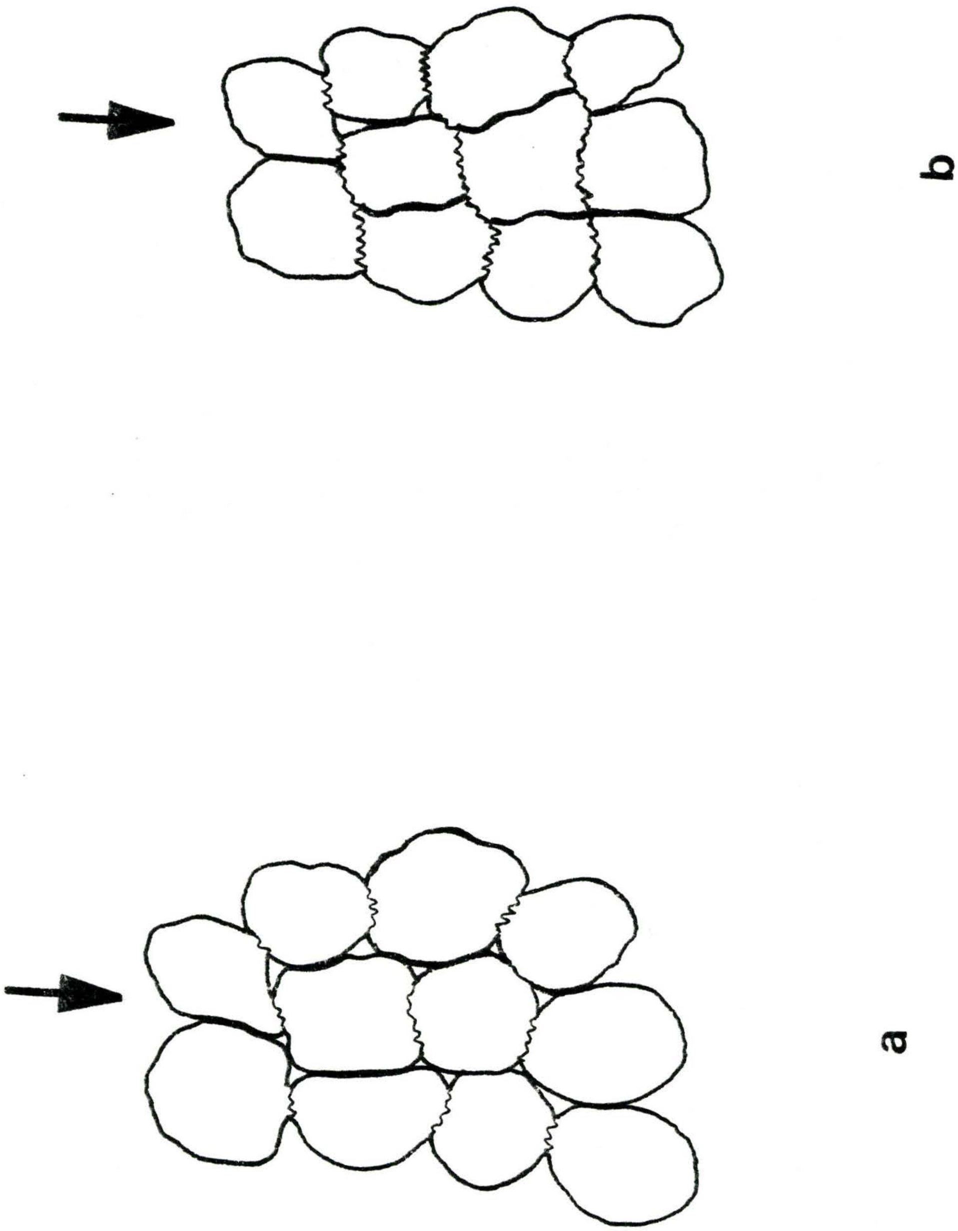
There is a direct relationship between microstylolites and the stylolite itself. A stylolite appears to be the result of an amalgamation of microstylolites in a swarm. Microstylolites are observed to the extensions of sutured grain contacts.

3.1.1 Origin of Microstylolites

Under conditions of pervasive pressure-solution, dissolution takes place at grain contacts normal to the direction of shortening (Fletcher and Pollard 1981). A sutured grain contact will form if the partners in contact are of a different solubility. Continued dissolution is likely to result in the alignment of two or more grain contacts (Trurnit, 1968). The extension and amalgamation of sutured grain contacts yields a microstylolite (figure 15).

There are two possible sources of seam material, both equally realistic. First, the dissolution of indididual dolomite crystals will release insoluble constituents from within. The crystals are observed to contain abundant inclusions.

Figure 15 Diagramatic representation of the formation of microstylolites by the extension and amalgamation of sutured grain contacts.


a
b

Secondly, Shukla and Friedman (1983) have reported that Lockport Formation dolomites have dark brown to black organic and amorphous material between the grains, an observation which was confirmed in these rocks. This material may serve as a second source of insolubles.

The soluble dolomite crystals provide mechanical support for the insoluble materials, internally and externally. Upon partial dissolution of the crystals, this material loses some of the support previously supplied to it by the whole grain. Hence, it will accumulate in the plane of dissolution, the microstylolite surface (Durney, 1972).

The initial mode of pressure-solution was pervasive pressure-solution. This mode is responsible for sutured grain contacts. However, once a microstylolite is formed, a second mode of pressure solution enters the picture. This is the mode characterized by discrete and extensive surfaces of solution, which is responsible for stylolitic features (Fletcher and Pollard, 1981). As microstylolites amalgamate to form stylolites, the former mode becomes less dominant, the latter mode more dominant.

This outlines the formation of one microstylolite. In the body of the rock, the process of pervasive pressure-solution is assumed to produce numerous sutured contacts. Likewise, the orientation of grain contacts normal to the direction of shortening, is also assumed to produce numerous microstylolites. Accumulation of insoluble material is a natural by-product of dissolution, as long as a source is available. Hence, many microstylolites can form within a rock under these conditions.

3.1.2 Origin of Microstylolite Swarms

The processes involved in the production of microstylolites still apply at this stage of stylolite development. But why do microstylolite swarms develop where they do?

The precursor carbonate was a bioclastic micrite (Shukla and Friedman, 1983) in which there were probably clay-rich "lenses". Originally, before pervasive pressure-solution, there may have been "lenses" in the dolomite, rich in interstitial clay material. The proposal of Heald (1956) and Weyl (1959) that small amounts of clay minerals enhance the rate of pressure-solution should be kept in mind.

With the onset of pervasive pressure-solution, microstylolites can form as outlined in section 3.1.1. In these "lenses" of interstitial clay minerals, dissolution is enhanced due to the abundance of clay minerals. An increased rate of dissolution would result in an increase rate of microstylolite formation within this zone (an increase rate of microstylolite formation will result in a greater numer of microstylolites within the clay-rich "lense", for a given period of time). Under the same conditions of formation, dissolution should produce more microstylolites inside than outside a clay-rich lens. There now exists a microstylolite swarm.

In a microstylolite swarm, it can be assumed that pressure-solution resulting in surfaces of solution is the dominant process. Pervasive pressure-solution was initially responsible for microstylolite formation within a domain, however, now it is not as prominent inside as it is outside the swarm.

3.1.3 Amalgamation, the Formation of a Stylolite

Amalgamation is the merger of two or more microstylolites into a dominant solution seam. This can be achieved by the dissolution of dolomite crystals between any two microstylolites, along the surface of solution. When a microstylolite merges with another, the result is a solution seam of higher order. Similarily, when several microstylolites merge laterally, they will form an even thicker seam. The thickness of this seam at any one point, is the combined thickness of all the microstylolites that converged upon that point.

With amalgamation comes a change in the wave-form of the resultant solution seam. Amalgamation of microstylolites through dissolution is analagous to the superposition of two or more waves.

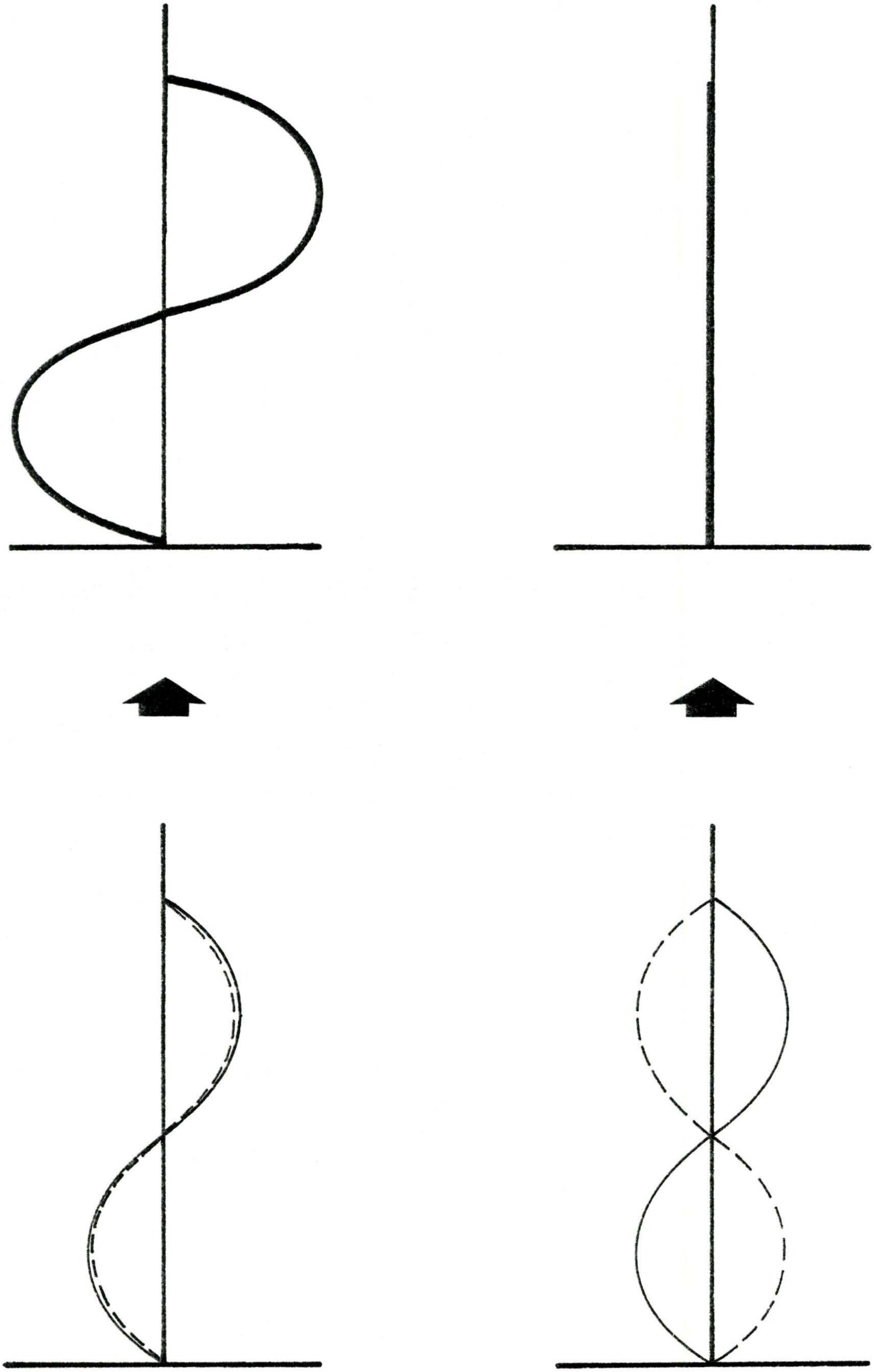
The principle of superposition states that the resultant wave is simply the algebraic sum of the waves. If there are two or more waves of the same amplitude, wavelength, and frequency, but differing in phase, the resultant wave will have the same frequency and wavelength. But the amplitude and phase of resultant wave depends on the phase difference of the original waves (figure 16).

For example, if the original waves are in phase, superposition of these will result in a wave of twice the amplitude, in the same phase. Conversely, if the original waves are a half wavelength out of phase, superposition of these will result in cancellation i.e. a "wave" of zero amplitude. These are two extremes of perfectly constructive interference, and perfectly destructive interference, respectively (Tipler, 1976).

The application of the superposition principle to microstylolites could explain the resultant wave form of the newly amalgamated solution seam. Microstylolites are far from being ideal waves. Their amplitude, wavelength, and frequency are seldom equal, and they are definitely out of phase with respect to one another.

Thus, superposition (amalgamation) of two or more microstylolites may produce a variety of wave-forms. The extreme cases are analagous to those above,though rarely observed. As one may realize, the amalgamation of dissimilar microstylolites will result in a combination of perfectly constructive and destructive interference patterns. The wavelength and amplitude will increase as frequency decreases (figure 17).

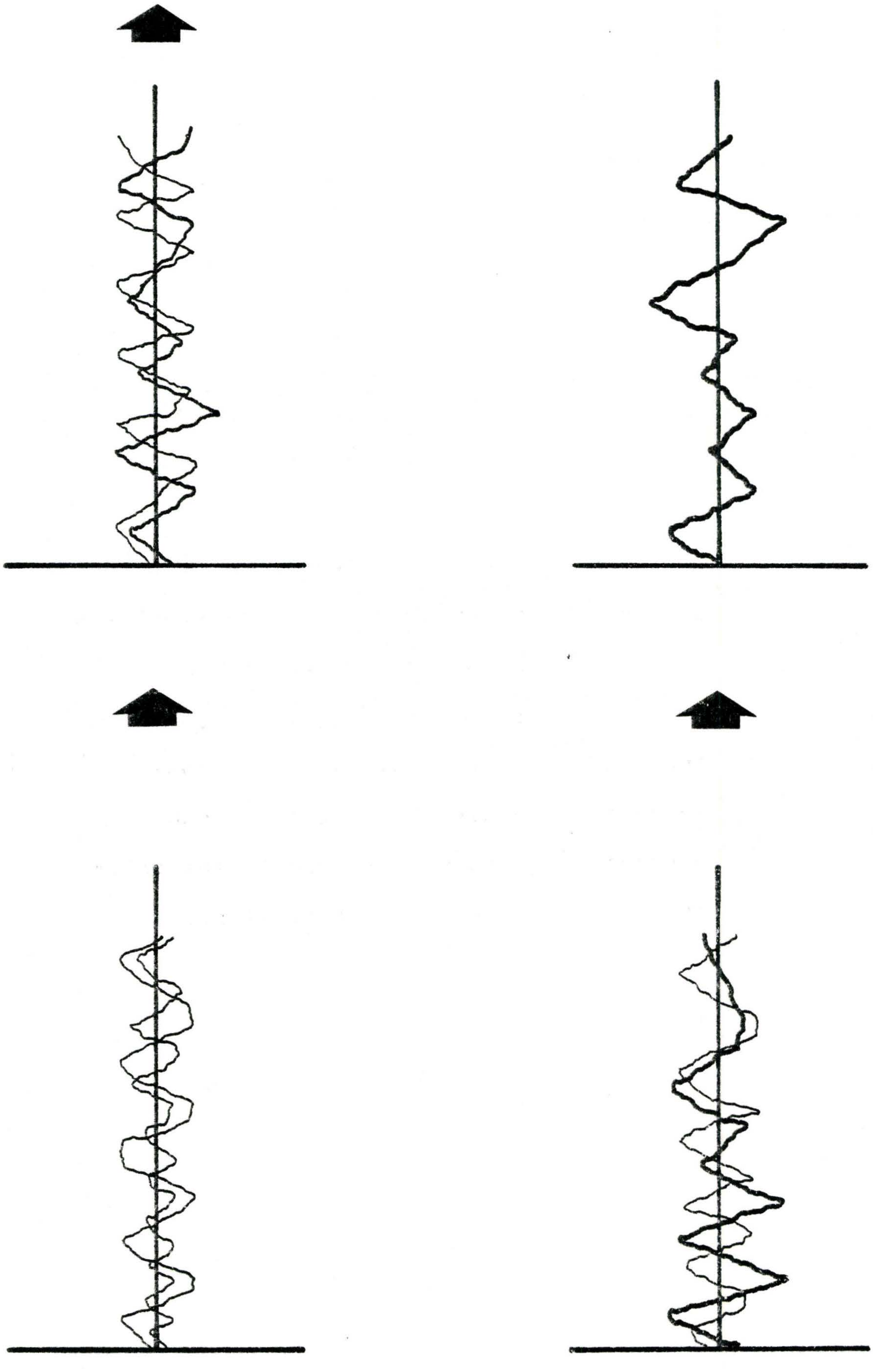
Figure 16 Diagramatic representation of the prin-iple of superposition. Diagram a) is an example of perfect constructive interference. Diagram b) is an example of perfect destructive interference.



a

b

Figure 17 Diagramatic representation of the superposition (amalgamation) of microstylolites. After the consecutive superposition of four microstylolites, the wavelength and amplitude of the resultant seam shows an increase, whereas the frequency shows a decrease. The resultant seam is the thickest "wave" in the last three steps.



The resultant solution seam is called a stylolite when it is recognizable in hand sample as a sutured seam. This can occur within a microstylolite swarm.

Stylolites reach their maximum cumulative thickness of insoluble seam material when the maximum amplitude and wavelength are reached, through amalgamation (superposition) of the last microstylolites present in a swarm. From this point onward, accumulation of insoluble seam material comes from dissolution of "dirty" dolomite crystals, and the incorporation of any microstylolite straggler from outside the original swarm domain.

3.2 Growth of the Stylolite

In the preceding section, the adolescent stylolite grew by the amalgamation of microstylolites through pressure-solution. This growth period results in a major accumulation of insoluble seam material. Conversely, the growth of the mature stylolite involves only a minor accumulation of insoluble seam material.

3.2.1 Growth in the Direction of Shortening

Observation suggests that growth proceeds through dissolution of the sockets, at near-equal rates, on both sides of the solution seam. The increase in amplitude of the stylolite and the absence of cumulative growth (amalgamation) on both sides of the seam, confirms this.

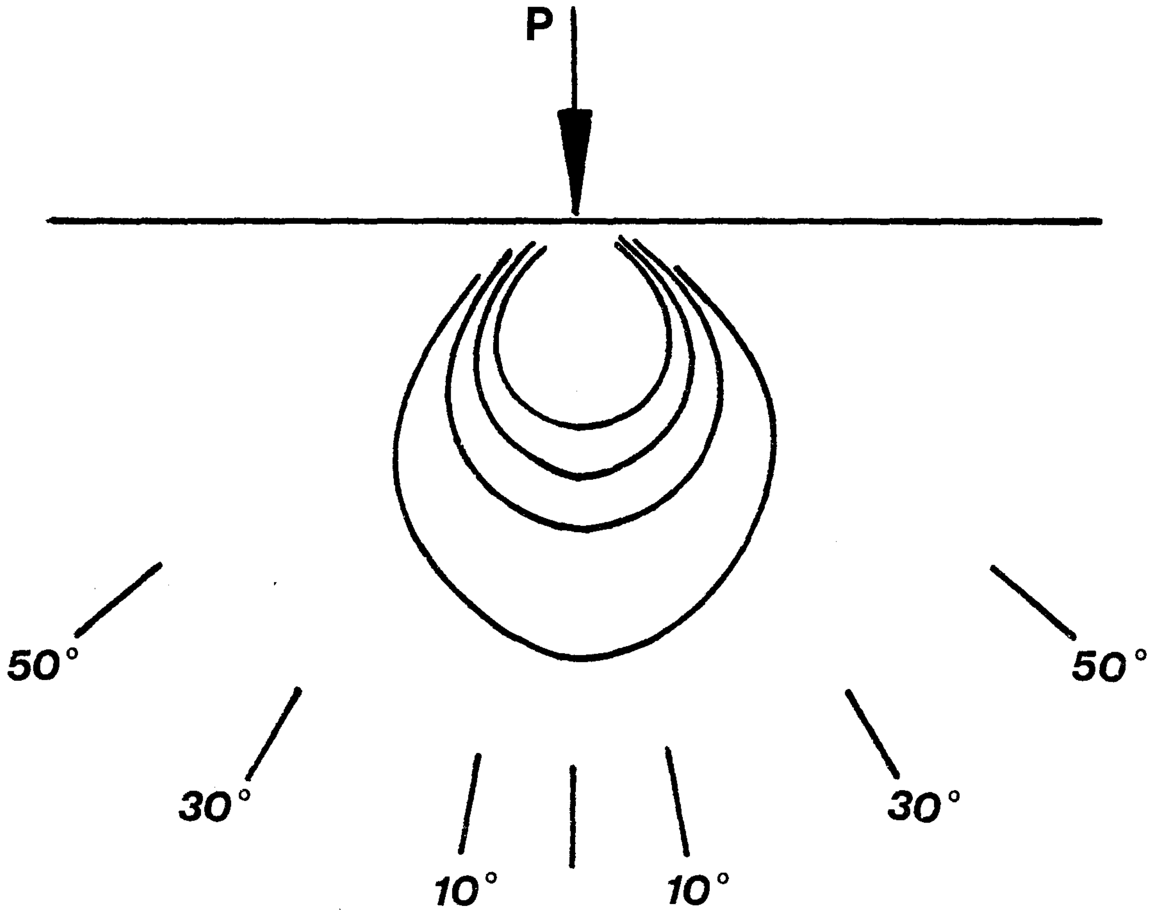
For growth to proceed in the fashion observed, there must be a solubility difference between the socket and the tip of a stylolite column. The socket must be more soluble than the tip. This difference may be inherent in the anisotropic dolomite crystals.

It is believed that differing stress solubilities are the result of a variation in stress of a body acted upon by a point load. In this case, the stylolite column acts as the point load, and the socket is the stressed body. The point vertical stress (in the socket) is maximum when the point load (the column tip) is at an angle of zero degrees relative to σ_1 (Bathurst, 1971), (figure 18).

Grains in the sockets are in a stressed state due to point loading by the column tips. According to Rieke's Principle, mineral grains that are under stress have higher solubilities i.e. they dissolve in preference to unstressed grains of the same mineral. Hence, the sockets on both sides of a solution surface will dissolve at the same rate, assuming that the applied stress is constant.

The result of dissolution of the sockets about a stylolite can be seen in thin-section. The sutured geometry of the adolescent stylolite tends to a higher degree of suturing, becoming sharp-peaked to sub-rectangular, in the mature stylolite. Striations are evident, due to deep interpenetration (vertical shearing of contacts) of the columns, in this mode

Figure 18 Diagramatic representation of the two-dimensional stress distribution in an elastic, isotropic material of unlimited extent. The distribution of stress in an elastic, anisotropic material of limited extent will not be as ideal as this, though analogous. Stress contours are at intervals of equal stress. P represents the point load. The angular measures represent an angle relative to σ_1 (after Bathurst, 1971).


P
50°
50°
30°
30°
10°
10°

of stylolite growth (figure 10).

Seam material is drawn out along the limbs, and caps the tip of the column. This is characteristic of advanced stylolite growth. Since the major source of insoluble seam material i.e. the microstylolite swarm is gone, the growing stylolite attenuates what material it already has. The production of striations is associated with this thinning phenomenon.

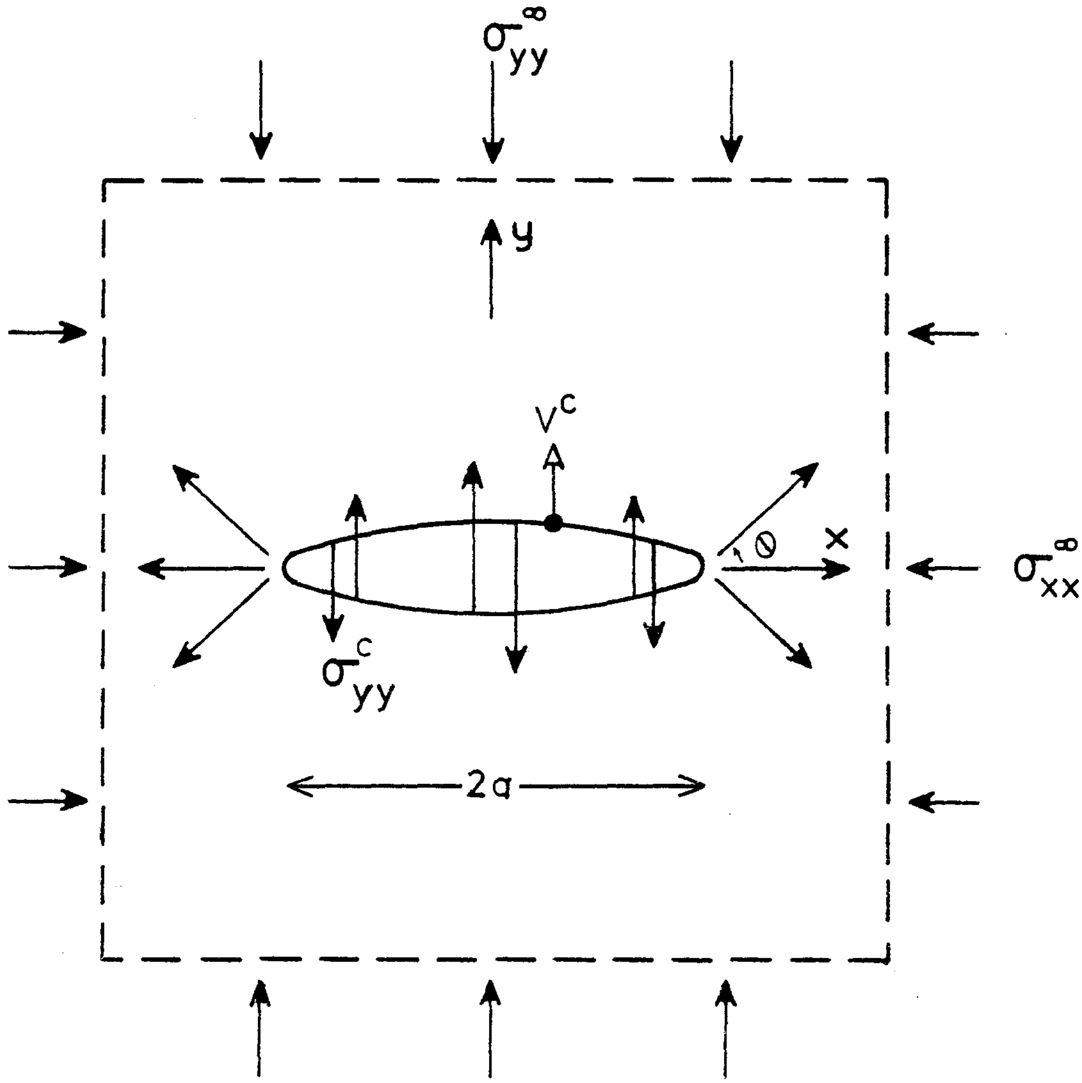
3.2.2 Propagation at the End of a Stylolite

While a stylolite is growing vertically, what happens, to it laterally? Observation suggests that the seam propagates by incorporation of microstylolites through dissolution.

A stylolite dies off towards its termini by a decrease in wavelength and amplitude. From the view of material lost, compaction is much greater in the central portion of the solution seam, than at its termination. The differential compaction sets up a stress concentration at the terminations of a stylolite (Fletcher and Pollard, 1981), (figure 19).

At the terminus, a symmetrically applied stress exists about the plane of the solution surface. Throughout this section, the only mode of pressure-solution considered has been dissolution about the surface of solution. But we should remember that pervasive pressure-solution has always been, (proceeding) in the background, outside the immediate influence of a stylolite domain.

Figure 19 Diagramatic representation of the compressive stresses acting upon a solution surface (2a), in the plane XY. Uniform remote compressive stresses σ_{yy}^{∞} and σ_{xx}^{∞} act normal and parallel to the surface. Compressive stresses σ_{yy}^{c} act upon the solution surface. σ_{yy}^{c} corresponds to the thickness of rock dissolved away along the surface. In this case the compressive stresses exceed the remote stresses and displacement occurs in the Y direction. V^{c} represents this normal displacement and one half of the material removed. In the region of the surface tip there is a strong stress concentration, symmetrical about the solution plane. This results in propagation in the X direction and relaxes the compressive stress acting upon the surface. (after Fletcher and Pollard, 1981)


σ_{yy}^{∞}
y
V^c
θ
x
σ_{xx}^{∞}
σ_{yy}^{c}
2a

Pervasive pressure-solution will be dominant at a stylolite terminus. The stress concentration set up by differential compaction provides a means for developing a whole new set of sutured grain contacts. Via the mechanism outlined in section 3.1.1, abundant microstylolites develop at various angles to the stylolite surface. A dendritic pattern of microstylolites is the observed result. They all converge at the terminus of the stylolite (figure 11).

Propagation proceeds by the familiar process of amalgamation through dissolution, and the constant generation of a new set of sutured grain contacts. The newly formed extension then goes through growth patterns similar to those of the stylolite itself.

See figures 20 and 21 for a summary of the model.

3.3 Growth Cessation

To every growing feature, there must come an end. But the question is how?

In the case at hand, one can only speculate about the "death" of a stylolite. Observational evidence does not lead to the answer. For the purpose of this study, the reason why a stylolite stops growing is not a critical factor to develop the model. Hence, this discussion will be brief.

3.3.1 Pressure Reduction

Pressure-solution will cease when the critical pressure required for an effective stress becomes so low, that stress-induced dissolution cannot act. The most feasible way to decrease the pressure is to erode away the overburden creating that pressure. This requires a substantial hiatus in sedimentation which creates the overburden in the first place.

3.3.2 Loss of Fluid

Pressure-solution is dependant upon the presence of a fluid to act as solvent and transport medium. If the pore fluid is lost then there is no source of solvent, and no transport. Fluids can be lost by extensive dewatering of the system, through cracks, joints, and natural lithological partings.

3.3.3 Effect of Cementation

Park and Schot (1968) and Bathurst (1971) prefer that pressure-solution initiate in a pre-complete cementation sediment. Thus the sediment is open to the pore fluids. In an open system, transport of solute ions away from the site of dissolution can be carried out relatively easily. In a completely cemented system, permeability is essentially lost. Transport of solute ions ceases, and the pore fluids will equilibrate. Hence dissolution will stop.

Figure 20 Summary diagram representing the two stages of stylolite growth. Stage one is represented by the amalgamation of microstylolites to form a stylolite. Stage two is represented by the growth of the stylolite in the direction of shortening. Note that the seam thickness up until the disappearance of the microstylolite swarm. After this point, the seam thickness decreases as growth proceeds. Outside of the microstylolite swarm straggler microstylolites are present. These become incorporated into the mature seam.

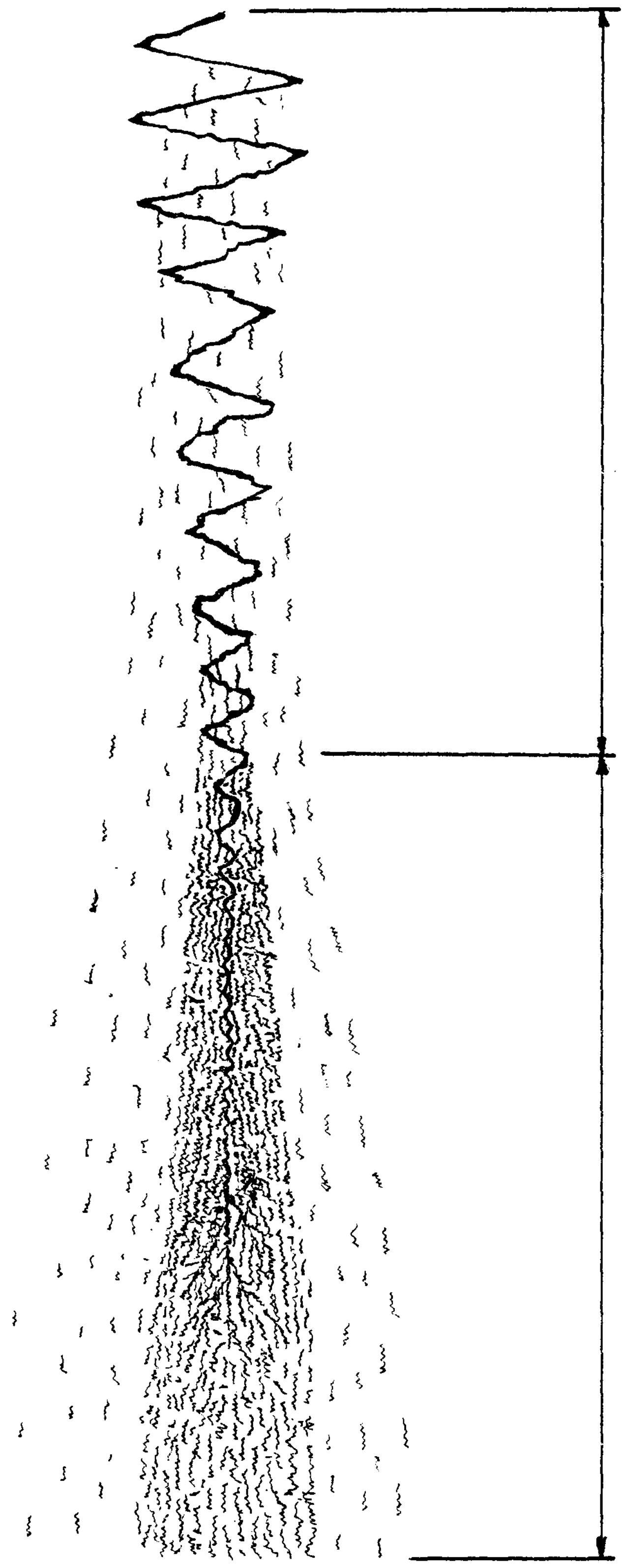
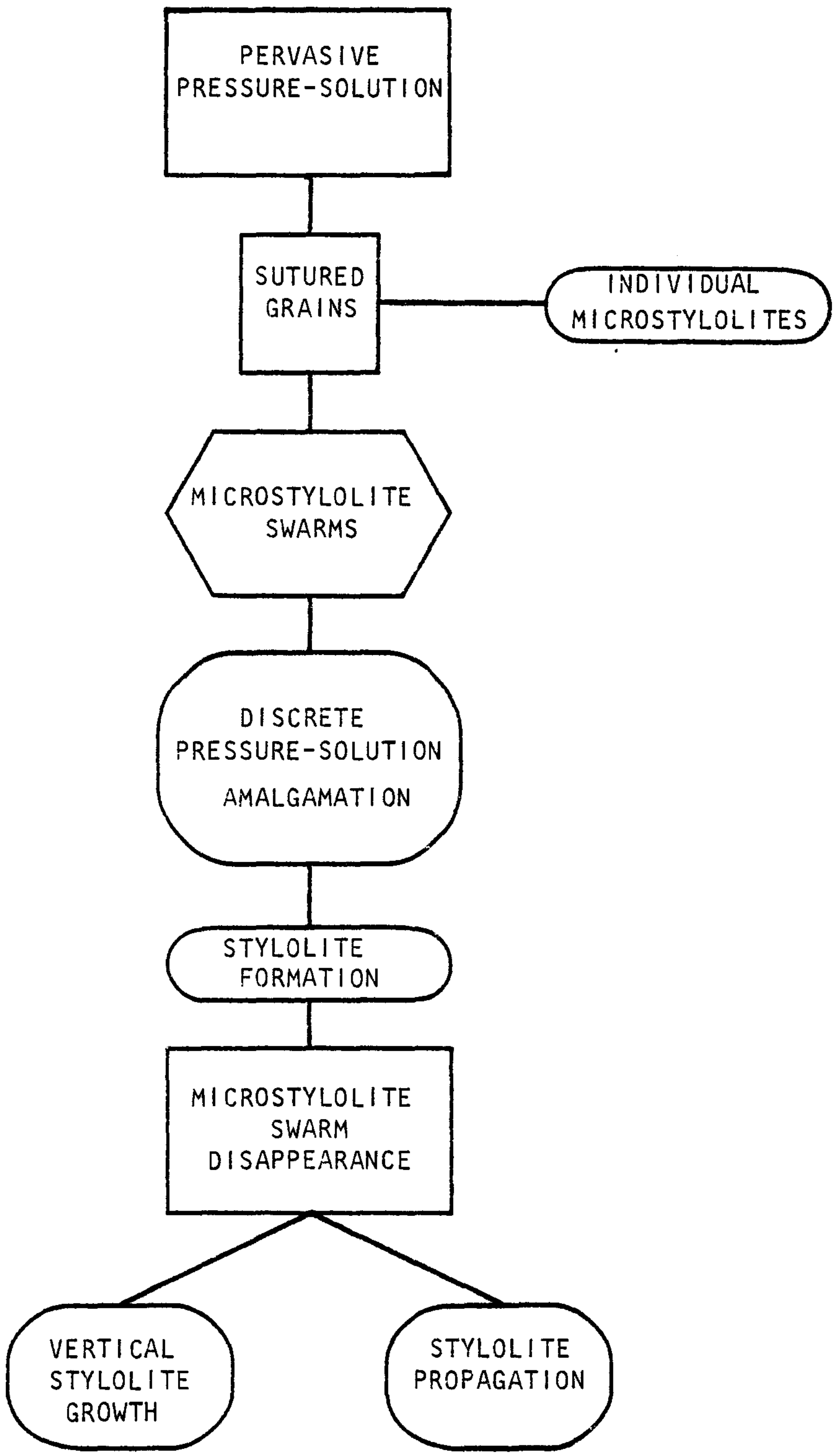

II
I

Figure 21 This is a flow chart representing stylolite formation. Initially, pervasive pressure-solution is the dominant mode. It may produce individual microstylolites, which continue to grow, or become incorporated into a stylolite. Or, pervasive pressure-solution may produce microstylolite swarms. At the point of amalgamation of micro-stylolites, discrete pressure-solution becomes dominant, and remains so throughout the rest of stylolite formation.


PERVASIVE PRESSURE-SOLUTION
SUTURED GRAINS
INDIVIDUAL MICROSTYLOLITES
MICROSTYLOLITE SWARMS
DISCRETE PRESSURE-SOLUTION AMALGAMATION
STYLOLITE FORMATION
MICROSTYLOLITE SWARM DISAPPEARANCE
VERTICAL STYLOLITE GROWTH
STYLOLITE PROPAGATION

CHAPTER 4

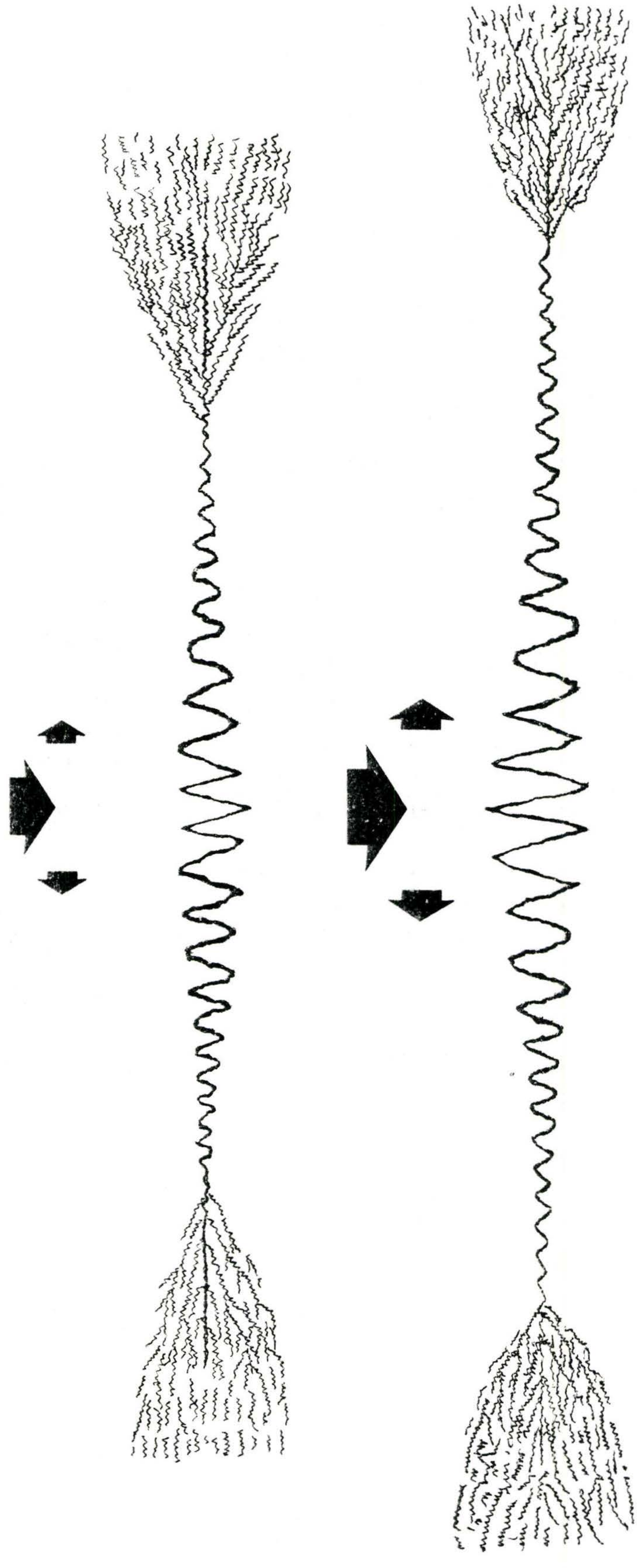
4.1 Summary and Implications

As a result of this model, it can be seen that stylolite formation is an active, evolutionary process. It requires two modes of pressure-solution, pervasive and discrete. Pervasive pressure-solution is the mechanism responsible for initiating new stages of growth. Discrete pressure-solution is responsible for inducing and maintaining transverse growth.

Amalgamation through dissolution is the key to stylolite formation. As a result, pressure-solution progresses from dissolution within a zone, to dissolution at a discrete surface. Amalgamation also reveals that the shortening is much greater than expected. It is not just the shortening as represented by the amplitude of a stylolite. The actual shortening is that which may have been represented by the cumulative thickness of a microstylolite swarm. Unfortunately one cannot determine the thickness of swarm that is no longer present.

Once a stylolite has grown, it is self-supporting. By this is meant that the differential shortening created by a stylolite is effectively used by the solution surface to propagate laterally. This propagation results in a gross hourglass form of the stylolite (figure 22). The central body of the solution seam is the most geometrically developed,

Figure 22 Diagramatic representation of how a stylolite extends laterally by growing vertically. The compaction in the body of the stylolite is felt at its extremities. The stylolite tries to relieve the stress at its termini by propagation. Thus, vertical growth aids lateral growth of the stylolite.



even though in space it is the most confined; by contrast the extremities of the stylolite are the least geometrically evolved, but occupy the most space.

Implications arise from this model that require further study. The first and foremost is; could this model be adapted to explain how stylolites form in other rocks, and not just argillaceous carbonates? If so, ideas about shortening of sedimentary piles will need revision.

If compaction is modestly estimated to be fifty percent more than represented by the stylolite alone, then fifty percent more of the contained fluids must be simultaneously released. These fluids must undergo lateral migration, as a result of compaction and because the stylolites represent impermeable barriers.

Assuming that redeposition of dissolved material took place in situ, then any one stylolite should have an elliptical pattern of reduced porosity around it. This too will affect fluid migration. More than that, the deposition of dissolved material may be a significant source of diagenetic cements, either locally or regionally (if the fluids are carried out of the compacted domain).

The result of this model is two-fold. First, the bulk compaction of the rock is not represented only by the amplitude of a stylolite. Secondly, fluid migration is markedly affected by this mode of stylolitization, with greatly extend migration path.

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