THE PETROGRAPHY AND CHEMISTRY OF FOSSIL BURROW MARGINS
THE PETROGRAPHY AND CHEMISTRY OF FOSSIL BURROW MARGINS

By

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A Thesis
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Title: The Petrography and Chemistry of Fossil Burrow Margins

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A great deal of information may be attained from trace fossils. Burrow margins represent zones of complex interactions, which may be recognized in the rock record. Sediment deformation results during organism penetration and reoriented particles tend to align with the burrow structure. Sixty-five percent of all elongate grains show less than $10^\circ$ tangential deviation parallel to burrow length, and 82% less than $20^\circ$ tangential deviation for grains measured around the circular burrow cross-section. As suggested by fluid dynamic theory, fluctuation in burrowing velocity appears to induce grain rotation. Sediment type and fluidity, in conjunction with the nature of burrowing, will control the preservation of reoriented grains.

Burrow walls are sites of metal accumulation. Metal cations become complexed to metabolites associated with decomposition of marginal organics, or to clay minerals entering the burrow. Some of these metals may also "scavenge" additional cations out of irrigated seawater. Concentrations are preserved as oxides or metal-rich cements within the marginal zone; characteristic of only those structures which are organically induced. Electron
probe scans across burrow structures produce high relative peaks for Fe, Al, Cu and Ni in the wall region. These analyses may allow valuable interpretations, expanding the realm of Ichnology.
ACKNOWLEDGEMENTS

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To my friends and peers, who provided the necessary buffer with the real world, I am truly indebted.

And to my mother, who extended the time and patience in typing this thesis, my thanks.
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CHAPTER 1
Introduction

1-1. Trace Fossil Structures and Applications

Ichnology, the study of trace fossils, has become an integrated and important component of the geological sciences (Seilacher, 1964; Crimes and Harper, 1970; Frey, 1975). Trace fossils are biogenic sedimentary structures, including tracks, trails, burrows and other organically induced disruptions. Often, textural patterns or even more subtle stain patterns will represent the only preserved record of organic activity (Martinson, in Crimes and Harper, 1970).

These preserved structures will often reflect aspects of the organism's lifestyle. In many instances, the trace fossil will provide information on the behavioral or physical nature of the organism responsible for the trace. Their presence in otherwise unfossiliferous rocks is likely a function of the highly sedimentary nature of preservation. Although inferences yielded from trace fossils are often indirectly obtained, the persistent appearance of these structures in the geologic record enables interpretations otherwise not possible.

An initial impression of trace fossils may be somewhat misleading, as suggested by the term "trace". Although most trace fossils are recorded at the sediment-
water interface (Crimes, 1970), organic impact on sediments is quite extensive and may control much of the sedimentary fabric (Crimes and Harper, 1970).

The effects of burrowing organisms on sediment are well documented (Rhoads and Stanley, 1965; Howard and Frey, 1973; Rhoads, 1970; Frey, 1975). The resulting biogenic structures are numerous and worth mentioning. Sedimentary stratification (depositional laminae, cross-beds, etc.) may be partially or wholly reworked, in the latter case producing an homogenous sediment. Bioturbation, as this is properly referred to, may also greatly increase the water content in the upper layers of the sediment (up to 80% - Rhoads and Young, 1970), creating a less stable environment.

Sediment ingestion is often selective (Newall, 1965) which may complicate the sedimentary record. Some deposit feeders, such as the polychaete Clymenella torquata, will ingest finer grain sizes leaving the coarses grains at the bottom of the burrow (Rhoads and Stanley, 1965; Featherstone and Risk, 1977). The finer particles are then egested at the sediment-water interface, producing a fining upwards sequence, in this case referred to as biogenic graded bedding.

Organisms dwelling in permanent or semi-permanent burrows may reinforce the linings of the burrow with larger grains or sometimes with flattish minerals (Fager, 1964).
This serves to produce lateral heterogeneity in the sediment (indirectly this may also help to stabilize the sediment, if burrow densities are high enough).

Trace fossils have many applications, and are used widely in the geological sciences. Unfossiliferous lithofacies may in fact be dated by trace fossils, as best exemplified with Cruziana in defining Lower Cambrian strata (Crimes, 1970). Stratigraphy may also be aided by using burrows as "way up" indicators, in regions of tectonic deformation. Stress fields may also be inferred with careful examination of tube distortion and orientation (Frey, 1975).

As mentioned earlier, the impact of burrowing organisms on sediment is extensive, and has dictated a necessity to incorporate organic structures into sedimentology. With the use of biogenic escape structures, eroded spreiten and bioturbation, depositional rates may be deduced, as well as the nature of sediment influx (Crimes and Harper, 1970). The character of the substrate, particularly its fluidity, may also be assessed by the degree of bioturbation or the extent of burrow wall reinforcement. Sediment accumulation as shadow deposits around trace fossil structures (surficial) may reflect paleo-current direction as will current-induced path diversion of a moving organism (Seilacher, 1964; Frey, 1975).

Trace fossils may also contain a great deal of useful paleo-ecological information. Such structures may
depict organism behaviour and response enhancing community reconstruction in micro-facies analysis. Trace morphology may indicate feeding modes, indirectly providing information on the nature of the substrate. It may also be possible to interpret oxygen availability with burrow depth and orientation. Rhoads (1968) believes that low oxygen marine environments are characterised by small diameter horizontal feeding traces, with an absence of body fossils (Rhoads, 1968; in Frey, 1975). The use of trace fossils has been extended to bathymetry (Seilacher, 1964), but depth indicators as such should be approached with caution (Frey, 1970; Crimes and Harper, 1970; Hayward, 1976).

1-2. **Focus and Area of Study**

This thesis will focus on the nature of burrow linings. The physical and chemical composition of the burrow walls may show discrete differences from the surrounding host sediment. For the most part, the study will examine *Skolithos* of Paleozoic age. These burrows are generally of vertical orientation, displaying near circular cross-sections. The *Skolithos* structure, during occupation, extended downwards into the sediment from the sediment-water interface. This simple morphology will provide a straight-forward approach to analyzing burrow walls.

Specimens investigated were taken from the Thorold Sandstone and the Nepean Quartzite. The Thorold Formation
is a greyish-green, quartz-rich sandstone-siltstone with shaley interbeds. The Formation extends from Dundas, Ontario, in the west, to Fulton, New York, in the east, and has generally been interpreted as representing a shallow, near shore environment of deposition. The Thorold specimens were from the West Hamilton area, where the facies has been discussed as a spreading deltaic system (Martini, 1971). According to this model, the high percentage of silt and clay in the samples investigated would suggest collection from a distal portion of the complex.

There is some question as to the age of the Thorold. The Formation may represent the final stage of deposition of the Medina Group (Martini, 1974), inferring a Lower Silurian age for the sandstone, or it could represent the lowermost segment of the Clinton Group (Boulton, 1957), suggesting Mid-Silurian age. Confusion here may have resulted from the apparent transgressive nature of the Silurian sea, whereby the Thorold youngs to the east, hence crossing a time boundary upon depositional advancement (Fisher, 1954). Although the Formation contains few body fossils, numerous forms of trace fossils have been studied and recorded (Pemberton, 1979).

The Nepean Formation is a cream-coloured, quartz-rich, coarse sandstone. The Nepean is observed
as a thin-thickly bedded unit, cropping out sporadically across the Ottawa-St. Lawrence basin (Wilson, 1946). The upper portion of this Formation, from which the samples were taken, represent an offshore marine environment of deposition. Hydraulic intensity appears to have been variable, with fluctuating rates of sediment influx (Greggs and Bond, 1972).

The Nepean Sandstone unconformably overlies Precambrian rocks and lies stratigraphically below the March Sandstone. This Lower Paleozoic sediment is probably of Lower Ordovician age. As with the Thorold, however, the picture is complicated by a Paleozoic sea transgressing from the southeast (Wilson, 1946). This Formation contains few body fossils, yet trace fossils are abundant, being most distinct in the upper portion of individual beds. Bioturbation has in fact altered much of the primary sedimentary structures (Greggs and Bond, 1972).

1-3. Methods

Samples were slabbed perpendicular to bedding surfaces, hence parallel to vertical burrow extension. Horizontal cuts were also performed, parallel to bedding, such that the circular burrow section could be seen. Thin sections of these cross-sections were taken and grain analyses made on the various specimens so as to
observe the nature of the burrow linings. Orientations were recorded for those grains associated with the inner wall surface.

The burrow walls were then further examined by electron probe scans across the biogenic structure. The scans recorded the presence of certain cations and their relative concentrations. Inorganic structures were also scanned, so as to assess possible mechanisms responsible for metal accumulation.
Plate 1-1 *Skolithos* sp. from the Thorold Sandstone.

Longitudinal view showing vertical nature of specimen (actual burrow size is 7.5cm)
Plate 1-2 Skolithos sp. from the Nepean Quartzite.

Cross-sectional cut displays several Skolithos burrows with additional organic activity observed as more complicated spreiten-bearing burrows. Note also laminae depression adjacent to structures.
CHAPTER 2
Grain Orientation Along Burrow Margins

2-1. Sediment Rearrangement

On a macro-scale, one may commonly infer the direction of organism movement by the depression or elevation of oxide stains, laminae or other semi-continuous bands within the sediment. The downwards deformation of laminae will be a function of a series of variables. Burrowing organisms penetrate sediment for different purposes, therefore the processes involved will also differ. Sediment may be eaten, excavated and ejected, or simply pushed aside (Boyd, 1964) as the organism drives into the substratum. Downwarping will then vary in accordance with the physical and mechanical interactions associated with penetration. These factors will include the size and shape of the sediment, the water content of the sediment, the rate of organism penetration, the drag force exerted by the organism (Boyd, 1964), the process involved in penetration and other biological variables which will differ with burrowers.

Sediment rearrangement is primarily observed in zones between differential adjacent sediment layers. Sometimes, sediment deformation is easily observed (Boyd, 1964), as where vertical burrowing has penetrated alternating beds of coarse and fine sand. Lack of layering,
however, should not suggest that the phenomenon is not operative. Sediment downwarping, implying particle translation, must be a common process upon burrowing.

In order to understand and interpret grain re-orientation, the physics involved in this process should be discussed. Since grain orientation is generally associated with fluid flows, the analogy will be drawn between an unidirectional flow and a burrowing organism, whereby the organism will be treated as a moving fluid. Although demanding of unconventional variable magnitudes, the inherent nature of this pseudo-flow should be enlightened by fluid dynamic theory.

A fluid correlation is necessary so as to isolate the pertinent mechanism(s) involved in sediment re-distribution. Initial confusion arises in the proper designation of flow type, as the organic burrower could exhibit laminar or turbulent character upon sediment penetration. This quality may be estimated by calculating the Reynold's number (Blatt, Middleton and Murray, 1980 p. 96)

\[ R_e = \frac{uL\rho}{\mu} \]

\( R_e \) = Reynold's number
\( u \) = velocity of fluid
\( \rho \) = density of fluid
\( L \) = hydraulic radius
\( \mu \) = fluid viscosity
Discussion of these variables would tend to favor a laminar-type flow for systematic burrowing. Although burrowing velocity might be comparable to current velocities, the high organism viscosity and small size would tend to keep the $R_e$ low. The equation does not consider, however, the irregular nature of an "organic flow". Variables such as coelomic pulsation, or appendage vibration, could very easily create a localized turbulent environment, as might a rapid sediment retreat.

The stress involved by the interaction of a particle on a moving fluid induces a flow resistance referred to as the drag (Rusnak, 1957). The important sediment variables embodied in this interaction are the size and shape of the grains, as well as the original orientation of the particle (Rusnak, 1957). The drag force may be represented by the following equation:

$$\text{Drag Force} = C_o \frac{A \rho V^2}{2}$$

- $C_o =$ coefficient of drag
- $A =$ projection area of the particle in the direction of motion
- $\rho =$ density of the fluid
- $V =$ velocity of the particle with respect to the fluid

With these expressions for the conditions of flow, it is now possible to interpret the burrow margin
stress regime. The movement or rotation of grains along a burrow wall may be correlated with the concept of sediment transport along the bottom of a watercourse by surface creep. This process is generally discussed as a function of the tractive forces exerted by fluid shear (Rusnak, 1957). An expression derived to predict particle equilibrium for shear vs. resistance may be written as (for a spherical particle):

\[ \tau_t = ap \eta g d \tan \theta = \text{shear stress along the bottom} \]

\[ a = \text{coefficient} \]
\[ p = \text{packing coefficient} \]
\[ 3 \]
\[ \eta = \text{density of the fluid} \]
\[ g = \text{gravitational constant} \]
\[ d = \text{diameter of the particle} \]
\[ \theta = \text{angle of repose of the grains} \]

As discussed in Blatt et al. (1980) p. 100, the shear stress may be equally well represented by the shear velocity \( U_\ast \), for shearing at the fluid-sediment interface. As stated above, the equation predicts particle equilibrium in a flow. Therefore, upon instantaneous velocity fluctuation (e.g. by a burrowing organism), the equation will become unbalanced and can achieve equilibrium solely by reorientation of interface particles (i.e. grain re-arrangement). Particle rotation will be a function of the instantaneous velocity fluctuation of the fluid (organism) on the sediment (burrow margin).
Sediment penetration is often characterized by changes in velocity. With decreased shear velocity or "effective drag" reduction, particle motion will cease. Stability will arise when the forces exerted on the particle are in equilibrium. In a burrowing regime, grains will seek their most stable orientation, reflecting a position of "least drag." Rusnak (1957) has listed the following particle factors which will also influence this position.

1. elongation of grains
2. roughness of bottom
3. packing of adjacent grains
4. rate of sediment supply

These and other elements will be discussed in detail with their relevance to burrowing organisms later in this chapter.

2-2. Analyses

Burrows examined were primarily Skolithos of the Nepean Sandstone. Grain analysis of Thorald Skolithos was not performed, as the grain size was too small for accurate assessment. The initial surfaces examined were perpendicular to bedding, because the Skolithos usually oriented vertically (see fig. 2-1). The burrows examined were typically 4 - 8 cm in vertical length and 3 - 5 mm in diameter. Thin sections were cut so as to contain both
Fig. 2-1 A.) Illustration depicting how samples were slabbed (parallel bedding & perpendicular to bedding).

B.) Hypothetical vertical section (perpendicular to bedding) with small rectangle representative of thin section site.

C.) Hypothetical horizontal section (parallel bedding) with small rectangle representative of thin section site.
sides of the structure. For additional burrow definition, the sections were cut approximately 10 microns thicker than the norm (30 microns). Grain orientations were measured along burrow margins, using only those grains which exhibited a ratio of at least 2:1 in the observed projection. Burrows were readily distinguished in thin section by a marked hematite enrichment along margins, which at times continued into the structure. A calcite rich cement was also found within individual burrows, probably related to an initially high porosity and permeability of the infilled region. Six burrows were examined, providing 128 such grains, allowing statistical validity to the documented results.

Additional insight was provided by viewing the horizontal surface (parallel bedding) (see fig. 2-1). Thin sections were cut so as to observe the circular section of the burrow and were taken at an approximately cylindrical segment of the burrow, generally midway along its length. Once again, six burrows were examined in this fashion.

2-3. **Control Measurements**

In order to produce an accurate interpretation of results, test regions were chosen, within which an equal number of grain orientations were taken. In thin
sections of vertical projections, linear test runs were performed, at some distance from burrowing activity. For thin sections of circular sections, a radius vector corresponding to that of the burrow was used to construct a similar circular image some distance away, around which grain orientations were taken.
Table 2-1. Distribution of margin grain orientations for 6 Nepean Skolithos, in vertical section. (recorded as degree of tangential deviation away from the burrow margin).

*Note:  (+) Inclined into burrow  
(-) Inclined out of burrow  
Viewing from stratigraphic top to bottom.
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<tr>
<td>BBS-V1</td>
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<tr>
<td>+4</td>
<td>2</td>
</tr>
<tr>
<td>-4</td>
<td>4</td>
</tr>
<tr>
<td>BBS-V2</td>
<td></td>
</tr>
<tr>
<td>+6</td>
<td>3</td>
</tr>
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<td>-5</td>
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<td>+7</td>
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</tr>
</tbody>
</table>
Table 2-2. Distribution of margin grain orientations for 6 Nepean Skolithos, in horizontal section. (recorded as degree of tangential deviation away from burrow margin).

*Note:  
(+) Inclined into burrow  
(-) Inclined out of burrow  

Viewing clockwise around the approximate circular perimeter.
<table>
<thead>
<tr>
<th>Specimen</th>
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<th>20-29</th>
<th>30-39</th>
<th>40-49</th>
<th>50-59</th>
<th>60-69</th>
<th>70-79</th>
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<td>-</td>
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<td>0</td>
<td>-</td>
<td>-</td>
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</table>
Fig. 2-2  Distribution of margin grain orientations for 6 Nepean Skolithos in vertical section (recorded as degree of tangential deviation away from burrow wall).

Fig. 2-3  Distribution of margin grain orientations for 6 Nepean Skolithos in horizontal section.
Plate 2-1  Photo-micrograph of *Skolithos* margin of the Nepean Quartzite. Overlay depicts grain tendency to parallelism with the burrow wall.

(25X enlargement)
Plate 2-2  Point light source projection of Skolithos (horizontal plane thin section) with circular image of burrow. Overlay depicts the near tangential nature of marginal grains.

(6X enlargement)
Plate 2-3: Diplocraterian burrow from the Thorold Formation, with spreiten enhanced by large quartz grains. Data shows tangential deviance measured around spreiten.

<table>
<thead>
<tr>
<th>Grain No.</th>
<th>Tangential Deviance (degrees)</th>
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<th>Tangential Deviance (degrees)</th>
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<td>12</td>
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</tr>
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<td>-26</td>
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<td>+4</td>
</tr>
<tr>
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<td>-7</td>
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<td>-2</td>
</tr>
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<td>+28</td>
<td>18</td>
<td>+15</td>
</tr>
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<td>21</td>
<td>-28</td>
</tr>
<tr>
<td>11</td>
<td>+8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: (+) inclined into burrow  
(-) inclined out of burrow  
Viewing from stratigraphic top → bottom
2-4. **Results**

Grains found at burrow margins were oriented parallel → sub-parallel to the length of the burrows. Of the 127 grain orientations observed in vertical section, 42% showed less than 10° tangential variation and 65% less than 20° variation (Standard Deviation = 19° mean = -4°) (see fig. 2-2 ; table 2-1).

In the horizontal plane, grains were oriented mostly in tangential fashion around the circular burrow section. Fifty grain orientations were measured of which 66% displayed less than 10° tangential variation and 82% less than 20° variation (Standard Deviation = 11° mean = -2°) (see fig. 2-3 ; table 2-2).

An additional *Diplocraterion* burrow was observed in the Thorold Sandstone (see plate 2-3). This specimen displayed a burrow lining composed of grains much larger than the surrounding sediment. Orientation measurements were taken parallel to the wall of the vertical section and continuing tangentially around the spreiten structure. Again, the variation is observed to vary only slightly from parallel → sub-parallel orientation; 57% showed less than 10° deviation with 76% less than 20°.

Control measurements produced random orientations. Controls used from the Thorold and Nepean Sandstone did not exhibit any preferred grain alignment of depositional origin. Such relict orientation might have produced ap-
parent trends in quartz grains, deterring from burrow results.

2-5. Discussion

Alignment preserved in documented specimens was often quite subtle (see plate 2-3). Few marginal grains, relative to the total number, exhibited ratios in excess of 2:1 for the x & y axes. The moderately well sorted sand grains also tended to conceal alignment, displaying subrounded profiles for the most part. In sediments displaying less particle uniformity, marginal alignment might be more pronounced in thin section.

From the examination of burrowing in terms of fluid parameters, it becomes apparent that velocity fluctuation of the burrower will be the likely determinant in producing alignment of grains along the sides of a burrow. This allows discussion of those variables which will influence the success of velocity changes in altering grain orientation. Investigation of these variables will help understand the character of burrow linings.

A). Particle interaction

The mechanics of grain movement will ultimately depend upon the interaction of adjacent particles. Compaction of sediment will dictate the freedom of movement of grains, thereby controlling the nature of reorientation. Grain shape and sorting will also influence the ease of
reorientation, as stresses are a function of effective surface area. In other words, an increase in the effective surface area of a grain in contact with a burrowing organism, will increase the potential force the organism can apply on that particle. Therefore the burrower will exert a greater directional influence on such marginal grains, fashioning a stability field for them in the direction of its movement. Elongated grains will tend towards parallelism with this principle directional stress.

The antithetical argument would involve a surface area increase in grain-grain contacts, encouraging greater stability in the direction normal to the contact. This may be visualized by comparing the difficulty in rotation of rectangular blocks and cubic blocks of equal mass, stacked separately. Not only is the gravitational force acting on a greater surface area for the brick shapes, but rotation demands an additional space parameter. Under such conditions in sediment, a new variable, that of water injection into the substrate, becomes an important consideration.

B). Water - content of sediment

The sediment water content will influence both the ease of particle reorientation and the tendency for grains to retain this position during diagenesis. Fluidity will be a function of sedimentation rate, grain size and
sorting, and bioturbation rates. Organisms burrowing in muds of high water content (greater than 60%), deform the sediment thixotropically (see fig. 2-4) (Rhoads, Speden and Waage, 1972). Rhoads et al. describe particle displacement by grain slippage past each other. Under these conditions burrow margins will be poorly developed. Grain alignment will therefore display a more random character, reflecting a lack of sediment cohesiveness. Dewatering upon diagenesis, with subsequent compaction, may also serve to contort marginal orientation. Note that this may not be strictly true for certain tube builders, which may selectively develop a burrow wall by differential grain cementation (Pemberton, 1976).

Where sediment is less saturated (less than 50% by weight), the substrate becomes much more cohesive in nature. Penetration induces plastic deformation, which may extend some distance from the inner wall surface (Rhoads et al.), depending on grain parameters. It is within this regime that grain reorientation resulting from burrowing will display best marginal alignment for potential preservation.

C) Biogenic factors

Many specific factors are encompassed under this heading, yet each may play a critical role in controlling
Fig. 2-4 Mass properties of sediments related to grain-size and water content (after Boswell, 1961).
cloddy
Silt & Sand

Water

fluid

thixotropic

plastic-dilatant

crumbly

Clay
burrow expression. Isolating these organic variables may guide interpretation for specific sedimentary burrowers.

i). Mode of burrowing

Burrowing must result in grain displacement, and this phenomenon will operate differently for different penetration modes. With excavation using appendages as with Callianassa, one would expect poor alignment at burrow margins, reflecting frequent avalanching of most parallel grains and suspension settling of mixed particles.

Rocking into the sediment, displayed by some bivalves, typical of the Arcoids, (Thomas, 1978) results in a variety of angular motions upon penetration. The lateral components will undoubtedly contort the vertical component, thereby confusing any secondary grain alignment. Divaricate ribbing and variation in valve width, typical of Arcoids (Thomas, 1978), will also serve to obliterate trends in grain orientation.

Coelomic pulsation should represent a logical mechanism to produce preferred marginal grain alignment. It enables rhythmic stresses to operate in conjunction with a variety of instantaneous velocities. This should be best exemplified by polychaete burrowing in sandy sediment.
Burrowers employing a proboscus or foot attachment to pull themselves into the sediment also provide a successful mode to develop preferred grain orientation. This style of penetration best parallels an unidirectional flow as discussed earlier with fluid dynamics. Coelomic pulsation provides the necessary instantaneous velocity changes - the mechanism predicted to account for particle reorientation. A large variety of organisms burrow in this fashion, encouraging the fluid model.

ii). Organic shape

Organic-sediment interaction will be affected to some extent by the shape of the burrower. The degree of metameric segmentation in burrowing polychaetes will affect the lining of their burrow. Pronounced relief in segments will induce grain rotations easier than would a smooth-sided counterpart. Epirelief will provide variable stresses around the convex ridges. Grains should be more easily mobilized under such conditions, and may in fact be "gripped" between segments. Extreme relief or the presence of parapodia, however, could effectively "stir up" the sediment upon penetration, limiting the potential for grain alignment. The same argument should hold for bivalves, the analogy existing with plications or growth bands.

Uniform dimensions from posterior to anterior should provide the most ideal form to induce parallel align-
ment. This will serve to decrease variation in stress vectors at individual sites along the margin, throughout burrowing. Lenticular design will promote collapse of the burrow sides upon penetration. Physical instability of the margin is induced in the tail region for two reasons. Adhesion between the burrower and the boundary grains will tend to draw the particles into the burrow, where tapering begins. Secondly, water currents flushing into the burrow will be restricted by the tail, enhancing a low pressure region within the structure (see fig. 2-5).

iii). Organic lining

Secretion of organic films by burrowers may control much of the character of burrow walls. The organic secretion may act to stabilize the sediment (Dapples, 1942), reinforcing the margins, or it may serve to lubricate the burrow, reducing the drag coefficient and hence increasing ease of penetration. Reduction in drag force lessens the shear stress acting on the walls, which in turn will decrease the need for particle reorientation (see equation no. 3).

The binding of grains might also inhibit secondary particle rotation. This coagulation process could induce preservation of the initial burrowing event, stabilizing reoriented grains. In some instances the film
Fig. 2-5  Idealized cross-section of lenticular organism penetrating sediment. Diagram displays representative stress regime that encourages burrow margin collapse.
secreted is a quick-setting proteinaceous material (Fager, 1964). Agglutination of such films, accomplished upon reaction with seawater (Myers, 1972), may be used as a cementing agent in grain selection process. It appears that some polychaetes such as Diopatra cuprea (Myers, 1972) and Owenia fusiformis (Fager, 1964) actually sift through the sediment or across the sediment surface for specific grains, which are then drawn into the burrow and cemented to the wall. Construction of a tube in this fashion is quite unrelated to the physical mechanism accounting for marginal grain alignment.

iv). Time of habitation

The time during which a burrow is occupied will play an important role in developing a burrow wall. A longer period of movement within will provide extended time to "smooth" the lining. Semi-permanent to permanent burrows, therefore, should display the greatest degree of preferred orientation along burrow margins, disregarding selection mechanism employed by some organisms (Fager, 1969).

Environmental inferences may therefore be inferred from inspection of burrow margins. Preservation from a stable environment should display good marginal grain orientation, reflecting the longer habitation period. Poor alignment would imply a less stable environment or
possibly a higher rate of bioturbation. These assumptions could be aided by the presence or absence of body fossils. Exceptions to the above arguments may be observed with some tube builders which can construct grain aligned margins in unstable substrate (Myers, 1972). Under such conditions, the burrows should contrast greatly from the host sediment.

In the same context, sediment deposition will place certain time restrictions on burrow habitation. It follows that environments of rapidly accreting sediment will display short lived burrow habitats, which should be recorded by inconsistent tangential grain orientation. The opposite will be true for environments of slow deposition. Trace fossils have been employed to infer sedimentation rates (particularly with the use of spreiten (Howard in Frey, 1975) ), however, this may provide an alternative procedure where specimens are limited.
CHAPTER 3
Microprobe Analyses

3-1. **Introduction**

The walls of burrows and organically constructed tubes show chemical variations from the surrounding sediment. The major difference is one of increased metal cation concentrations (Aller, 1978; Aller and Yinst, 1978; Pemberton, 1979). Aller (1978) observed Mn$^{2+}$ and Fe$^{2+}$ concentrations in excess, surrounding the tubes of the sedentary polychaete Clymenella. Aller and Yinst (1978) observed a similar phenomenon with Fe$^{2+}$ and Mn$^{2+}$ as well as additional metals (especially Zn$^{2+}$) within the inner wall of Amphitrite ornata, a sedentary deposit feeding polychaete worm. Pemberton (1979) briefly extended this work to a study of Skolithos burrows from the Thorold Sandstone, where he observed similar anomalous concentrations for Fe, Al and K along burrow margins.

It becomes apparent that further work is warranted, particularly with regard to fossil specimens. Understanding the processes involved in metal concentration should provide an insight into the interactions of organisms and sediment. It is the intention of this report to show that concentration is induced by biologic parameters and characteristic of only those structures
that are organically produced.

3-2. Procedure

Skolithos burrows of the Nepean Sandstone, examined earlier for grain orientations were used for elemental analyses with an electron microprobe (rock stubs from thin sections were the actual specimens examined). Skolithos burrows from the Thorold Sandstone were also examined, so as to provide a different chemical environment; the Thorold Formation is richer in Fe and Al. Scans were run across burrow margins, such that both sides of the structure were crossed in the horizontal as well as the vertical plane. In most instances, the scan distance (base of charts), was between 8 and 12 mm, with the burrow region centred between the two end points.

Additional scans were taken of inorganic sedimentary structures. If in fact the metal concentration is related to organically induced mechanisms, inorganic structures should show different distributions. A mud-cracked portion of the Thorold Formation was scanned, with particular emphasis placed on the margins, adjacent to infill. A non-bioturbated sediment was also analyzed, to examine the nature of random oxide placement.

Complications could arise resulting from in-
organic diagenetic processes acting on the margins of burrows. The porosity, as discussed earlier with Nepean specimens, is greater within the burrow, which may have permitted easier percolation of metal carrying fluids upon compaction. This prompted examination of sediments prior to diagenesis, which would exclude percolation processes, and allow isolation of cation emplacement time. Burrows of Corophium volutator impregnated with polyester resin were used from the Minas Basin in the southern region of the Bay of Fundy.
Fig. 3-( Electron probe scan of Thorald Skolithos showing relative concentrations of Fe and Al across the burrow structure.

Fe - Red
Al - Black
Fig. 3-3 Electron probe scan of Nepean Skolithos showing relative concentrations of Fe and Al across the burrow structure.

Fe - Red
Al - Black
Fig. 3-3 Electron probe scan of Nepean *Skolithos* showing relative concentrations of Ni across the burrow structure.
Fig. 3-4 Electron probe scan of Nepean Skolithos showing relative concentrations of Cu across the burrow structure.
Fig. 3-5  Electron probe scan of Thorald *Skolithos* showing relative concentrations of Cu across the burrow structure. *Note in this case the margins are defined by a relative decrease in concentration, upon entering the infill region.*
Fig. 3-6  Electron probe scan across *Corophium volutator* burrow from the Bay of Fundy showing relative concentrations of Fe and Al.

Fe- Red  
Al- Black
Fig. 3-7  Electron probe scan across Thorald mudcrack showing relative concentrations of Fe and Al.

Fe - Black
Al - Red
3-3. Results

From the foregoing analyses, it becomes apparent that the Skolithos burrow margins represent regions of metal cation concentration. The high relative peaks are characteristic for Al and Fe, and generally for Cu and Ni, although less pronounced. The latter two are present in only trace amounts in samples scanned. One important observation taken from this investigation was that the burrow margin represents a zone, rather than a discrete boundary, between sediment within and outside of the burrow.

In some scans, peaks increased gradually towards the burrow margin, then fall off upon reaching the marginal inner side (see fig. 3-1). At times, a metal decrease just outside the outer wall is observed (see fig. 3-4 ), followed by relative maxima within the margin itself. More commonly, sudden rises occurred at the marginal zone and remained anomalously high until reaching the burrow fill region (see fig. 3-2 ). Others displayed relative peaks at burrow margins by showing relative lows within the burrow (infill region) (see fig. 3-5 ). Although Fe concentrations may show this behaviour,
this is most typical for Cu and occasionally Al. Although this does not outline the burrow as distinctly as peaks at margins, it does allow definition of the inner boundary of the burrow wall.

*Corophium volutator* burrows from the Bay of Fundy also show marginal concentrations of Fe, Al and Cu, analogous to the fossil specimens. This corresponds directly with the results obtained by Aller and Yinst (1978). It therefore seems reasonable to assume that the mechanism(s) involved with metal concentration take place prior to major diagenetic events.

The mudcrack from the Thorald Sandstone does not display the high peaks along its margins, even though clay accumulations are observed in these regions. Clay boundaries were observed around many of the Thorold *Skolithos*, which did show metal concentrations, so the lack of cations associated with this marginal clay is an important observation which will be discussed later.

3-4. Discussion

Metals along burrow margins are located in pore spaces or between grain boundaries as metal-rich cements or oxides (i.e. hemetite). Clay minerals at these sites also record high cation concentration. The interparticle position of metal complexes suggests a fluid source for
these cations, excluding the possibility of heavy mineral boundary grains, as with the selective Owenia (Fager, 1964). The marginal placement of metal-rich clays suggests the need for cation mobility in the wall region.

A). Mobilization

In order for a burrow lining to become enriched in metal cations, there must be a source for these elements. The increasing Mn and Fe concentrations with depth within the walls of Amphitrite burrows, as observed by Aller and Yinst (1978), are offset by rapidly diminishing concentrations in the surrounding sediment, away from the sediment-water interface. The oxides of the two elements occur as particle coatings or interstitial precipitates which may be dissolved and mobilized upon reduction (Aller and Yinst, 1978). This results primarily from the activity or metabolites of microbial organisms. Oxidation of FeS and FeS\textsubscript{2} can also lead to the mobilization of Fe\textsuperscript{2+} (Stumm and Morgan, 1970).

Loosely bound cations may be further mobilized by the burrowing activities of the organism. Aller (1978) recorded Mn\textsuperscript{2+} and Fe\textsuperscript{2+} existing in higher concentrations directly above Clymenella burrows. He concluded that this was the result of tube construction and sediment irrigation by the burrower. Irrigation allows oxidation of the
sediment surrounding the burrow. This provides a transport mechanism, such that ions being flushed out of pore waters are quickly replenished by the reworking process of irrigation. These metal cations, therefore, are being mobilized and allowed to move about within the sediment and into the water overlying the sediment. They will become lost from the system unless complexed again in some fashion.

B). Mechanisms of Concentration

i) Organic factors

An organic film or lining incorporated into a burrow or tube is vulnerable to microbial attack (Martin and Haider, 1973). Although Fager (1964) states that Owenia was able to protect the lining against bacterial attack, it is likely that the lining was constantly added to during life. Amphitrite burrows display excessive microbial populations directly above burrow openings during habitation, suggestive of their activity in the area (Aller and Yinst, 1978) (this will also be a function of excretion).

Reworking of these substances may systematically breakdown the organic polymers within the burrow walls to simple inorganic components, such as CO₂, H₂O or NH₃. This process often does not go to completion, as secondary
polymers are created upon enzymatic and chemical reactions of the metabolic products. It is under these circumstances that humic and fulvic acids are produced, which together represent 50-80% of the reworked organics (see fig. 3-8). Both of these complexes are inexacty known, but models have been proposed to interpret their structure (see. fig. 3-9).

These two acids are considered to be the most important compounds in complexing and chelating metal cations (Mortensen, 1963; Rashid, 1971, 1972; Duncan and Francis, 1972; Schnitzer and Khan, 1972). Rashid (1971) has extensively documented the various complexing abilities of humic acids. Where these compounds are present, various metals will be complexed, depending on both the molecular weight of the humic acid and the oxidation state of the metal. Rashid (1971) concluded that the lowest molecular weight fractions (less than 700), display the most effective potential for compound formation, with a general decline as the molecular weight increases (see table 3-1). A more dramatic difference was observed for the metal holding capacity of humic acids for di- and tri-valent metals. Divalent cations were complexed much more readily than were trivalent metals (3 - 4 times greater). The metal adsorption serves to stiffen the acid and complex (Aller and Yinst, 1978), allowing it to coagulate in situ.
Lignin and other plant polyphenolic compounds

Microbial degradation

Methoxyphenols
demethylation

Intermediate Phenols

Microbial degradation

Microbial cells

Acids, sugars, and other simple organic compounds

Microbial degradation

CO₂, H₂O, NH₃, and other simple inorganic compounds

ring cleavage and oxidation

Numerous mono-, di-, and trihydroxy phenols, benzoic acids, and other aromatic compounds

enzymatic & autoxidation

Phenolic radicals & hydroxybenzoquinones

Peptides and amino acids from decomposing organic residues and from autolysis of microbial cells

HUMIC ACID

Fig. 3-8 Schematic representation of humic acid synthesis in soil. (after Martin and Haider, 1970)
Fig. 3-9  A.) Diagramatic representation of Humic acid (in Schnitzer and Khan, 1972).

B.) Structure of Fulvic Acid as proposed by Schnitzer (in Schnitzer and Khan, 1972).
Table 3-1

Metal holding capacity of different humic acids and their fractionated components for various di- and tri-valent metals

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<th>Fraction</th>
<th>Trivalent metals</th>
<th>Divalent metals</th>
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<td></td>
<td></td>
<td>Al</td>
<td>Fe</td>
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<td>68-2-1-1</td>
<td>Parent</td>
<td>21.4</td>
<td>42.5</td>
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<td>Less than 700</td>
<td>27.2</td>
<td>76.6</td>
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<td>Parent</td>
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<td>48.4</td>
</tr>
<tr>
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<td>Less than 700</td>
<td>41.4</td>
<td>64.9</td>
</tr>
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<tr>
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<td>11.1</td>
<td>21.2</td>
</tr>
<tr>
<td>Lagoon</td>
<td>Greater than 100,000</td>
<td>17.2</td>
<td>27.1</td>
</tr>
<tr>
<td>68-2-2-1</td>
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</tr>
<tr>
<td>68-2-2-1</td>
<td>Less than 700</td>
<td>48.3</td>
<td>95.0</td>
</tr>
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</table>
ii) **Clays**

An intimate association is often observed between clays and humic acids (Rashid, 1972). Metal-rich clays associated with burrow linings may be the result of clay mineral adsorption of metal-carrying humic or fulvic acids. Clay minerals flushing into the burrow will display electrochemical attraction towards the organic acids, whose carboxyl groups may become bound by Van der Waals forces to the clay surface (Rashid, 1972). Marginal clays, once situated in this cation rich environment, will also adsorb cations in a variety of ways.

There are four major classes of association between clays and cations. The first three sites are exchangeable in nature, whereas the fourth tends to remain as a permanent complex (Grim, 1968).

a) Broken bonds  
b) Lattice structure substitution  
c) Hydrogen replacement on exposed hydroxyl groups  
d) Cation fixation

a). **Broken bonds**

When dislocation of the silica-alumina octahedral-tetrahedral bond occurs, unsatisfied charges can be balanced by the adsorption of cations. This is influenced by grain
size, such that a decrease in grain size creates an increase in the cation exchange capacity (Fields, 1960). This is the primary mode of association for kaolinite and halloysite and is also important in illite and chlorite.

b). **Lattice structure substitution**

Silica in the tetrahedral sheet may be replaced by aluminum and aluminum by magnesium in the octahedral site. This creates an imbalance of charge and cations may be adsorbed to correct this imbalance. Smectite and vermiculite show lattice substitution accounting for as much as 80% of the total cation exchange performed by the clay mineral (Grim, 1968).

c). **Hydrogen replacement on exposed hydroxyl groups**

The structural hydrogen of the hydroxyl group may be replaced by an exchangeable cation. The exact procedure is somewhat debatable, yet this appears to take place in kaolinite and halloysite (Fields, 1960).

d). **Cation fixation**

Fixation occurs with the emplacement of cations on the basal planes between the unit layers (Volk, 1938, in Grim, 1968). Volk showed that potash fixation is often accompanied by the secondary formation of mica in argillaceous soils.
Understanding exchange adsorption in clay minerals is further enhanced by the following three mechanisms proposed by Farmer (1971).

1). Direct co-ordination
2). Indirect co-ordination
3). Base conversion to protonated cation

Each of these mechanisms may be present in the four clay associations, but will depend on the cation present as well as the nature of the sediment. The results of Farmer's analyses were determined by infrared spectroscopy.

1). Direct co-ordination
Direct co-ordination is accomplished by the associated vibrational energy of the co-ordinated molecules, with strength varying according to the polarizing power of the cation. Generally, this bond is the result of Van der Waals forces; however, as in the case of ammonium, co-ordination is achieved by Hydrogen bonding (Farmer, 1971).

2). Indirect co-ordination
Indirect co-ordination results from the attachment of a cation through a bridging molecule, typically water, or an alcohol group. The complexing arises from the superposition of adsorbing molecules in inner and outer spheres of co-ordination (Farmer, 1971).
3). **Base conversion to protonated cation**

This concentrating reaction is a function of the adsorbed base being converted to its protonated cation on clay surfaces saturated in hydrogen or other inorganic cations. This often occurs as a fixation process - trapping the protonated cation between layers, strongly decreasing the exchange potential. This process may help explain the acidity of layered silicates.

\[
H
\]

\[
M^{++} \rightarrow (O-H\rightarrow N= C_{6}H_{6})^{m}_n
\]

\[
M^{n+} (H_2O + nB \rightleftharpoons M(OH)_{n} + nHB^{+}
\]

**iii) Scavenging**

Aller and Yinst (1978) believe that the accumulation mechanism is related to a different electrochemical process. Innermost burrows become enriched slightly in Fe and Mn oxides which accumulate by diffusion from the more reduced portions of the burrow wall. These metals then "scavenge" other metals such as Cu, Zn, Co, Ba and Ra from irrigated seawater cycled into the burrow.
Scavenging, as documented by Goldberg (1953), appears to be an electrochemical phenomenon, resulting from charge attractions induced by the metal hydroxides. The ferric hydroxides represent electropositive sites and will therefore scavenge negatively charged ions (Aller and Yinst, 1978). The subaqueous chemistry of many metals, particularly transition elements such as Ti or Zr, is known to be anionic, even though their oxidation states predict cationic behaviour (Goldberg, 1953). The hydrated oxides of manganese are electronegative, hence should attract positive ions (common metals). These cations may then become fixed as sulphates, which may or may not be further oxidized (Aller and Yinst, 1978).

From the preceding discussion it becomes apparent that cation concentration is an intricate process. The metal cations are mobilized by organic action (microbial action with sediment irrigation) and concentrated along burrow margins as a direct or indirect result of secreted organic film. Fossil specimens preserve this accumulation as metal-rich cements or oxides as well as in clay minerals which may have also accumulated in response to organic activity.
CHAPTER 4
CONCLUSION

There is a great deal of information that may be gained from trace fossils. Examination of burrow walls may help predict both the style of burrowing and the nature of the environment. The marginal regions may be sites of intense reworking and chemical reaction. This activity may be preserved in the rock record, from which deduction can be made. The following conclusions may be drawn concerning burrow margins.

1. Sediment penetration results in grain displacement around the burrowing organism. The character of displacement will vary between burrowers.

2. A fluid dynamic discussion involving the analogy of a burrower to a viscous flow predicts grain rotation to be a function of instantaneous velocity fluctuations of the organism. The degree of particle rotation and subsequent preservation of this reorientation will depend on a variety of sediment and biologic variables that will differ with specific environments.
3. Parallel grain alignment at burrow margins appears to be a consistent phenomenon. Results show that 65% of all elongate grains in vertical section, exhibit less than 10° tangential deviation and 82% less than 20° for horizontal section.

4. Chemically, burrow margins seem to represent extensions of the sediment-water interface. Organic films secreted by many burrowers, allowing burrow stability and lubrication, become enhanced regions of microbial decomposition. Metabolites produced by these organisms may directly or indirectly serve to concentrate mobilized metal cations from seawater and the surrounding sediment.

5. Metals are generally preserved as oxides or metal-rich cements within the burrow margin, or bound in associated clay rims.

6. Burrow structures may be clearly identified by accumulations of Cu, Ni, Fe and Al in the margin zone; occasionally by relative deficiencies in the infilled region.

7. These characteristics appear to be exclusively associated with organic structures, reflecting the organic mechanisms responsible for them. Margins of inorganic structures do not show any of the metal
concentrations typical of burrow walls. This suggests a possible use of such tests in predicting the organic/inorganic construction mode for questionable structures. Trace fossils may therefore be more clearly identified or challenged, depending on the results of such analyses.
Addendum
CHAPTER 5
Early Proterozoic Dubiofossils: Observations
5-1. Bar River Formation: Case Study

The Bar River Formation is the uppermost unit of the Cobalt Group, the youngest member of the Huronian Supergroup. Although there is some question as to the precise age of this Formation, it appears conformable with the underlying Huronian sequence, suggesting an age between 2100 and 2300 ma. It is older than 1390 ma; the K-Ar age for a dike cutting the Formation (Hofmann, 1967).

The Bar River Formation in the study area is a thickly bedded quartzite. Close examination shows thin green and purple argillaceous zones interrupting the quartzite in fine lenses. Towards the bottom of this sub-section, bedding surfaces become more abundant and clarity of sedimentary stratification more distinct. Sedimentation is dominated by repetitious fining upward sequence with argillaceous interruptions.

Crossbedding is often present, in conjunction with ripple marks, periodically separated by mud-cracked surfaces. These features, together with the presence of kaolinite and pyrophyllite, suggest that the Bar River
was deposited in a shallow marine, near shore paleoenvironment, subject to fluctuation in water level; questionably of tropical nature (Wood in Young, 1973). One additional interesting piece of evidence pertaining to paleo-environment was recorded in a small corrugated sand structure. Examination with a scanning electron microscope depicted a square shaped impression, approximately 60 microns in size. This could represent a salt grain imprint requiring marine deposition and implying an intertidal-type environment. This is far from conclusive but does fit well with other sedimentary facies indicators.

The area of study involved a specific horizon located on the east side of road 639 approximately 23 km north of Elliot Lake. The paleontological significance of this site was first discussed by Hofmann (1967), who investigated this general location east of Flack Lake. The horizon involved in this account was not observed by Hofmann or others, as it was systematically excavated by removing the beds above it. The horizon crops out sparingly at the north of the exposure and was traced southwards in the direction of dip where it was observed by displacing overlying strata.

The importance of this specific horizon became
evident upon sampling the subsurface bed. Preservation of this argillaceous zone was extraordinary, recording crispness in structures not observed in horizons elsewhere in this rock exposure. Details in surficial structures were remarkably clear, displaying little, if any, diagenetic alteration.

This abnormal clarity was observed in what will be referred to as a "pod" within the horizon. Surface definition decreased in a radial fashion away from the pod, from which all samples were taken. This unique section was blanketed by a 24 cm sand layer, which may have rapidly buried the horizon, subsequently protecting it from physical and chemical reworking.
5-2. Surficial markings

In recent years, interest in the Bar River has focussed around markings across the surface of many beds (Hofmann, 1967, 1971). The most dominant marking type on Bar River specimens are the corrugated spindle form (Rhysonetron structure, after Hofmann, 1967). These elongated spindles show distinct corrugation, the sections of which may be slightly inclined. In some cases a medial band can be observed within the trace or case, which emphasizes its bilateral symmetry (see plate 5-1).

Lengths vary from a few millimeters to twenty or more centimeters in curved convoluted orientations, often in quite an intricate array. Marking patterns are complex and do not really fall into any typical mud-crack pattern. They are neither polygonal nor uniform in size, and are seen in places to overlap one another. Widths show some variation as well as the number of corrugations per unit width. These features were examined and correlated and although variation is observed in the forty-five specimens recorded, most structures are 4.5 - 5.5 mm wide with 4.5 - 5.5 corrugations per centimeter. (Corrugations show an increase per centimeter with a decrease in marking width).

It was initially suggested that the Rhysonetron structures could represent primitive traces of early metazoans (Hofmann, 1967), but this was subsequently
Plate 5-1 Example of Bar River bedding surface, displaying corrugated structure amidst an intricate array of additional structures.
discarded in favour of a mud-crack hypothesis (Hofmann, 1971). Hofmann (1971) described the development of these structures in a five stage process (see fig. 5-1).

This proposal calls for "the reduction, if not elimination, of the pelitic layer, possibly by solution under considerable pressures" (Hofmann, 1971 p. 37). Evidence for intensive compaction pressure during diagenesis is not observed. Preservation is good, with little vertical distortion. Cross-beds are quite fresh-looking and ripples are seen as smooth sinusoidal traces. Hofmann (1971) allows for this compaction effect by total pressure absorption in the argillaceous layer, resulting in its reduction to minimal or nil thickness. This is supported by the recording of a maximum mud thickness of 150 microns in his samples. This is not observed in the samples I have collected. In many instances, the horizon with the most detailed preservation shows a very thin pelitic top, less than one millimeter thick. Some of these surfaces, however, possess argillaceous layers several millimeters thick. The internal mud layers, which would also have been subject to similar diagenetic stress (on Hofmann's assumption of pressurized origin of the surface structures), are observed to range from 0.5 - 11.5 mm in thickness.
FIGURE 5-1

Presumed stages of development of rhysonetron structure.

1. Accumulation of mud
2. Development of crack
3. Filling and covering of crack by sand
4. Compaction of mud, squeezing of sand cast. Spindle forms
   (Manchuriophycus stage)
5. Further reduction of volume of mud, and compression of spindle
   (Rhysonetron stage)

(After Hofmann, 1971)
It also seems strange to observe such unique mud-cracks in rocks that also display typical mud-crack structures. Several horizons throughout the Bar River display typical polygonal desiccation patterns. Curved orientation is uncommon, and none were observed to overlap. Although the preservation of these shrinkage structures is in many cases superb, there are no examples of corrugation or medial band formation accompanying any of them. The stratigraphic closeness of these mud-cracks to the surficial structures in question suggests comparative diagenetic conditions.

Another explanation proposed to account for these features was that they were a form of subaqueous shrinkage features. Young (1969) explains this occurrence as a consequence of salinity changes, from saline to fresh water. He allows for corrugations by suggesting they resulted from injection processes of silt into a muddy matrix. Several of the corrugated Bar River specimens, however, are found on a very fine argillaceous veneer overlaying a fining upwards sand sequence, which in cross-section was observed to be completely barren of any injections. Silt injection producing such evenly symmetric patterns qualitatively seems somewhat unlikely.

Other problematical Precambrian structures of
similar age, have been observed elsewhere. Curving sinuous markings, often many centimeters long and 3 - 5 mm wide, were observed on a ripple marked bedding surface of Ajibik Quartzite (Michigan, U.S.A.) of middle Huronian age (Faul, 1949). In 1960, C. E. Bye, a prospector, reported peculiar worm shaped casts and traces in the Lorrain Quartzite, an upper Huronian Formation of the Cobalt Group (Frarey and McLaren, 1963). These markings, observed in Johnson Township of the Algoma District, Ontario, were further investigated by Frarey and McLaren (1963), who concluded "the structures appear to be fossil relics of tapering, branching tubes deposited in ripple troughs and filled presumably contemporaneously, to produce casts and moulds in a lithologically uniform sequence." (Frarey and McLaren, 1963 p. 462). Lauerma and Piispanen (1967) found identical structures in quartzite from Kuusamo in northeastern Finland, dated between 1800 and 2600 ma. Young's proposal (1969) for subaqueous shrinkage formation actually focussed on vermiform structures he located in the Gordon Lake Formation, stratigraphically below the Bar River. Kauffman and Steidtmann (1980) recorded what they believed to be burrows from the Medicine Peak Quartzite of southeastern Wyoming of 2300 - 2400 ma. The Bar River, therefore, does not represent a unique occurrence within the Huronian of worm shaped structures.
The Bar River does possess, however, unique attributes. In association with the corrugated spindles, several other interesting traces are observed which suggest an organic origin. A corrugated type of slightly different contour is observed with ridges oriented in a plane parallel to bedding. Thinner semicircular traces are noted, in many cases linking, similar to those found by Frarey and McLaren (1963). Rod-shaped bodies, at times tightly intercalated, are also recorded on some rippled surfaces.

A very special marking type was discovered on the bedding surface of two particular samples. Small circular-elliptical structures were observed with an estimated diameter of between 15.0 and 17.5 mm, represented by impressions of rings with spacings of approximately 0.5 to 1.0 mm. An additional trace of questionably related origin displayed a cross-like form contained within the perimeter of a lesser defined ring. Resemblance with late Proterozoic medusoids is undeniable. Sedimentary origin becomes complicated, since they are specifically seen in connection with corrugated spindles. Inorganic mechanisms proposed for one, must also be compatible with the others.

Striated traces parallel to bedding were also observed (see pl.5-2). They are strikingly similar
Plate 5-2 Complicated surface patterns exhibiting a variety of trace types. Note particularly the *Rhyzocorallium*-like traces observed in the upper right hand corner.

(photograph to scale)
to the deposit feeding trace commonly referred to as Rhyzocorallium. Other non-corrugated sand structures could easily be confused with Planolites traces, as trace size and pattern are remarkably alike. The extreme diversity in traces observed enhances an argument for early metazoan evolution.

5-3. Internal structures

Slabs were cut perpendicular to the bedding surface to examine for any internal structures. The resulting cross-sections showed the sequence of muds and sands, both varying in thickness and regularity. Many of the sandy layers were possibly storm induced, as fining upwards sequences were preserved quite well, containing some well rounded pebbles up to 8 mm in diameter. The muds appear as dark bands of irregular thicknesses, occasionally displaying signs of surface scour. Contained within the dark layers are lighter sandy-silt structures possessing random orientations, in varying densities. The majority of these structures range between 5 to 30 mm in length and 2 to 4 mm in width.

Over 400 cross-sectional surfaces were observed. Close examination of many of these sand structures suggests a very interesting mode of formation. Many of the vertical forms are seen extending upwards into the overlying sed-
iment. Slight "veeing" of the fine grained mud layer indicates possible direction of movement, and faint boundaries are commonly observed separating this structure from the surrounding sediment. The vertically progressing casts are not observed to pass through more than 2 cm of sediment, but this upper limit is commonly encountered. (see plate 5-3).

Other structures observed in these cuts appear to penetrate downwards into the sediment, as predicted by laminae downwarping. The most important aspect of these approximately cylindrical bodies was the multidirectional character of individual structures. One structure, for example, upon penetration into an argillaceous zone, extends towards the top of the layer then abruptly changes direction and moves along a tight sinuous path through the clay layer, along approximate horizontal co-ordinates. (see plate 5-4). Some structures appear to initially extend downwards into the sediment, then change their path and push upwards into the overlying sands.

A water or gas escape structure interpretation for these elements must also be considered. As well documented by Kauffman (1980), Lowe's (1975) analysis of volatile escape structures are characterized by the following criteria; using his most organic-appearing structures (Type B Pillars):
a, near-vertical orientation; b, upward tapering tube boundaries; c, tubes terminating in an acute apices with no consistent relationship to bedding planes; d, downward and commonly upward bending of laminae truncated by the channels; e, simple to complex tube morphologies with branching occurring near the base of the channels and tapering upward; f, irregularly undulating and constricted channel boundaries; g, unstructured to poorly structured tube fillings, commonly with coarser sediments than the surrounding matrix; and h, common association with beds bearing deformed laminae due to fluid migration.

Bar River structures, in contrast, show much varied orientation, with equal tendency to a horizontal nature as to vertical. Vertical tapering does not appear to be common, and in many circumstances rounded to bulbous endings terminate structures. The sand bodies occur as discrete units, opposing the branching tube morphologies Lowe's water structures exhibit. A volatile escape mechanism does not seem to offer a reasonable solution on these grounds.

A sand-silt injection process leading to the development of these sub-surface structures (and as discussed earlier, the surface traces also) is proposed by Young (1969). Yet many of the specimens from this account exhibit no vertical component whatsoever. As stated earlier,
Plate 5-3  Cylindrical structure passing through sand layer. Note the apparent path which appears to possess a near horizontal direction as well.

(Vertical component passes through 1.3cm sand layer)
Plate 5-4  Apparent multidirectional pathway of a Bar River sand structure which appears to move upwards into the argillaceous layer (light colour) then follow a sinuous course throughout it.

( Stratigraphic bottom to right of page )
others possess more than one direction of motion, and some of the near vertical forms may show direction of movement either up or down in the same argillaceous horizon. Young's (1969) structures from the Gordon Lake Formation may have been produced by his proposed injection process; however, Bar River analogues do not appear to have been formed by the same.

5-4 Analyses

The next logical step should be analogous tests, as performed earlier on Paleozoic burrows. From this standpoint, microprobe scans were run on Bar River specimens, which were carefully selected so as to avoid complications or sampling bias. Only those sand structures that passed through sand layers were considered, so that amplified results with clay-rich zones would not be encountered. This enables direct analogy with scans of *Skolithos* in terms of marginal concentration.

Grain orientations were also carried out, although grain size was slightly smaller than Nepean samples and not as simple to work with. It was necessary to use different photomicrographs in conjunction with thin sections to interpret accurate marginal orientation. The results are listed in fig. 5-5.
Fig. 5-2  Electron probe scan across Bar River tubular structure (seen in Plate) showing relative concentrations of Fe and Al.

Fe- Red
Al- Black
Fig. 5-3  Electron probe scan across Bar River tubular structure showing relative concentrations of Fe and Al.

Fe- Red
Al- Black
Fig. 5-4  Electron probe scan across tubular structure (5-2), showing relative concentrations of Cu.
Fig. 5-5 Distribution of margin grain orientations for 3 Bar River structures in vertical section (recorded as degree of tangential deviation away from structure margin).

<table>
<thead>
<tr>
<th>Total No. of grains</th>
<th>Tangential Deviation (degrees)</th>
<th>Total No. of grains</th>
<th>Tangential Deviation (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+13</td>
<td>0 - 9</td>
<td>0</td>
<td>50 - 59</td>
</tr>
<tr>
<td>-15</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>+6</td>
<td>10 - 19</td>
<td>0</td>
<td>60 - 69</td>
</tr>
<tr>
<td>-4</td>
<td>20 - 29</td>
<td>0</td>
<td>70 - 79</td>
</tr>
<tr>
<td>+1</td>
<td>30 - 39</td>
<td>+1</td>
<td>80 - 90</td>
</tr>
<tr>
<td>-2</td>
<td>40 - 49</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

![Histogram chart showing distribution of tangential deviation](image-url)
5-5. **Results and Conclusions**

The results of these analyses are most intriguing. The similarity of the marginal cation concentrations is undeniable, in fact remarkably similar. The Bar River structures show distinct peaks in marginal zones with relative decreases within and around the structure. The relative Cu deficiency within one of the Bar River sand structures (see fig. 5-4), closely resembles Cu patterns with burrows of Thorold Skolithos. This suggests a similar mechanism of accumulation.

Grains found at structure margins were oriented parallel or sub-parallel to the length of the structure. Of the 46 grain orientations observed in vertical section, 61% showed less than 10° tangential variation and 83% less than 20° variation (Standard Deviation = 12°, mean = -2°) (see fig. 5-5). A volatile escape mechanism inducing grain orientation should also produce grain alignment within the escape structure. Such internal alignment is not observed.

A reevaluation of possible metazoan life in early Proterozoic times is in order. The abundance and variety of organic-like structures preserved in the Bar River appears both qualitatively and quantitatively too similar to documented trace fossils to be purely coincidental.
The key to understanding the evolution of multicellular life may lie in Huronian age sediments, from which primeval eco-systems may have arisen.
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