THE PETROGRAPHY AND CHEMISTRY OF FOSSIL BURROW MARGINS

THE PETROGRAPHY AND CHEMISTRY OF FOSSIL BURROW MARGINS

By

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A Thesis

Submitted to the Faculty of Undergraduate Stud-

ies in Partial Fulfillment of the Requirements

for the Degree

Bachelor of Science

McMaster University

April 1982

Bachelor of Science   McMaster University
    (Geology)   Hamilton, Ontario

Title: The Petrography and Chemistry of Fossil

        Burrow Margins

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Number of Pages: xii, 104.

ABSTRACT

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 or-
ganism penetration and reoriented particles tend to
align with the burrow structure. Sixty-five percent of
all elongate grains show less than 10° tangential de-
viation parallel to burrow length, and 82% less than
20° tangential deviation for grains measured around the
circular burrow cross-section. As suggested by fluid
dynamic theory, fluctuation in burrowing velocity ap-
pears to induce grain rotation. Sediment type and flu-
idity, 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 min-
erals 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 interpreta-
tions, expanding the realm of Ichnology.

ACKNOWLEDGEMENTS

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CHAPTER 1

Introduction

1-1. Trace Fossil Structures and Applications

Ichnology, the study of trace fossils, has be-
come an integrated and important component of the geo-
logical sciences (Seilacher, 1964; Crimes and Harper,1970;
Frey,1975). Trace fossils are biogenic sedimentary struct-
ures, including tracks, trails, burrows and other organ-
ically 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-

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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 bio-genic structures are numerous and worth mentioning. Sed-imentary 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 bio-genic 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 sed-
iment (indirectly this may also help to stabilize the sed-
iment, if burrow densities are high enough).

Trace fossils have many applications, and are used
widely in the geological sciences. Unfossiliferous litho-
facies may in fact be dated by trace fossils, as best ex-
emplified 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 de-
formation. Stress fields may also be inferred with care-
ful 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 sediment-
ology. With the use of biogenic escape structures, eroded
spreiten and bioturbation, depositional rates may be de-
duced, as well as the nature of sediment influx (Crimes
and Harper, 1970). The character of the substrate, part-
icularly 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 bathymmetry (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 Ordivician 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 <u>Skolithos</u> sp. from the Thorold Sandstone.
Longitudinal view showing vertical nature
of specimen (actual burrow size is 7.5cm)
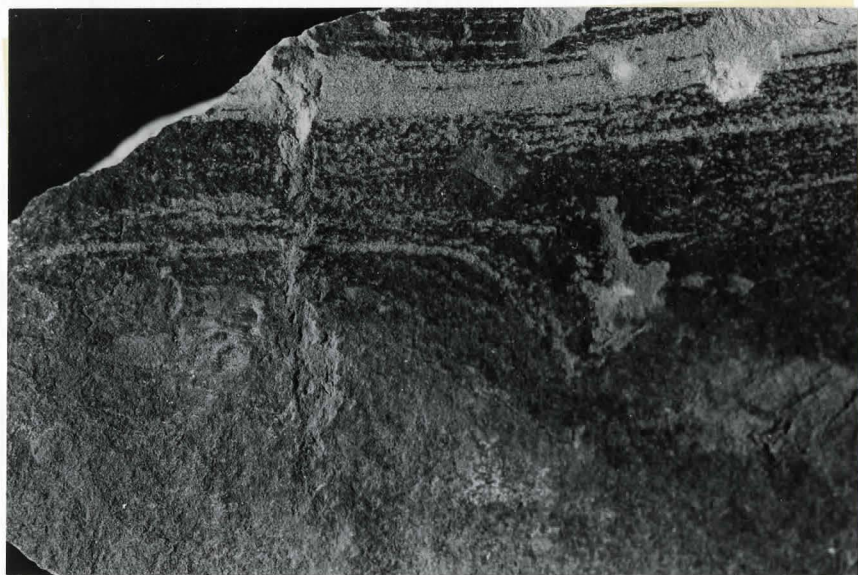
Plate 1-2 <u>Skolithos</u> sp. from the Nepean Quartzite.
Cross-sectional cut displays several
<u>Skolithos</u> burrows with additional organic
activity observed as more complicated
spreiten-bearing burrows. Note also lam-
inae depression adjacent to structures.

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-con-
tinuous bands within the sediment. The downwards de-
formation 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 alter-
nating 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 psuedo-flow should be enlightened by fluid dynamic theory.

A fluid correlation is necessary so as to isolate the pertinent mechanism(s) involved in sediment redistribution. 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

$$R_e = uL\rho/\mu$$

1

u = velocity of fluid

ρ = density of fluid

L = hydraulic radius

μ = fluid viscosity

Discussion of these variables would tend to favour 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:

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

C_D = coefficient of drag

A = projection area of the particle in the direction of motion

ρ = density of the fluid

V = velocity of the particle with respect to the fluid

2

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) :

$$\tau_t = ap\varrho gdtan$$

3

τ_t = shear stress along the bottom

a = coefficient

p = packing coefficient

ϱ = density of the fluid

g = gravitational constant

d = diameter of the particle

= 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_*, 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 rearrangement). 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 (per-
pendicular to bedding) with small
rectangle representative of thin
section site.

C.) Hypothetical horizontal section (par-
allel bedding) with small rectangle
representative of thin section site.

A.)

B.)

C.)
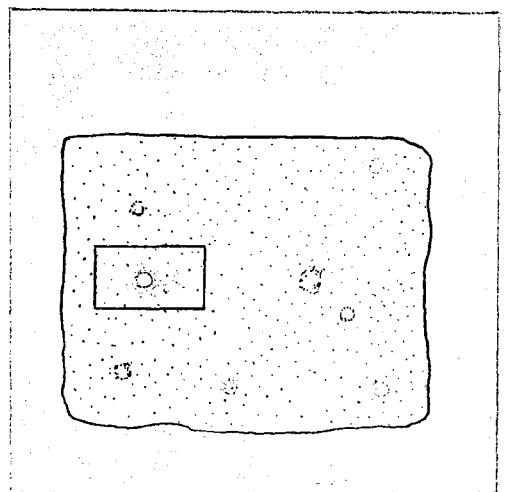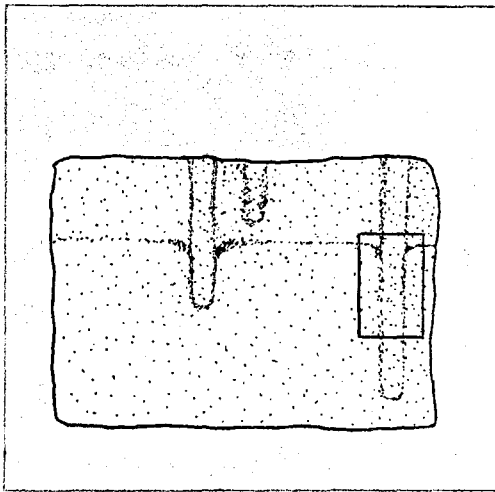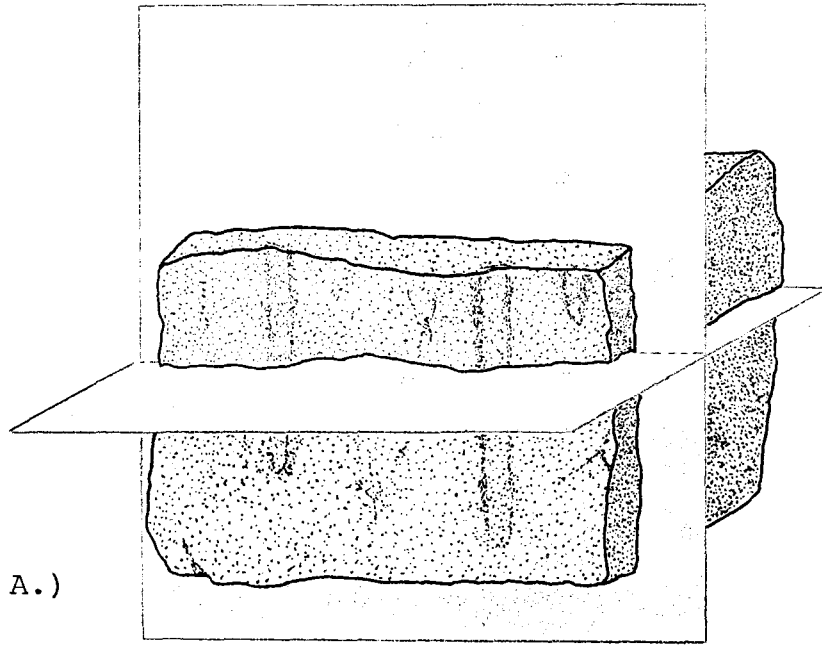
sides of the structure. For additional burrow definition,
the sections were cut approximately 10 microns thicker
than the norm (30 microns). Grain orientations were meas-
ured along burrow margins, using only those grains which
exhibited a ratio of at least 2: 1 in the observed projection.
Burrows were readily distinguished in thin section by a mark-
ed hematite enrichment along margins, which at times con-
tinued 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 sec-
tion 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 orienta-
             tions for 6 Nepean <u>Skolithos</u>, in vert-
             ical 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.

Specimen   Tangential Deviation

		0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-90
BBS-V1	+	4	2	O	1	1	1	-	-	1
	-	4	4	3	1	O	O	-	-	O
BBS-V2	+	6	3	1	-	-	O	-	-	1
	-	5	1	3	-	-	1	-	-	O
BBS-V3	+	7	2	1	-	1	O	1	-	1
	-	4	O	2	-	1	1	O	-	O
BBS-V4	+	3	2	2	O	O	1	O	-	-
	-	7	3	O	1	1	O	1	-	-
BBS-V5	+	5	3	4	1	-	1	-	O	O
	-	2	4	2	O	-	O	-	1	1
BBS-V6	+	4	2	2	1	-	1	-	O	O
	-	3	2	1	O	-	O	-	2	1

Table 2-2. Distribution of margin grain orienta-
           tions for 6 Nepean <u>Skolithos</u>, in hori-
           zontal 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.

Specimen	Tangential Deviation								
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-90
BBS-H1	+2	-	-	-	-	-	-	-	-
	-4	-	-	-	-	-	-	-	-
BBS-H2	+3	1	-	1	-	-	-	-	-
	-3	2	-	0	-	-	-	-	-
BBS-H3	+3	-	1	-	-	-	-	0	-
	-4	-	0	-	-	-	-	1	-
BBS-H4	+2	1	1	-	-	-	-	-	-
	-2	0	1	-	-	-	-	-	-
BBS-H5	+4	1	-	0	-	-	-	-	-
	-1	2	-	1	-	-	-	-	-
BBS-H6	+4	1	1	1	-	-	-	-	-
	-1	1	0	0	-	-	-	-	-
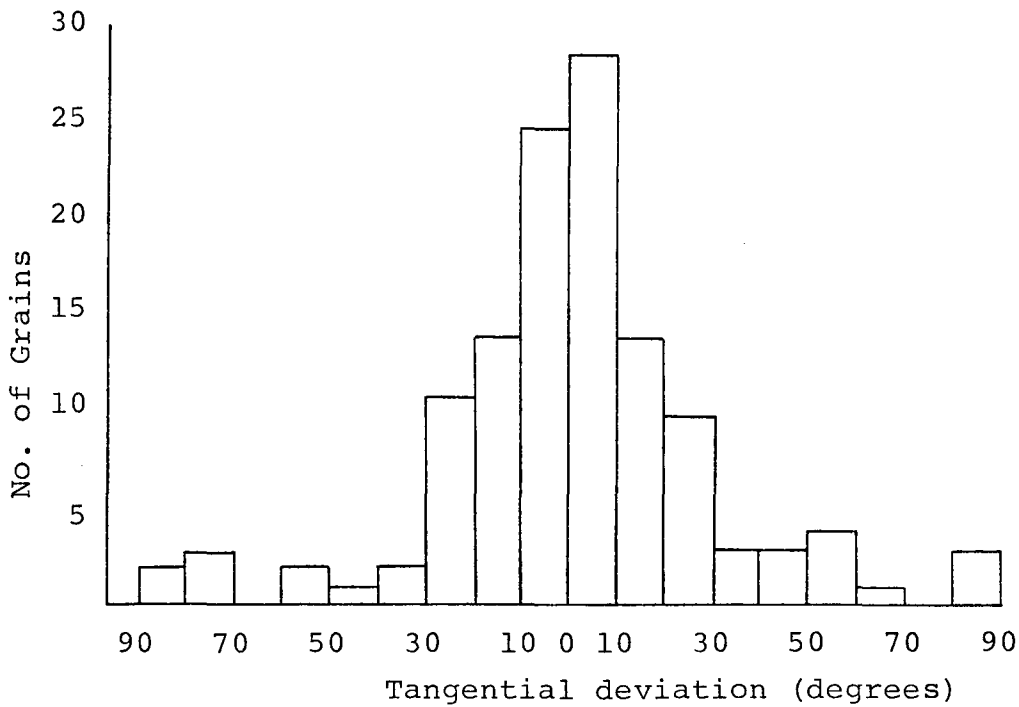
Fig. 2-2   Distribution of margin grain orientations for
6 Nepean Skolithos in vertical section (recorded
as degree of tangential deviation away from
burrow wall).
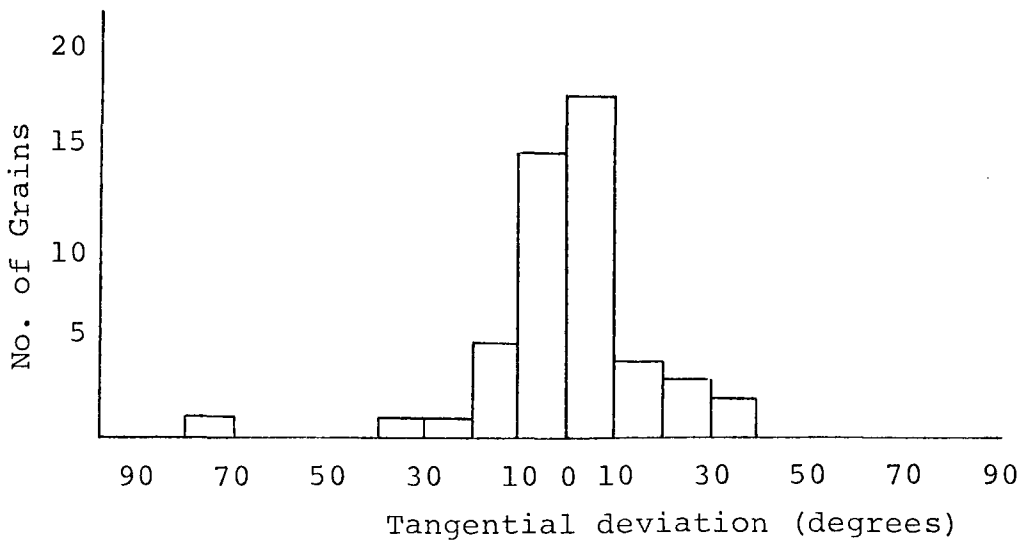
Fig. 2-3   Distribution of margin grain orientations for
6 Nepean Skolithos in horizontal section.

Plate 2-1   Photo-micrograph of <u>Skolithos</u> margin

of the Nepean Quartzite. Overlay depicts

grain tendency to parallelism with the

burrow wall.

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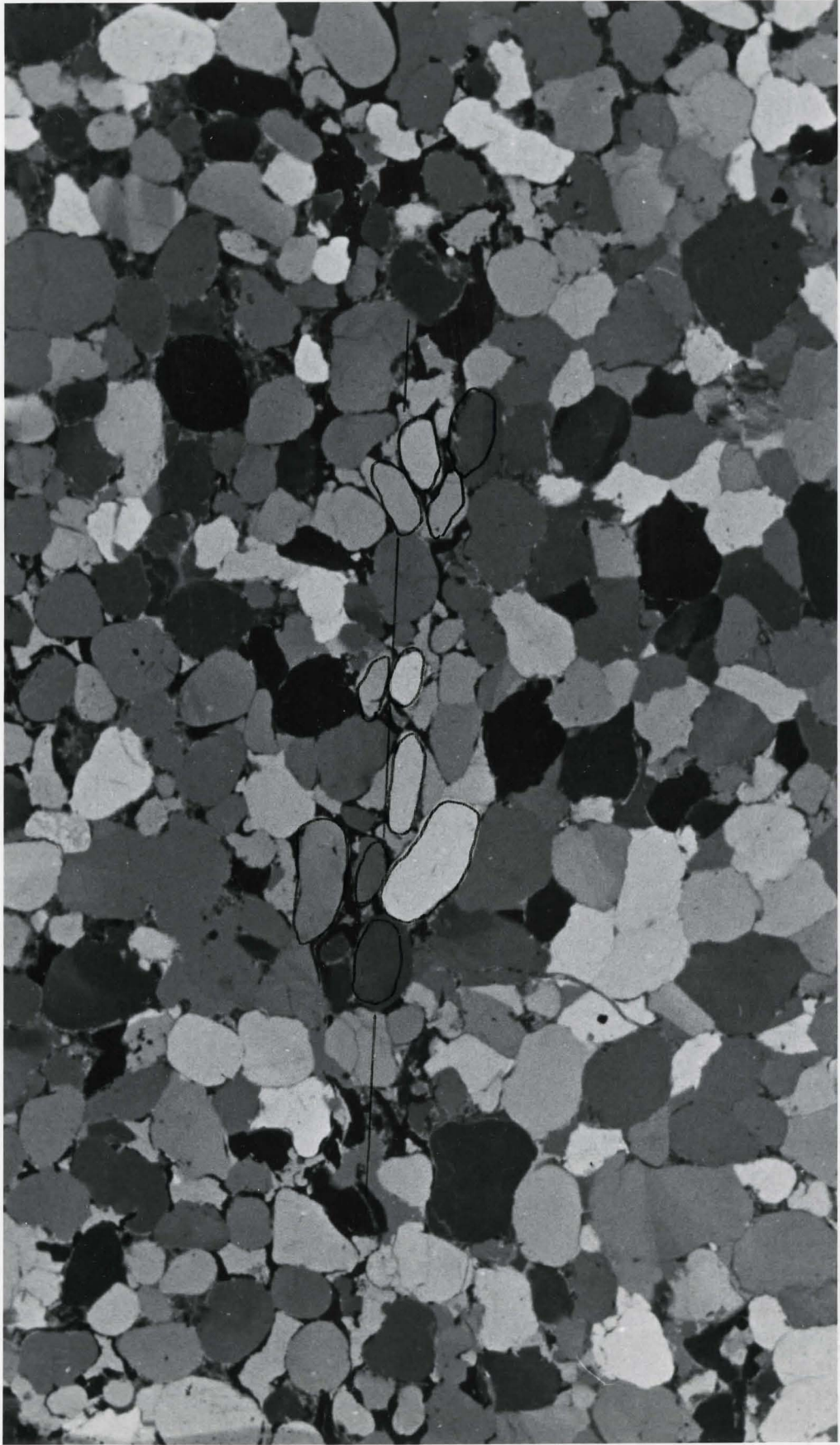
Plate 2-2   Point light source projection of Skol-
            ithos (horizontal plane thin section)
            with circular image of burrow. Over-
            lay depicts the near tangential nature
            of marginal grains.

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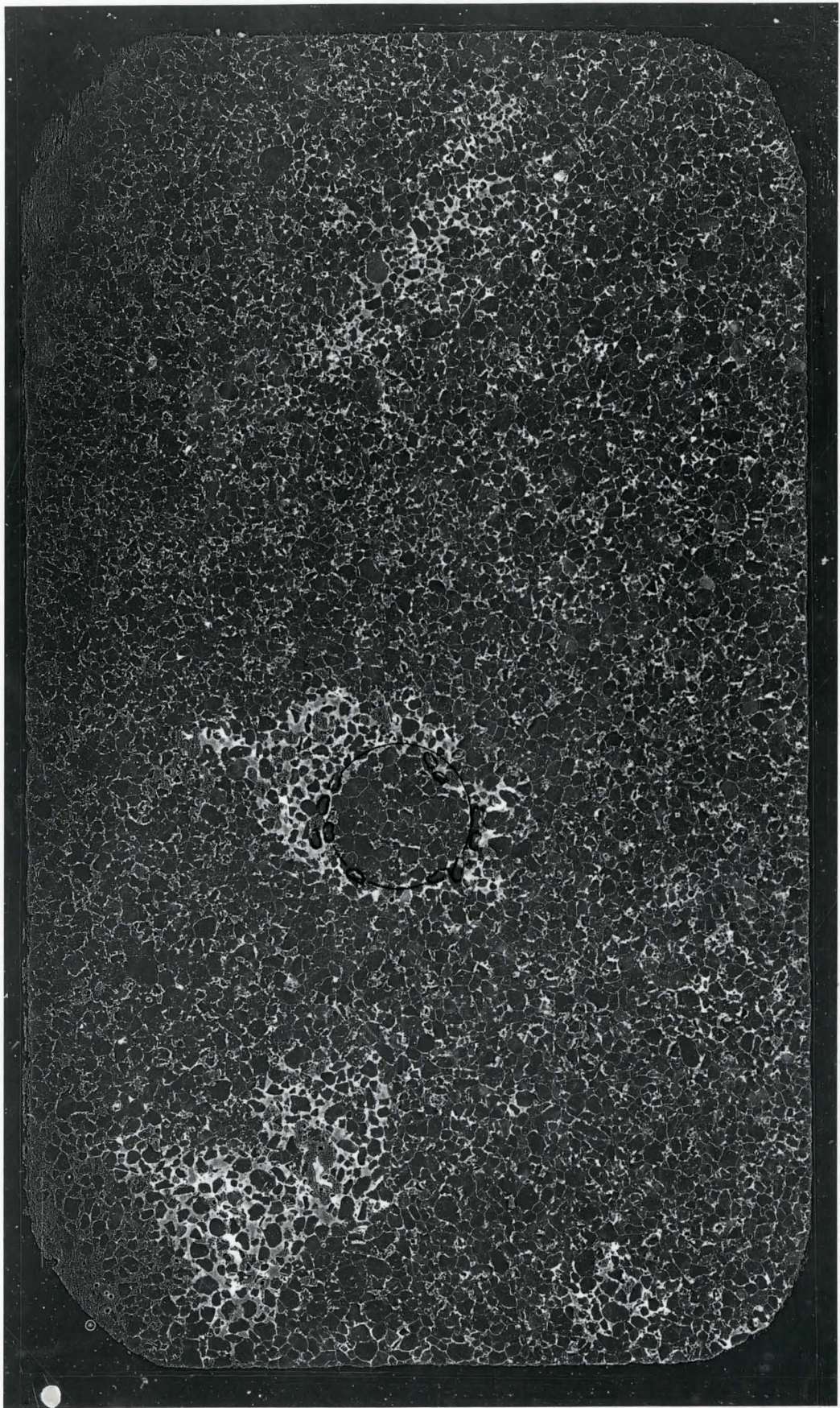
Plate 2-3: <u>Diplocraterian</u> burrow from the Thorold
Formation, with spreiten enhanced by large
quartz grains. Data shows tangential dev-
iance measured around spreiten.

Grain No.	Tangential Deviance (degrees)	Grain No.	Tangential Deviance (degrees)
1	+9	12	0
2	+3	13	-15
3	-14	14	+75
4	-9	15	-22
5	-26	16	+4
6	-7	17	-2
7	+28	18	+15
8	-2	19	+10
9	-7	20	+7
10	+4	21	-28
11	+8		

[*]Note: (+) inclined into burrow

(-) inclined out of burrow

Viewing from stratigraphic top → bottom
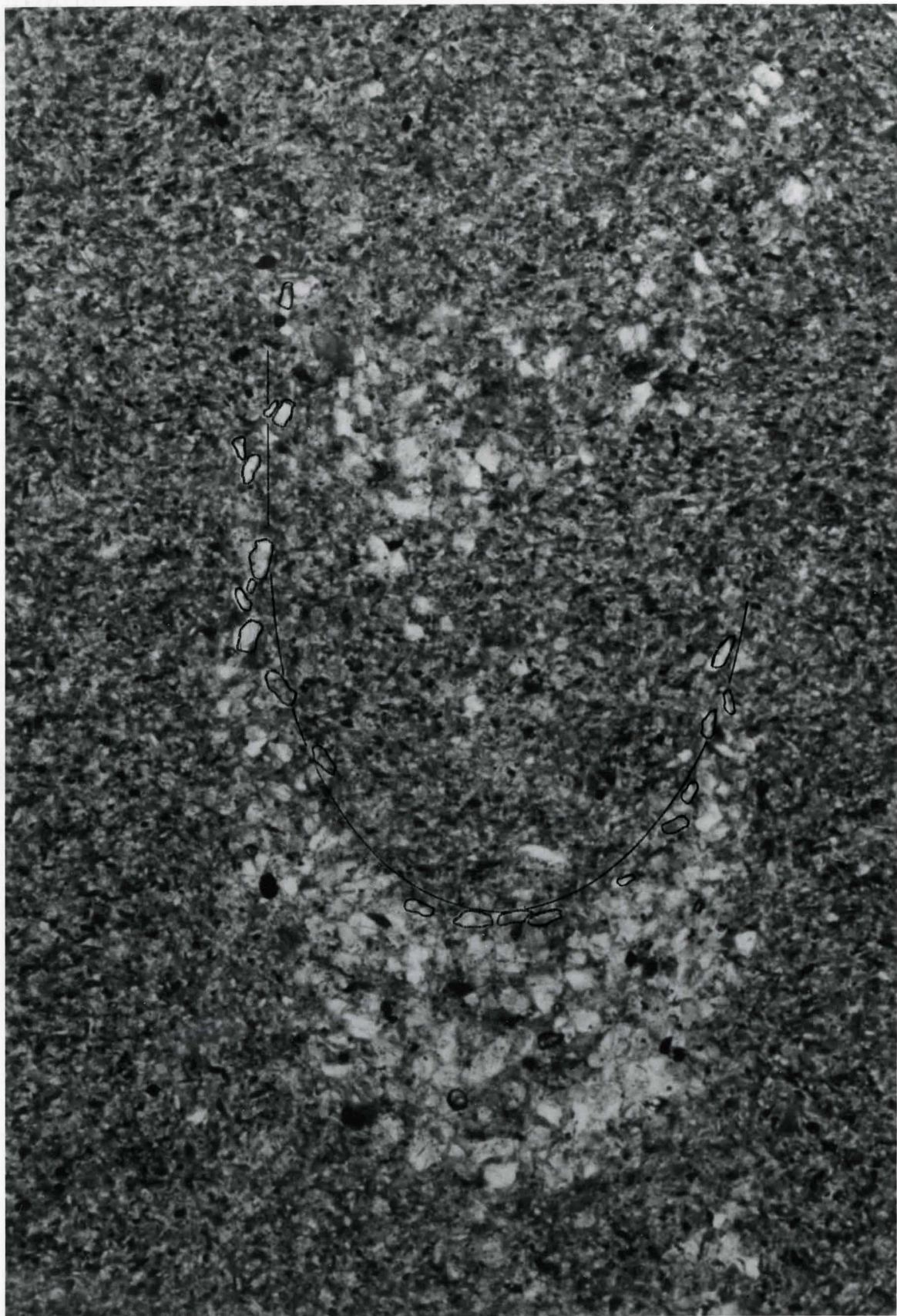
2-4. Results

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, detracting 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 dis-
playing 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 fluc-
tuation 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 influ-
ence 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. Com-
paction 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 seperately. 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 dis-
placement 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).

Water

fluid

thixotropic

50   50

plastic-dilatant

cloddy   crumbly

Silt & Sand   50   Clay
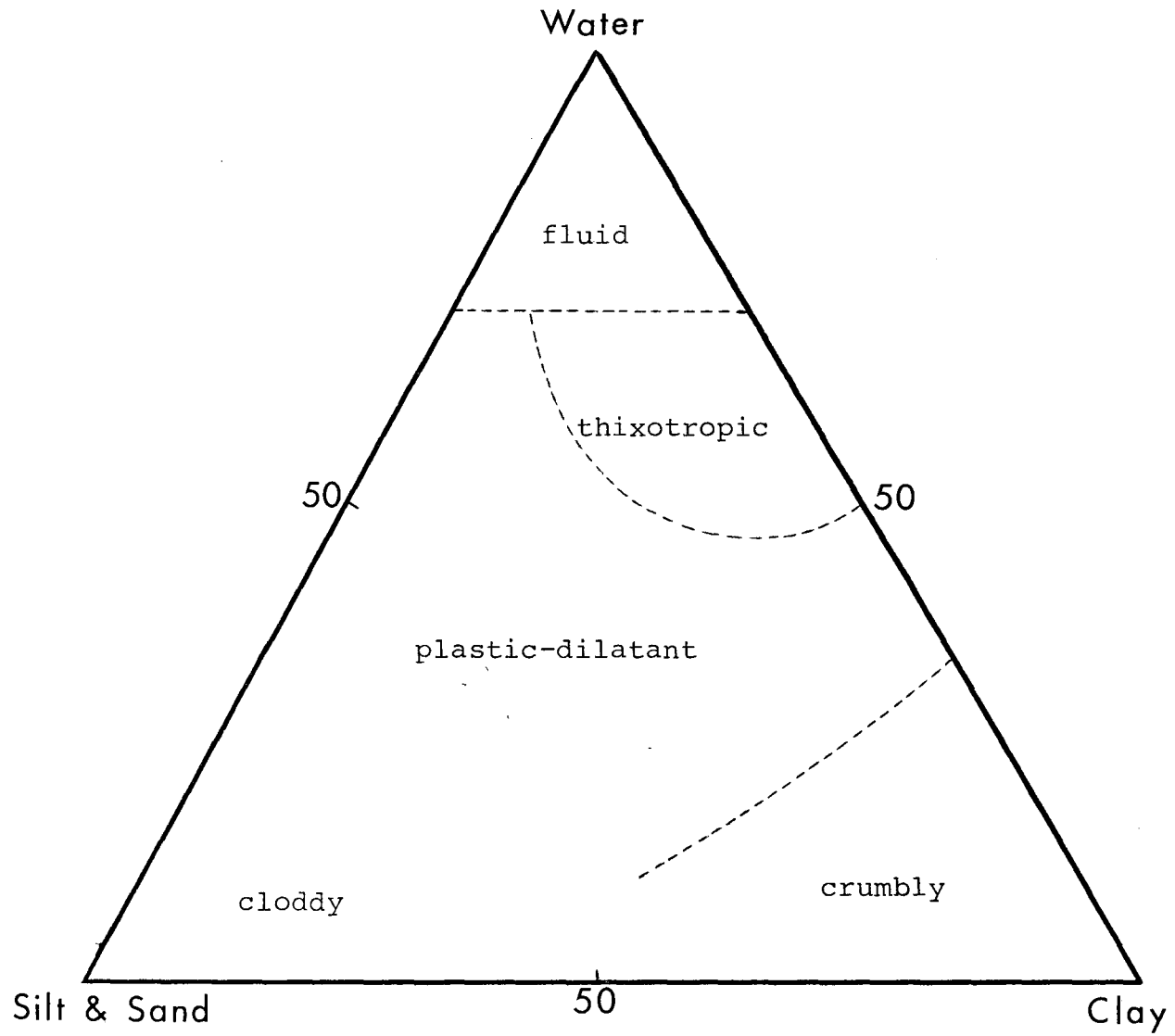
burrow expression. Isolating these organic variables may guide interpretation for specific sedimentary burrowers.

i). <u>Mode of burrowing</u>

Burrowing must result in grain displacement, and this phenomenon will operate differently for different penetration modes. With excavation using appendages as with <u>Callianassa</u>, 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 attach-
ment 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). <u>Organic shape</u>

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 secre-
tion 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 increas-
ing 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 second-
ary particle rotation. This coagulation process could
induce preservation of the initial burrowing event, sta-
bilizing reoriented grains. In some instances the film

Water influx

Water diversion

Zone of
pressure collapse

Grains dragged
in by adhesion
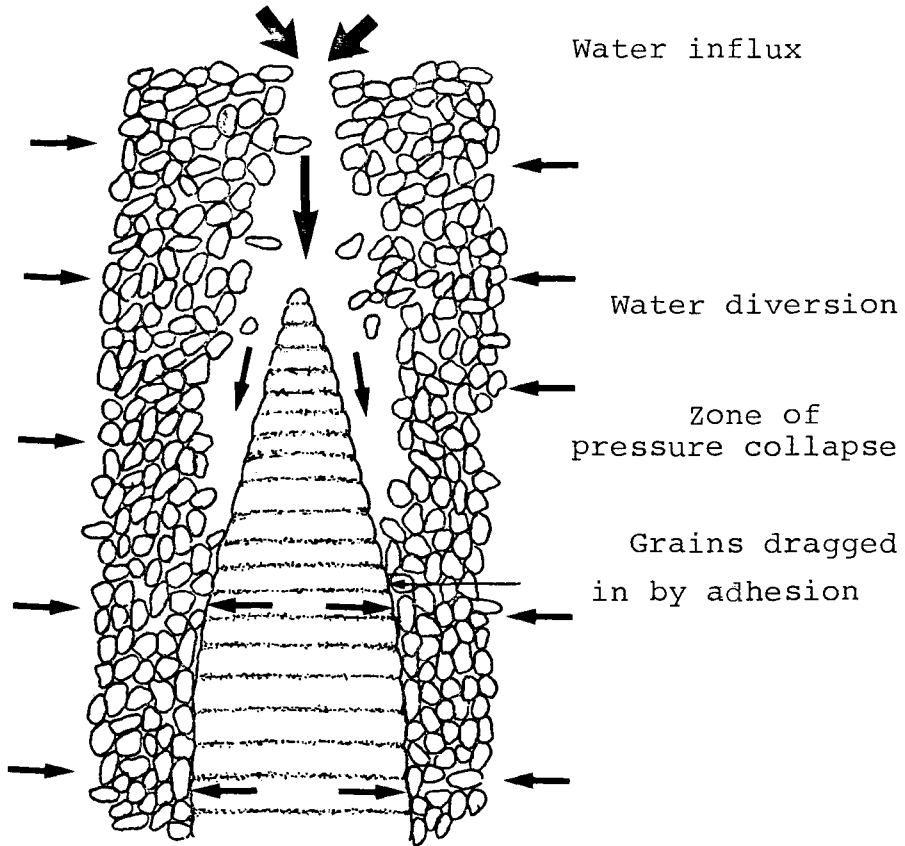
Fig. 2-5 Idealized cross-section of lenticular organ-
ism penetrating sediment. Diagram displays
representative stress regime that encourages
burrow margin collapse.

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 cement-
ed to the wall. Construction of a tube in this fashion
is quite unrelated to the physical mechanism account-
ing 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 perma-
nent burrows, therefore, should display the greatest de-
gree of preferred orientation along burrow margins, dis-
regarding selection mechanism employed by some organisms
(Fager, 1969).

Environmental inferences may therefore be in-
ferred 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 sed-
ment. 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 anomolous concen-
trations for Fe, Al and K along burrow margins.

It becomes apparent that further work is war-
ranted, particularly with regard to fossil specimens.
Understanding the processes involved in metal concentrat-
ion should provide an insight into the interactions of
organisms and sediment. It is the intention of this re-
port 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 ex-
amined). Skolithos burrows from the Thorold Sandstone
were also examined, so as to provide a different chem-
ical 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 in-
stances, the scan distance (base of charts), was be-
tween 8 and 12 mm, with the burrow region centred be-
tween the two end points.

Additional scans were taken of inorganic sed-
imentary 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

INTENSITY

Burrow Margin   Infill   Burrow Margin
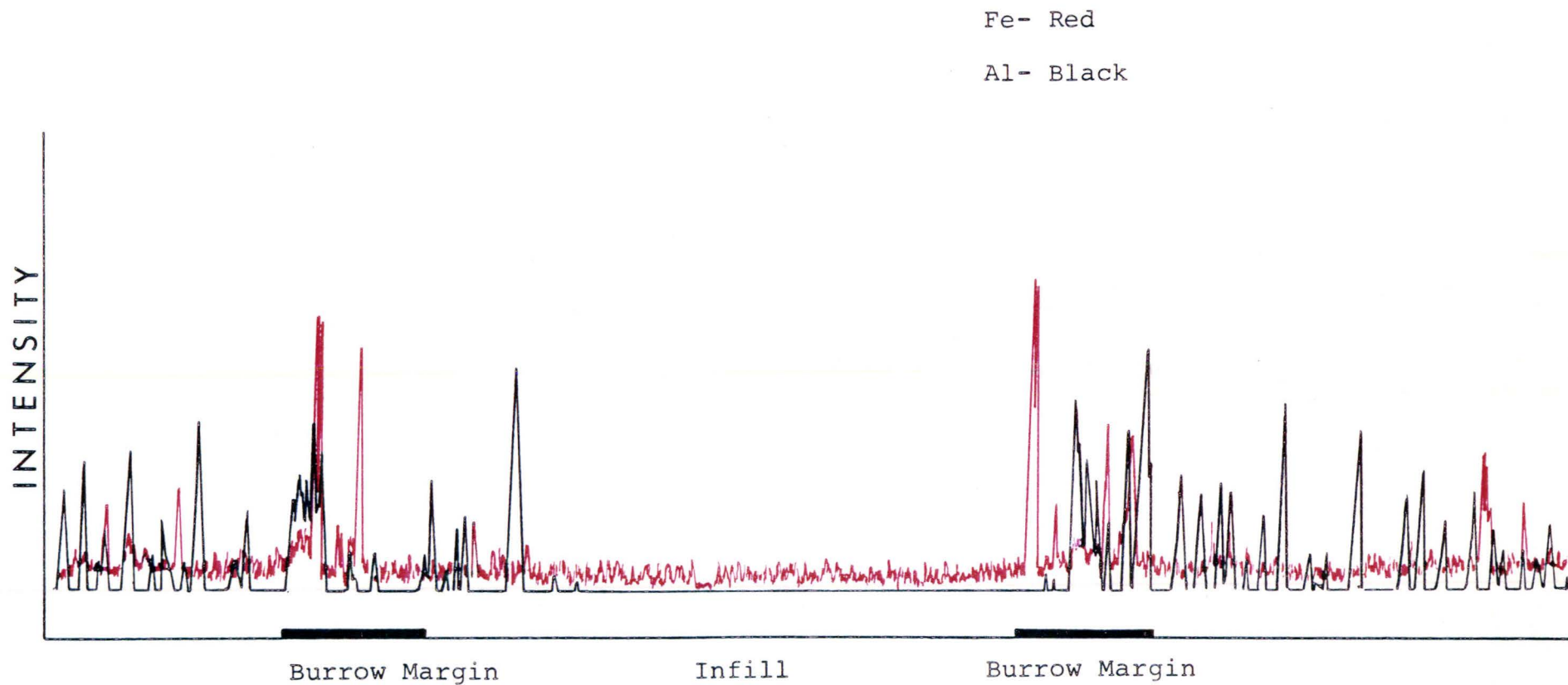
Fig. 3-2 Electron probe scan of Nepean Skolithos showing relative relative concentrations of Fe and Al across the burrow structure.

Fe- Red

Al- Black

INTENSITY

Burrow Margin   Infill   Burrow Margin
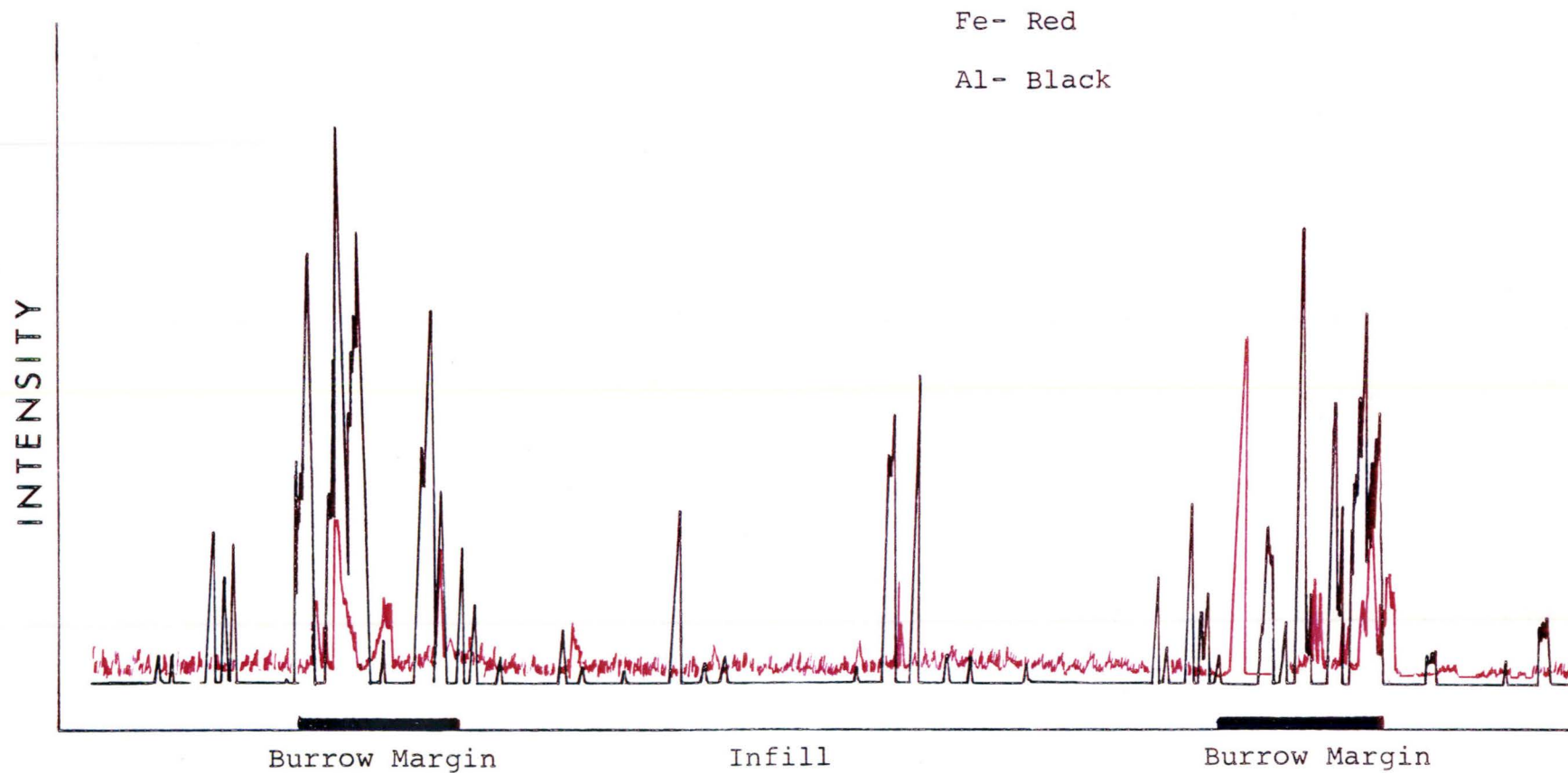
Fig. 3-3   Electron probe scan of Nepean <u>Skolithos</u> showing relative

concentrations of Ni across the burrow structure.

INTENSITY

Burrow Margin   Infill   Burrow Margin
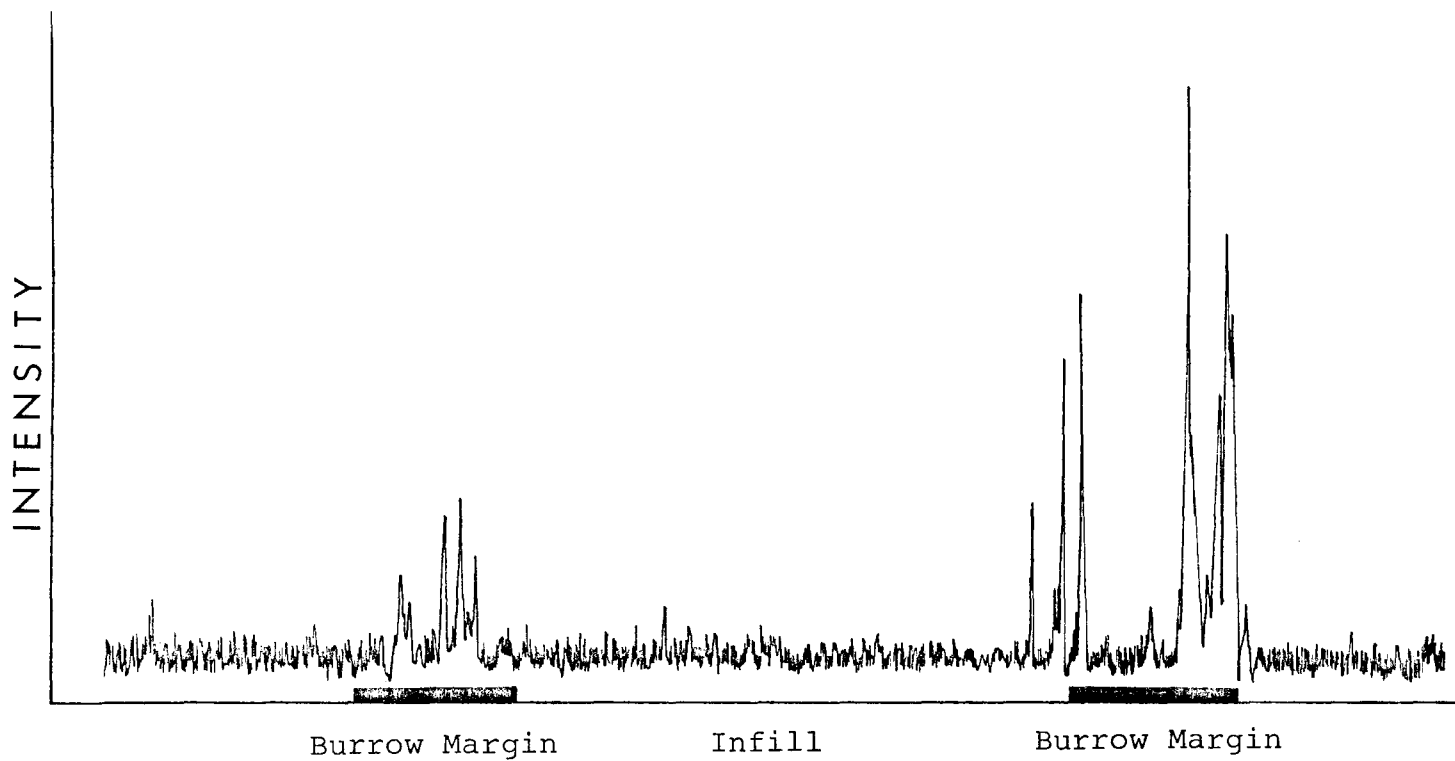
Fig. 3-4 Electron probe scan of Nepean <u>Skolithos</u> showing relative
concentrations of Cu across the burrow structure.
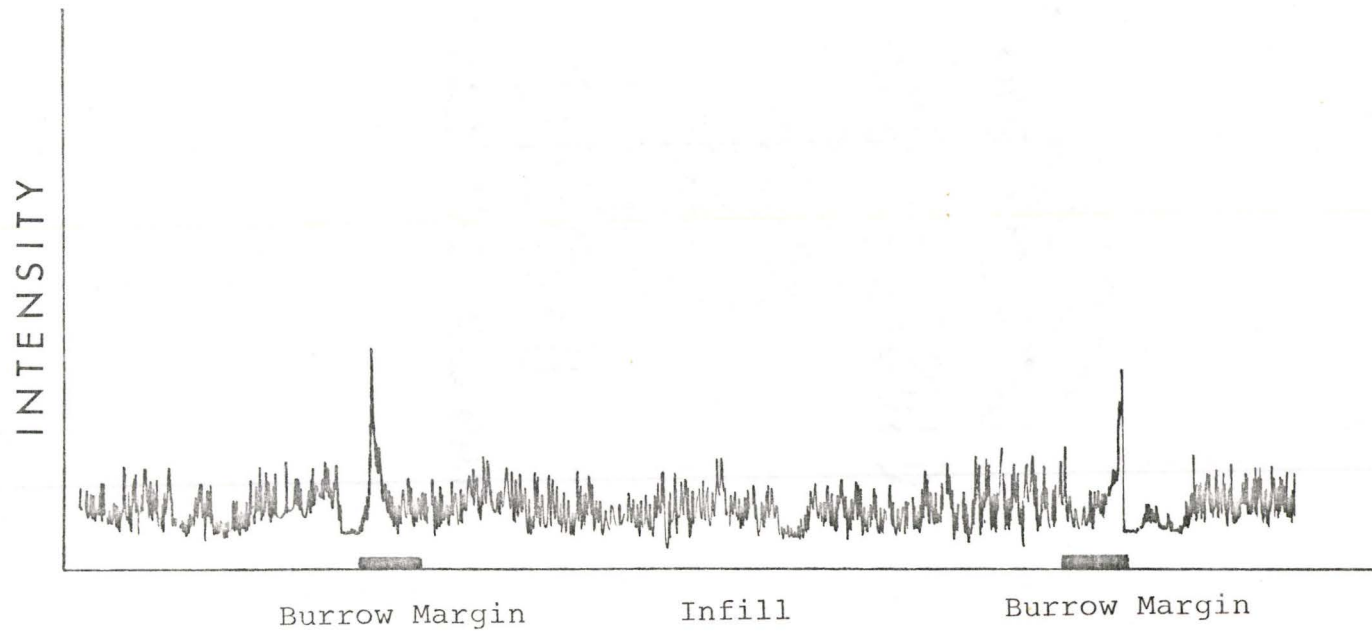
Fig. 3-5 Electron probe scan of Thorald <u>Skolithos</u> showing relative concentrations of Cu across the burrow structure. *Note in this case the margins are defined by a relative decrease in concentration, upon entering the infill region.

INTENSITY

Burrow Margin   Infill   Burrow Margin
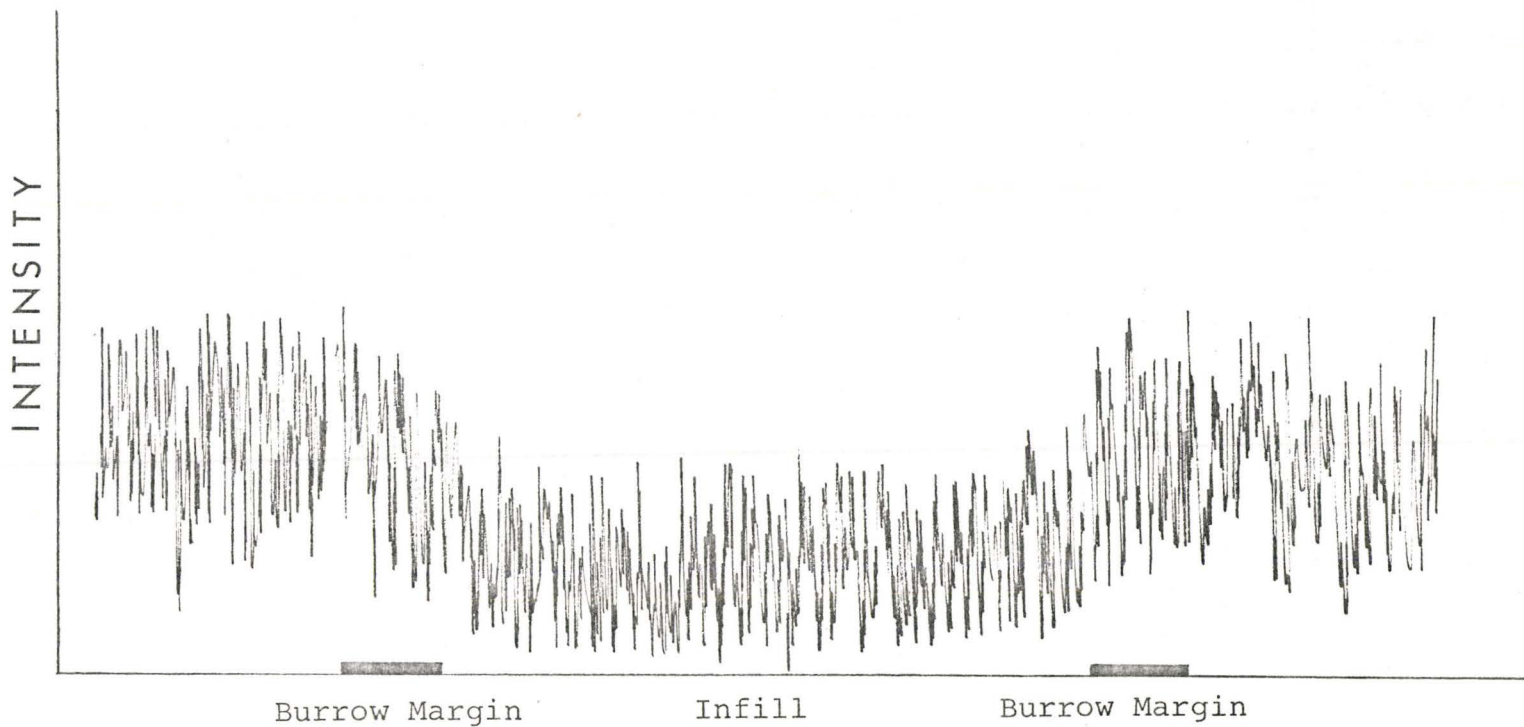
Fig. 3-6 Electron probe scan across Corophium volutator burrow from the Bay of Fundy showing relative concentrations of Fe and Al.

Fe- Red

Al- Black

INTENSITY

Burrow Margin   Infill   Burrow Margin
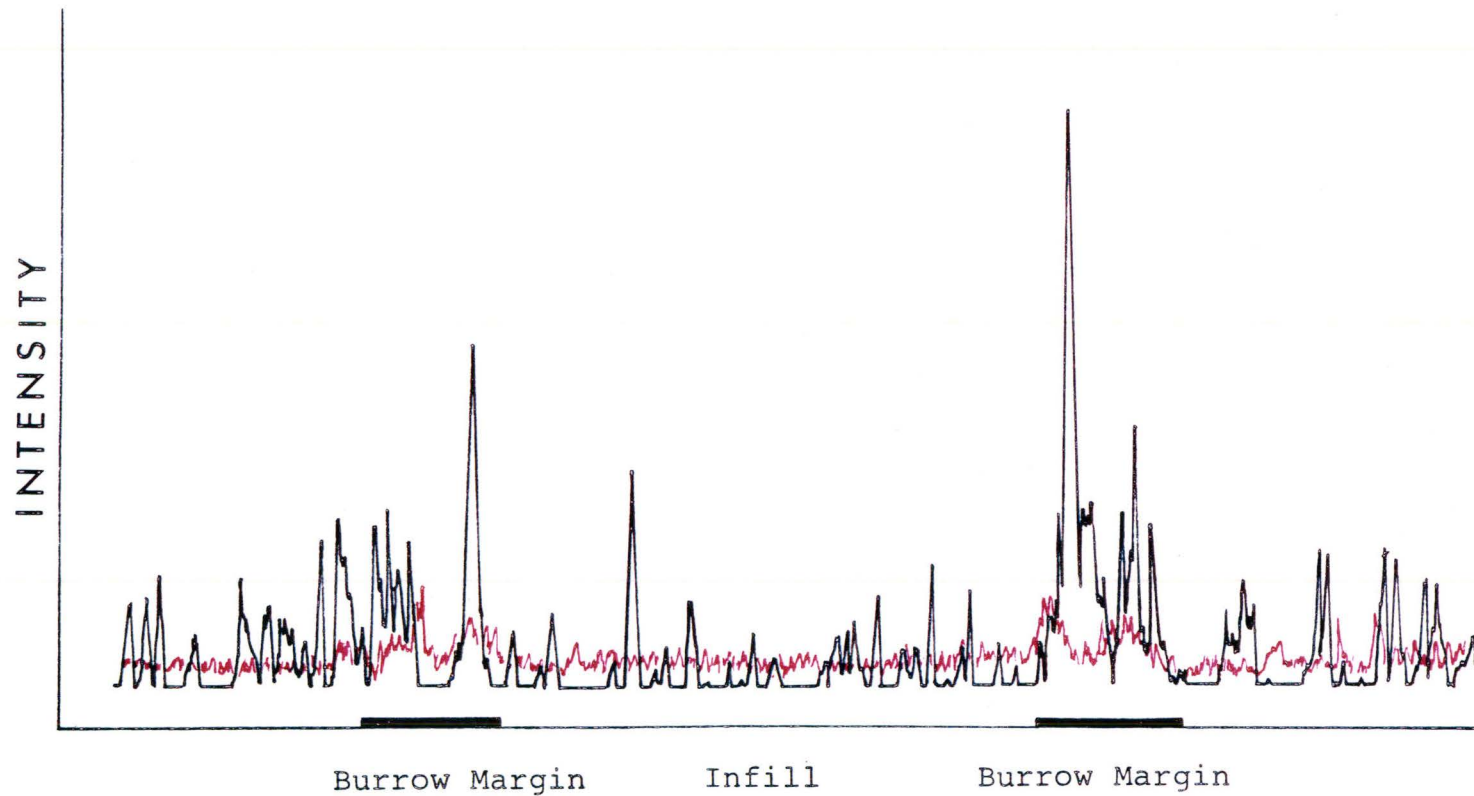
Fig. 3-7   Electron probe scan across Thorald mudcrack showing relative concentrations of Fe and Al.

Fe- Black

Al- Red

INTENSITY

Structure Margin   Structure Margin
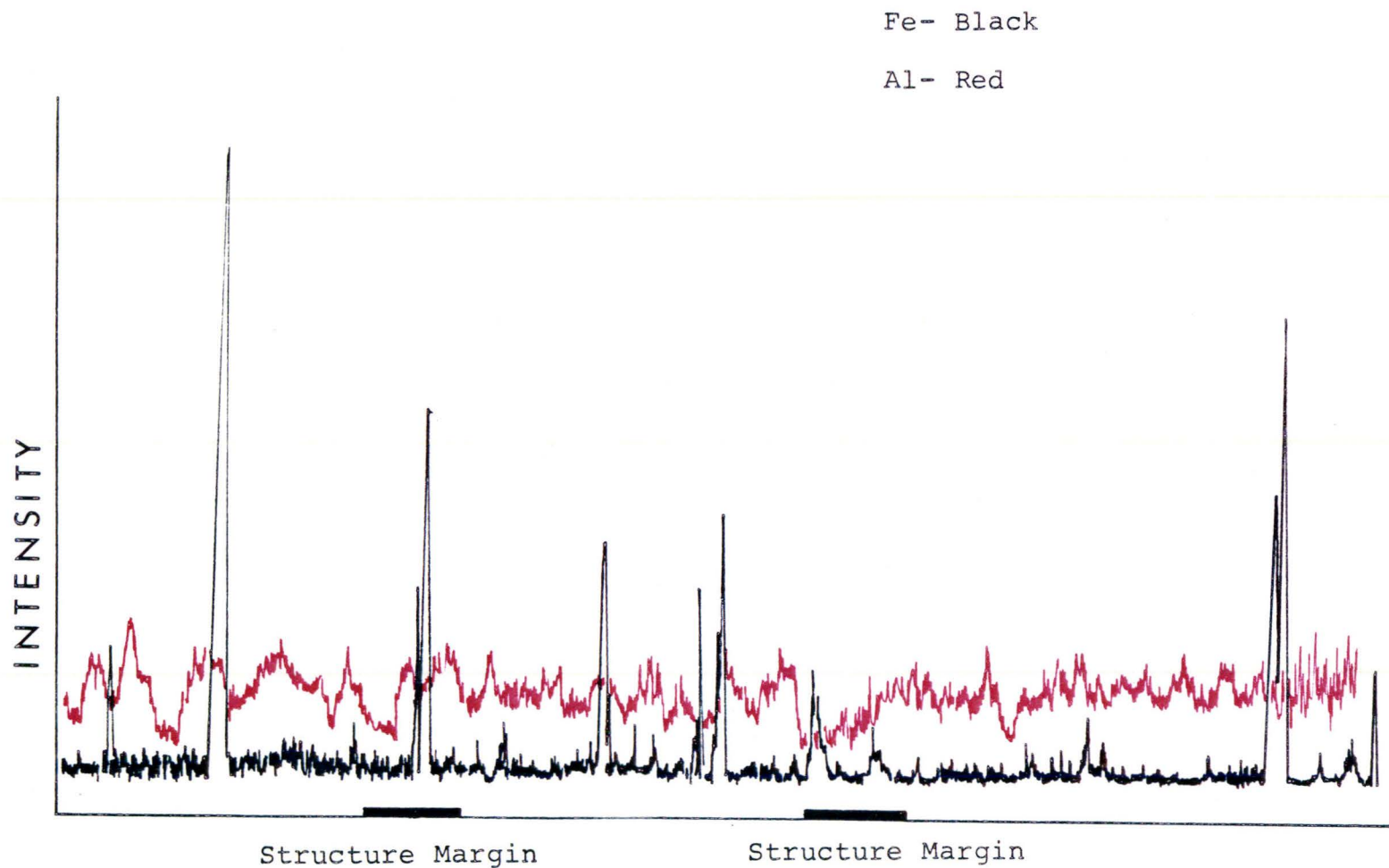
3-3. Results

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 anomolously 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 concen-
trations in the surrounding sediment, away from the sed-
iment-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_2 can also lead to the mobilization of Fe^{2+} (Stumm
and Morgan, 1970).

Loosely bound cations may be further mobilized by
the burrowing activities of the organism. Aller (1978)
recorded Mn^{2+} and Fe^{2+} existing in higher concentrations
directly above Clymenella burrows. He concluded that this
was the result of tube construction and sediment irriga-
tion 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). <u>Mechanisms of Concentration</u>

      i) <u>Organic factors</u>

      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 <u>Owenia</u> was able to protect the lining against bacterial attack, it is likely that the lining was constantly added to during life. <u>Amphitrite</u> 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 CO_2, H_2O or NH_3. 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 inexactly 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   │                    │  Organic residues   │
│ plant polyphenolic  │                    │     in general      │
│     compounds       │                    │                     │
└─────────────────────┘                    └─────────────────────┘
          │                                          │
      Microbial                                  Microbial
      degradation                                degradation
          ▼                                          ▼
┌─────────────────────┐                    ┌─────────────────────┐
│   Methoxyphenols    │                    │ Acids, sugars, and  │
│                     │                    │ other simple organic│
└─────────────────────┘        microbial   │     compounds       │
                               synthesis   └─────────────────────┘
 demethylation │
              │                                              Microbial
              ▼                                              degradation
┌─────────────────────┐          ┌──────────────┐                │
│   Intermediate      │          │   Microbial  │                │
│       Phenols       │          │     cells    │                │
└─────────────────────┘          └──────────────┘                ▼
     oxidation of aldehyde                           ┌─────────────────────┐
  │  groups, -oxidation of                           │ CO₂, H₂O, NH₃, and  │
  │  side chains, hydroxyl-                           │ other simple inor-  │
  │  ation of ring carbons,                           │  ganic compounds    │
  ▼  decarboxylation, oxi-                            └─────────────────────┘
     dation of methyl groups
```

oxidation of aldehyde groups, -oxidation of side chains, hydroxylation of ring carbons, decarboxylation, oxidation of methyl groups

CO_2, H_2O, NH_3, and other simple inorganic compounds

┌─────────────────────────────┐
│ Numerous mono-, di-, and   │   ring cleavage
│ trihydroxy phenols, ben-   │   and oxidation
│ zoic acids, and other   │
│ aromatic compounds   │
└─────────────────────────────┘

        │   enzymatic &
        │   autoxidation
        ▼

┌─────────────────────────────┐   ┌─────────────────────────────┐
│ Phenolic radicals   │   │ Peptides and amino acids   │
│ & hydroxybenzoquin-   │   │ from decomposing organic   │
│ ones   │   │ residues and from autoly-   │
└─────────────────────────────┘   │ sis of microbial cells   │
                                     └─────────────────────────────┘

                    ┌─────────────┐
                    │ HUMIC   │
                    │   ACID   │
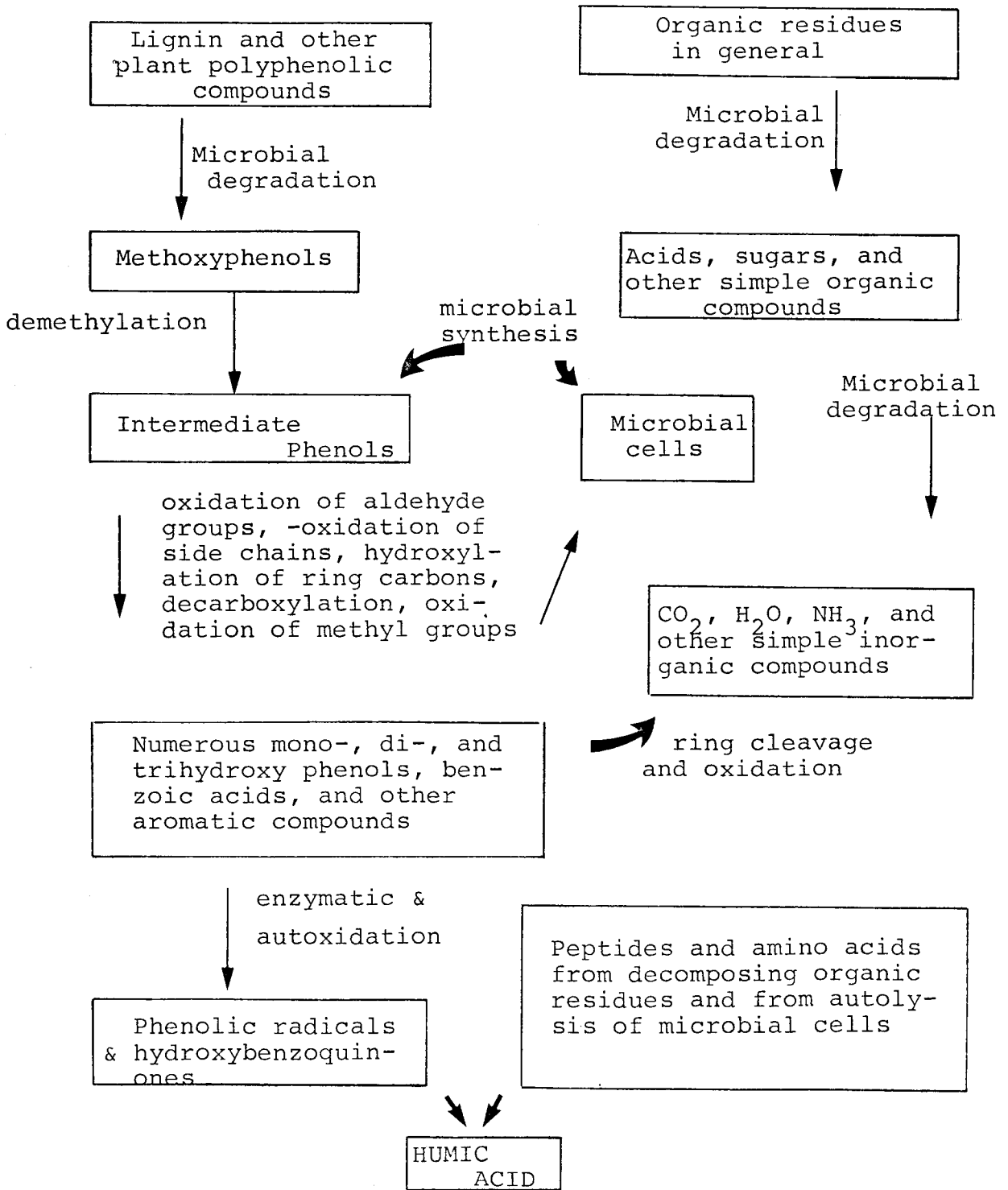   └─────────────┘

Fig. 3-8   Schematic representation of humic acid
            synthesis in soil. (after Martin and Haider, 1970)

Fig. 3-9   A.) Diagramatic representation of Hum-
           ic acid (in Schnitzer and Khan, 1972).

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

(A)

(B)

Table 3-1

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

| Sample | Fraction | Amount of Metal Complexed by One Gram of Organic Matter (Mg) | | | | |
| | | Trivalent metals | | Divalent metals | | |
		Al	Fe	Cu	Co	Ni
68-2-1-1	Parent	21.4	42.5	95.8	146.0	168.0
68-2-1-1	Less than 700	27.2	76.6	127.3	186.1	210.1
68-2-1-1	700- 10,000	18.9	37.9	94.3	113.7	148.4
68-2-1-1	10,000-100,000	3.4	9.3	33.8	23.6	25.2
68-2-1-1	Greater than 100,000	8.1	23.3	41.4	57.2	68.3
Lagoon	Parent	28.8	48.4	115.8	123.4	134.9
Lagoon	Less than 700	41.4	64.9	158.1	186.1	199.5
Lagoon	700-10,000	25.7	30.9	70.0	87.6	162.3
Lagoon	10,000-100,000	11.1	21.2	33.8	32.8	36.4
Lagoon	Greater than 100,000	17.2	27.1	50.2	88.0	120.1
68-2-2-1	Parent	36.9	64.4	180.3	157.4	205.0
68-2-2-1	Less than 700	48.3	95.0	211.7	199.7	216.6

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 electro-chemical attraction towards the organic acids, whose car-boxyl 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 be-tween clays and cations. The first three sites are ex-changeable 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 mechanisma 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).

$$H$$
$$|$$
$$M^{++} - (O - H - N = C \ C_6H_6 \ )_m$$
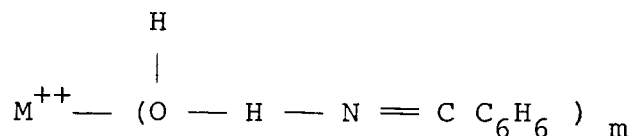
3). Base conversion to protonated cation

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.

$$M^{n+} \ (H_2O + nB \rightleftarrows M(OH)_n + nHB^+$$
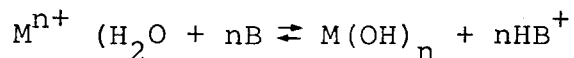
iii) Scavenging

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 electro-negative, 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 ap-parent that cation concentration is an intricate process. The metal cations are mobilized by organic action (micro-bial 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 res-ponse 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 na-
ture 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 ro-
      tation to be a function of instantaneous velocity
      fluctuations of the organism. The degree of par-
      ticle rotation and subsequent preservation of this
      reorientation will depend on a variety of sediment
      and biologic variables that will differ with spec-
      ific 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 or-
ganic/inorganic construction mode for questionible
structures. Trace fossils may therefore be more clear-
ly 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 Huron-
ian Supergroup. Although there is some question as to
the precise age of this Formation, it appears conform-
able 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 Forma-
tion (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 paleo-environment, 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 struc-
tures.

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.

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)
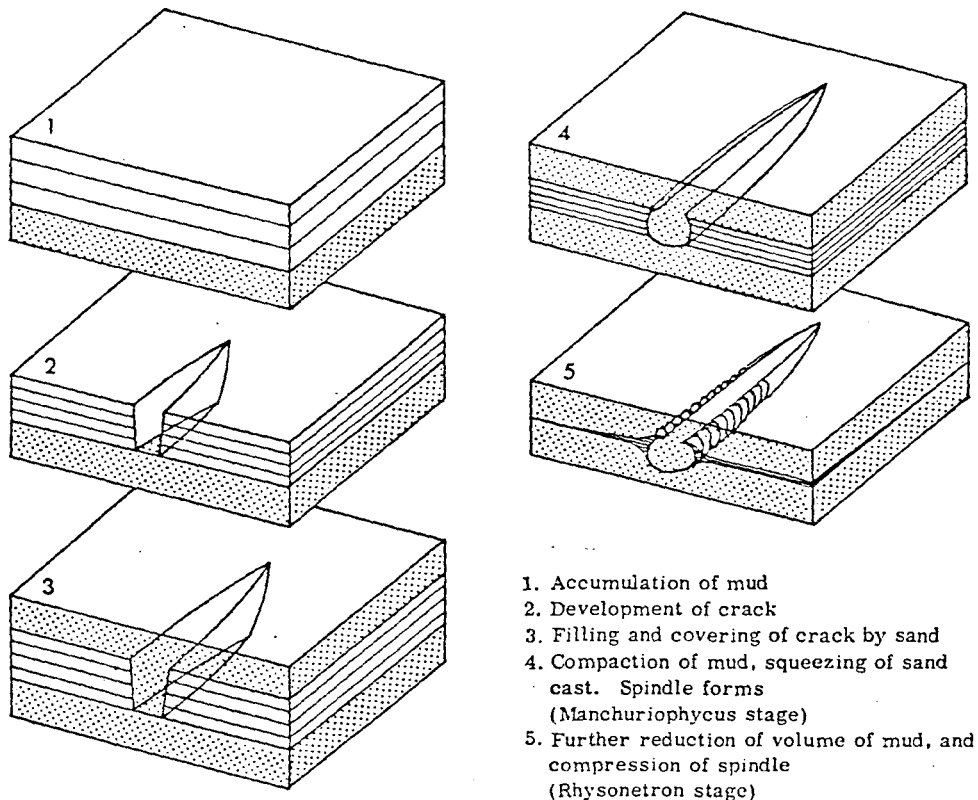
FIGURE   Presumed stages of development of rhysonetron structure.

5-1   (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 over-
lap. Although the preservation of these shrinkage struc-
tures 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 compar-
ative diagenetic conditions.

Another explanation proposed to account for
these features was that they were a form of subaqueous
shrinkage features. Young (1969) explains this occur-
rence as a consequence of salinity changes, from saline
to fresh water. He allows for corrugations by suggest-
ing 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 partic-
            ularly the Rhyzocorallium-like traces
            observed in the upper right hand cor-
            ner.

                (photogragh 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 di-
versity in traces observed enhances an argument for early
metazoan evolution.

5-3. Internal structures

Slabs were cut perpendicular to the bedding sur-
face to examine for any internal structures. The result-
ing 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 up-
wards 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, occas-
ionally displaying signs of surface scour. Contained with-
in the dark layers are lighter sandy-silt structures pos-
sessing 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 mechamism 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
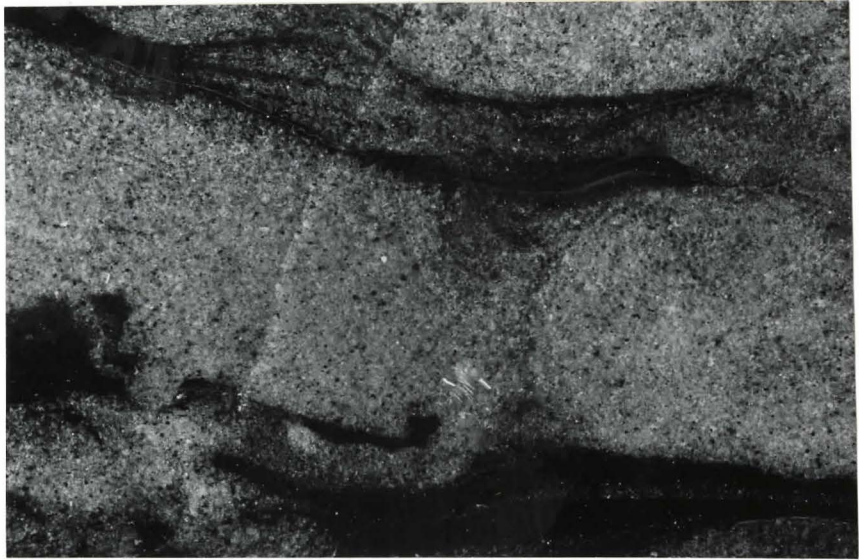   sand layer)

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
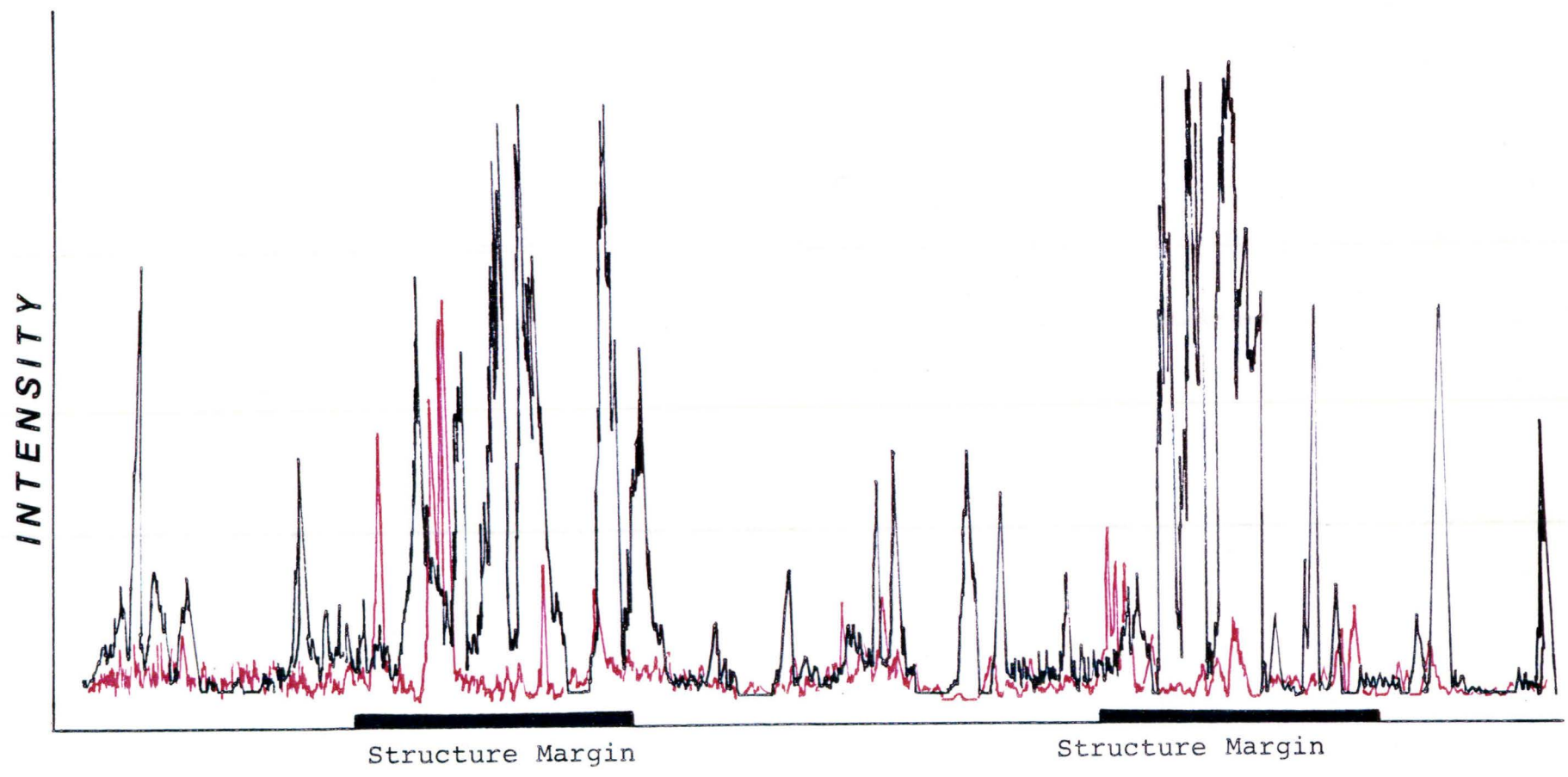Fe and Al.

Fe- Red
Al- Black

INTENSITY

Structure Margin   Structure Margin

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

Fe- Red

Al- Black

INTENSITY
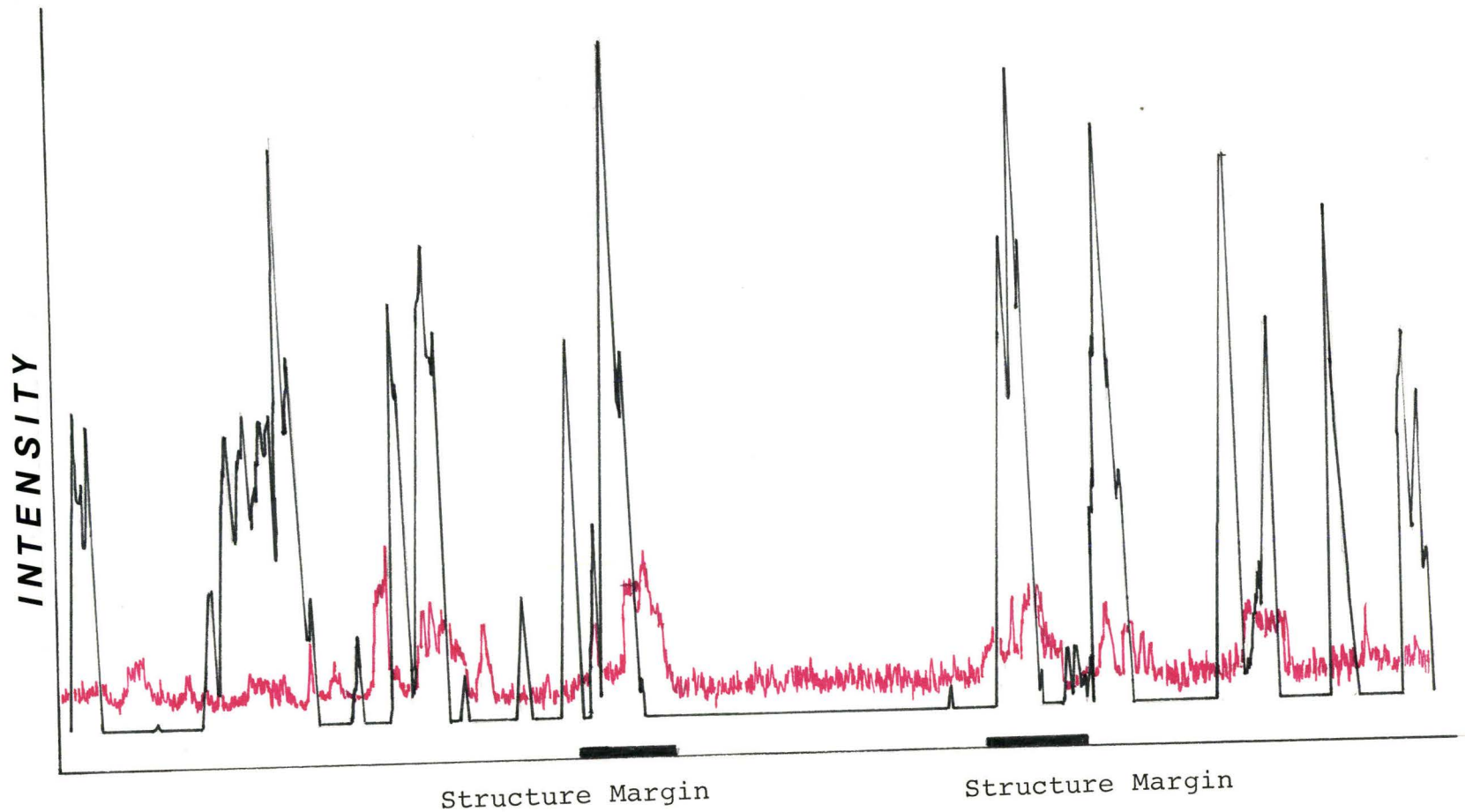
Structure Margin

Structure Margin

Fig. 5-4 Electron probe scan across tubular structure (5-2), showing relative concentrations of Cu.

INTENSITY

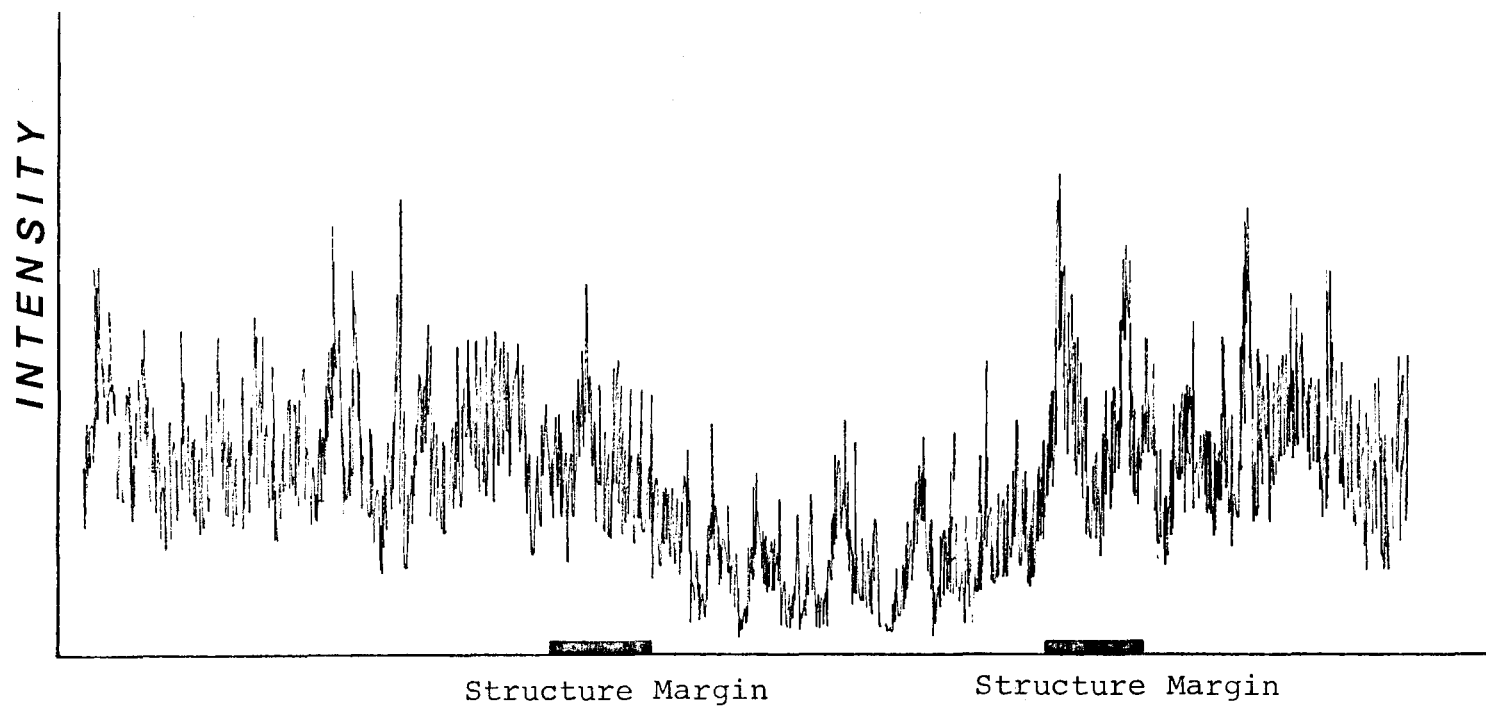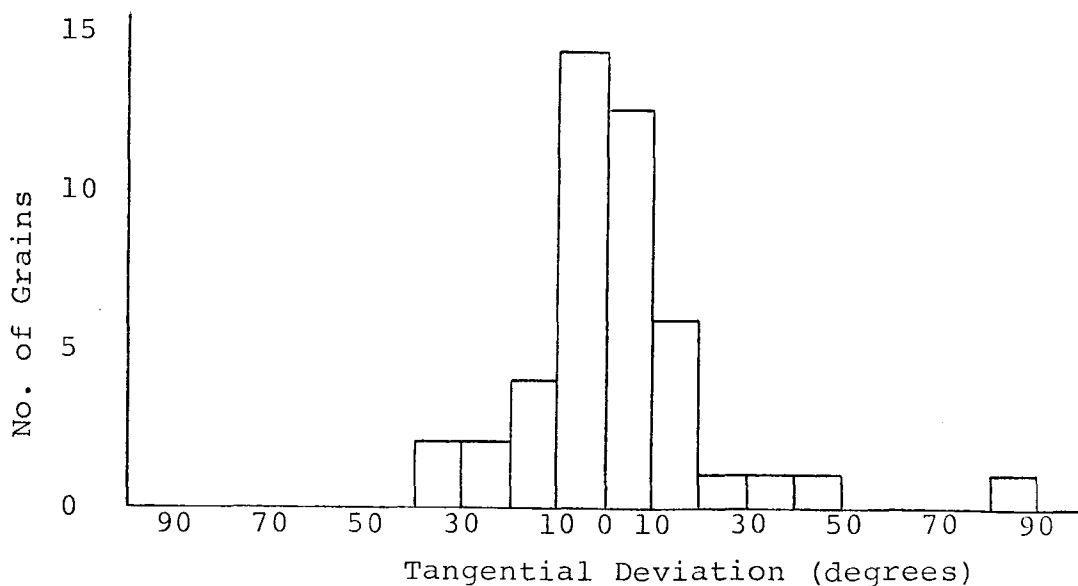Structure Margin   Structure Margin

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).

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

Tangential Deviation (degrees)

5-5. Results and Conclusions

The results of these analyses are most intriging. 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 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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