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A new Silurian *Konservat-Lagerstätte* from the Eramosa
Dolostone of the Southern Bruce Peninsula, Ontario,
Canada

by

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Graduate Program
in
Geology

Submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

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Abstract

A new Silurian (lower Ludlow) biota from the Eramosa Dolostone in southern Bruce Peninsula provides an unusual window into the diverse, but normally poorly preserved biota in a very shallow water marine environment. The flora consists of both dasycladalean and non-dasycladalean thallophytic algae, an important but rarely preserved component of any marine paleoecosystem. The fauna contains phyllocarid crustaceans, and several soft-bodied and lightly sclerotized arthropods and worms similar to the older Brandon Bridge (Llandovery) fauna of Wisconsin, including an arthropod of uncertain affinity with a pair of large grasping anterior appendages. Also present within this biota are brachiopods, cephalopods, gastropods, trilobites, chelicerates, sponges, and conularids. In contrast to the Wisconsin fauna, there is also a significant echinoderm fauna, including ophiuroids and lepidocentrid echinoids (perhaps the oldest echinoids yet found in Canada).

The biota occurs within very thinly laminated, light to very dark brown, petroliferous dolostones downslope from a slight paleo-topographic high produced by patch reefs within the underlying Amabel Formation. Calcitic faunal elements are very poorly preserved and normally decalcified, though the echinoderm and trilobite material is articulated. Chitinous organisms are preserved as thin films, sometimes secondarily mineralized. Many of the organisms are represented by carcasses, the articulated phyllocarids having intact jaw elements. The fauna is mostly autochthonous, as the very large number of echinoids are all preserved in life position with oral surfaces oriented downward.

Also examined in this study is the regional geology, stratigraphy and sedimentology of the Eramosa as it relates to the biota, using a variety of techniques including the use of Ground Penetrating Radar to image the subsurface.

Keywords: Silurian, lagerstätten, Eramosa, phosphatization, taphonomy, dasyclad, algae, worm, arthropod, phyllocarid, echinoid, GPR, ground penetrating radar

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Introduction

The fossil record is the only means by which we can understand what life on earth was like before man's recorded history. Unfortunately, the fossil record is highly biased towards organisms with mineralized skeletons, and skews our picture of the past. The bulk of the true biotic diversity of the past is hidden from our view. That bias not only becomes more intense the farther back in time one looks, but also varies significantly between different types of environments. The very-shallow marine environment is one of the most difficult to preserve due to high wave energies during deposition, frequent reworking by biological and physical processes, diagenetic alteration and, often complete removal by erosion.

The Paleozoic has in particular suffered from extreme bias within the fossil record. A very few *Konservat-Lagerstätten* (sensu Seilacher 1970) have given us glimpses into the true diversity of the Lower Paleozoic, those being the Cambrian Burgess Shale of British Columbia, the Lower Devonian *Hunsrückshiefer*, and Pennsylvanian Mazon Creek biota. Most recently, two new exceptionally preserved biotas have been described from the Silurian, from the Brandon Bridge of Wisconsin (Mikulic, Briggs and Kluessendorf 1985a, 1985b) and the Gasport Dolomite of western New York State (LoDuca 1995). Kluessendorf (1994) and LoDuca (1995) observed that these and other Silurian *Konservat-Lagerstätte* were predictable in nature, occurring under similar paleoenvironmental conditions and often containing similar biotic components. This study adds a new Silurian *Konservat-Lagerstätte* with a much higher diversity than those previously discovered and, using a

multidisciplinary approach, will attempt to ascertain whether the paleoenvironmental and paleoecological features of the Eramosa are consistent with their model.

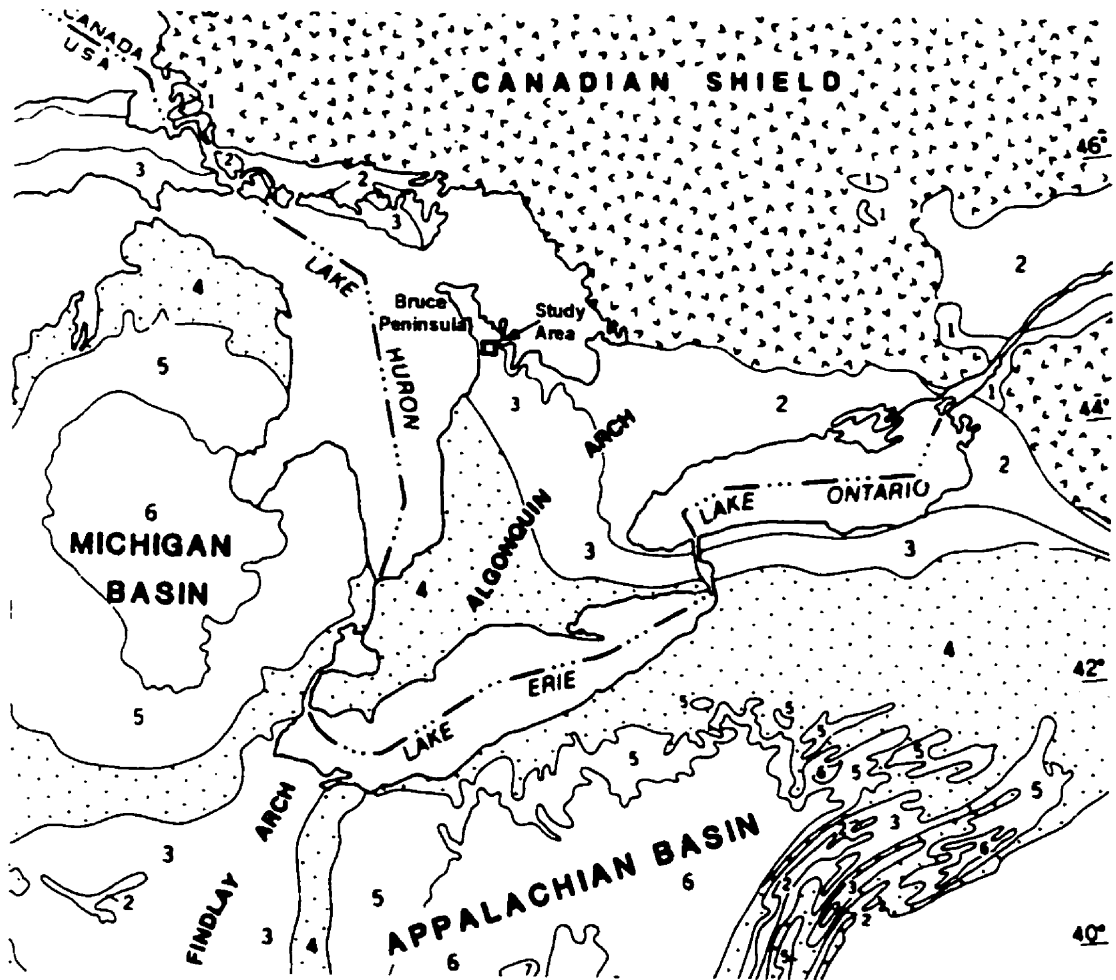
Study Area and Methods

This study concentrates on the Silurian rocks of the Eramosa Formation exposed in the Southern Bruce Peninsula region of Ontario, Canada (Figure 1). Most attention is focused upon the exposures in the Wiarton Quarries of Owen Sound Ledgerrock Ltd. Other outcrops examined during the course of this study include the rocks of two other nearby quarries, Ebel Quarries and Georgian Bay Marble & Stone, the Shadow Lake quarries of Owen Sound Ledgerrock Ltd, and exposures just west of Owen Sound and at Rockport.

The Wiarton Quarries of Owen Sound Ledgerrock Ltd. lie on the north and south side Bruce County (Oliphant) Road 21, about 4 km west of Hwy 6 north of Wiarton (UTM 484850E/4955150N; NTS Cape Croker Sheet 41A/14). Dolostones within these quarries are excavated by hand using large saws of various types, carefully lifted out and, depending upon its ultimate use, either used as is, split by hand or slabbed by saws. The final product is used as ornamental stone, floor tiles, flagging stone, facing stone, and other finished and unfinished stone for a variety of purposes. Escalating demand for high quality building stone at this facility results in rapid changes in quarry configuration, thus exact locations of representative sections vary.

Extensive sampling was conducted within the main fossil deposit over several summers. Lighter sampling and reconnaissance over the entire area of the

Figure 1. Study location map and regional geology. 1. Cambrian, 2. Ordovician, 3. Silurian, 4. Devonian, 5. Mississippian, 6. Pennsylvanian. (modified after Carter 1990)



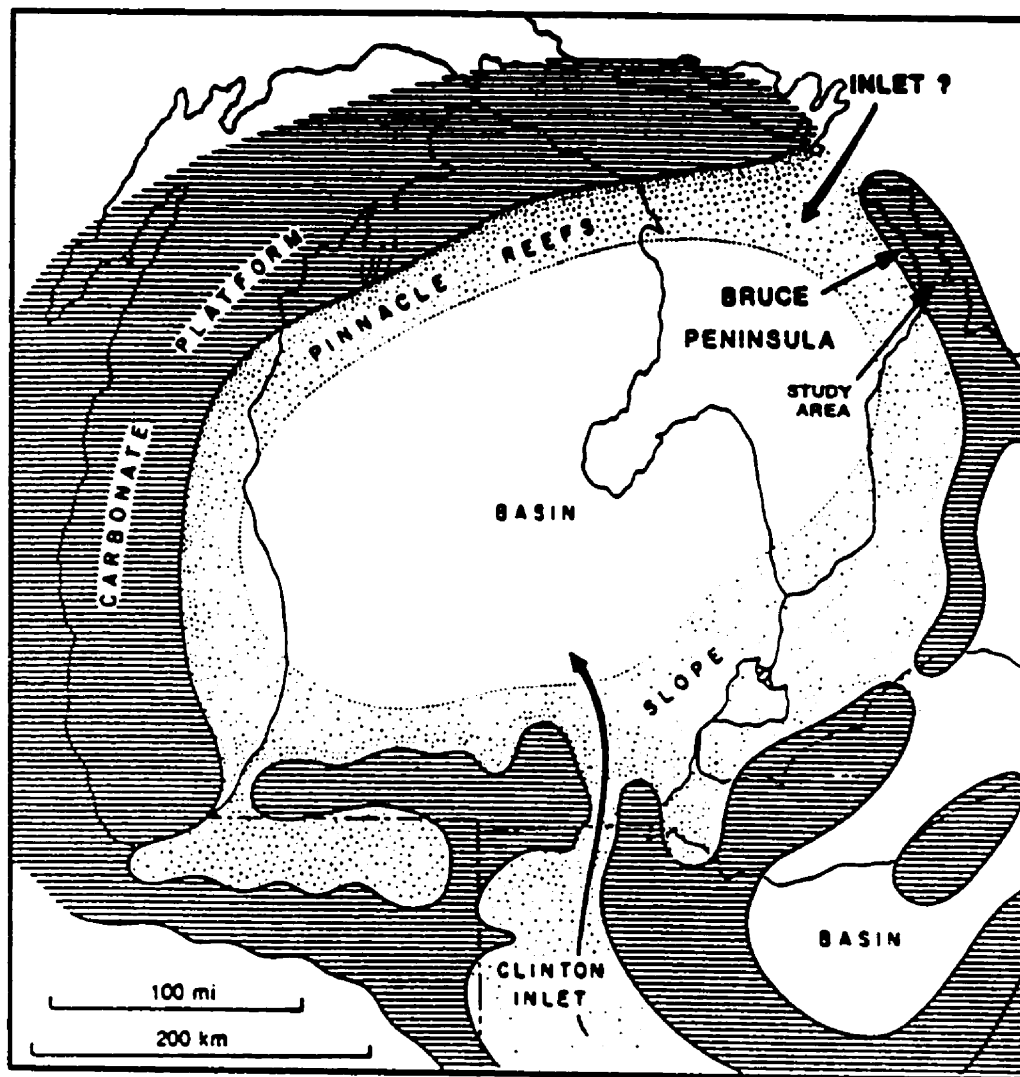
quarry exposures was carried out repeatedly over several years as new material was uncovered by ongoing quarry operations. Ground Penetrating Radar was used in an attempt to image the subsurface stratigraphy within the two primary quarries and along the road between them. In the lab, samples were photographed using a variety of techniques, including low angle lighting and submersion within ethyl alcohol, in order to record faint structures and images through calcitic (and other) coatings. Fossil specimens from this study will be repositied at the Royal Ontario Museum, Toronto, Canada.

General Geologic Setting

During the Silurian, the Taconic Orogeny was underway, and resultant crustal thickening led to isostatic subsidence of the eastern margin of the North American craton. The Appalachian Basin formed over the downflexed area adjacent to the Taconic Mountains. The "peripheral bulge" or "forebulge" formed as the Findlay/Algonquin Arch immediately east of the Appalachian basin. The Eramosa Dolostone was deposited during the early Late Silurian (Early Ludlow) in a broad band extending across the Appalachian Foreland Basin, over the Findlay/Algonquin Arch and into the Michigan Basin. The present day outcrops extend across western New York State and southern Ontario. The Warton area lies on the eastern edge of the Michigan Basin near the northwestern flank of the Algonquin Arch (Figure 2).

During this time, the region was dominated by a fairly shallow water carbonate platform with low elastic input. The nearest shoreline lay an unknown distance to the north, but the erosion of all Silurian rocks north of the Bruce Peninsula obscures its position. However, the Canadian Shield does not appear to have been

Figure 2. Upper Silurian paleogeography of the Michigan Basin. (modified after
Gill 1985)



a major source of sediment during most of the Silurian. Similarly, within the Appalachian Basin, most clastic sedimentation came not from the inferred northern shoreline, but from the Taconic Orogenic belt to the east. Zenger (1965) suggested that several temporally and areally restricted increases in clastic input into the still dominantly carbonate shelf could probably be attributed to sediment coming from the northern landmass, and contributing to the sandy Penfield facies near Rochester, and the increased clastic component of the Decew, Vinemount and Eramosa.

Numerous small patch reefs developed on the shallow carbonate bank of the Bruce region, but on moving southwestward towards the basin center, water depth increased and the carbonate bank gave way to deeper carbonate sediments and larger, less numerous patch reefs. Deeper into the basin, the patch reef belt gave way to the pinnacle reef zone (Sanford 1969, Gill 1985), which in turn passed into the deep basin. Subsidence rates were highest towards the center of the basin, producing great thicknesses of alternating carbonate and evaporite rocks, but decreased towards the more stable tectonic "hinge" of the shallow shelf surrounding the basin where depositional thicknesses were much less. When sea level dropped below the level of much of the basin-encircling platform, salinity of the Michigan basin increased sufficiently through evaporation to deposit gypsum and salt. Subsequent sea level rise(s) flooded the platform, enabling sufficient water exchange, to again lead to carbonate deposition within the basin.

During the Silurian, the study area was approximately 20 degrees south of the equator, with North America rotated clockwise approximately 45 degrees (Van der Voo 1988) relative to its present orientation. At this latitude, global air circulation

patterns would have a major easterly wind direction, translating to a northeasterly direction in the present-day continental configuration. Using bioherm morphology and stromatoporoid growth patterns in the Lockport Group, Crowley (1973) confirmed a roughly northeasterly wind direction. In the study area, these winds would have been blowing from offshore, towards the basin center, resulting in a lack of significant storm surge. The restricted amount of fetch in such a shallow, near-shore setting would have even limited fair-weather wave activity (Irwin 1965), and result in a very low-energy environment.

Stratigraphy

The name "Eramosa beds" was first proposed by Williams (1915) for the thin-bedded dark grey or chocolate-brown bituminous dolostones comprising the "top of the Lockport member of the Niagara formation", exposed along the banks of the Eramosa River between Rockwood and Guelph, Ontario. Since that time, the Eramosa has seen a variety of stratigraphic interpretations, most of which concentrated on the rocks on the eastern flank of the Algonquin Arch in the Niagara region of Ontario and western New York State (summarized in Figure 3). Shaw (1937) defined the Eramosa as the entire succession between the Guelph Dolomite and the Gasport Member of the Lockport Dolomite, gave it formational status, and subdivided it into an upper Speedwell Member and a lower Ancaster member. Cumings (1939) assigned the Eramosa to the uppermost member of the Lockport Dolomite, underlain by the Suspension Bridge Member (named therein) and overlain

Figure 3. Stratigraphic nomenclature for the Silurian Lockport Group of western New York and southern Ontario.

Shaw (1937)	Cummings (1939)	Howell and Sanford (1947)	Bolton (1957)	Zenger (1965)	Sanford (1969)	Rickard (1975)	Brett et al. (1995)
Guelph Formation	Guelph Formation	Oak Orchard Member	Guelph Formation	Oak Orchard Member	Guelph Formation	Guelph Dolomite	Guelph Dolomite
Eramosa Formation	Eramosa Member	Eramosa Member	Eramosa Member	Eramosa Member	Eramosa Member	Eramosa Formation	Eramosa Dolomite
Lockport Fm.	Suspension Bridge Member	Goat Island Member	Goat Island Member	Goat Island Member	Goat Island Member	Goat Island Formation	Vinemount Member
Gasport Member	Gasport Member	Gasport Member	Gasport Member	Gasport Member	Gasport Member	Gasport Formation	Ancaster Member
							Niagara Falls Member
							Pekin Member
							Gothic Hill Member

by the Guelph. Howell and Sanford (1947) stated that the Eramosa Member overlies the Goat Island Member and is overlain by the Oak Orchard Member (both terms introduced by them).

Bolton (1953, 1957) included the bituminous dolomites of Williams (1915), and, continuing the correlation across the Algonquin Arch, the thin, non-bituminous beds at or near the top of the Amabel Formation (lateral equivalent of the Lockport Formation) in his Eramosa Member. Zenger (1965) placed the Eramosa as a member of the Lockport Formation, overlain by the Oak Orchard Dolomite, and extended it only as far east as the Tonawanda-Lockport area of New York. Rickard's (1975) correlation chart elevated the Lockport to group-level status and the Eramosa Dolomite to a formation-level unit underlain by the Goat Island Dolomite and overlain by the Guelph Dolomite.

Bolton (1957) correctly observed that thin-bedded, bituminous dolostones occur at different levels at different localities within the often otherwise monotonous Amabel to Guelph dolostone sequence and that they grade laterally into massive bioherms. From this, he concluded that "the Eramosa, in the northern part of the Ontario Peninsula at least, is a particular facies directly associated with the development of bioherms in the Wiarton member". Liberty (1966) and Liberty and Bolton (1971) again emphasized their belief that the Eramosa Member was "not a consistent unit at the top of the Lockport, but rather is inter-reefal between Lockport bioherms". This confusion between often temporally recurrent lithofacies and the formal stratigraphic "formation" as a continuous, mappable unit bounded by traceable surfaces, has hampered clear stratigraphic interpretation of many of the carbonate

units within the Silurian of Ontario and New York State, many of which are poorly fossiliferous because of intense dolomitization. Although placing the Eramosa Member at the base of the Guelph formation rather than the top of the Amabel/Lockport, Winder and Sanford (1972), Armstrong (1988, 1993), Armstrong and Meadows (1988), and Armstrong and Goodman (1990) all continued to describe a discontinuous interreefal "Eramosa facies".

Brett et al. (1995) formally revised the lower and middle Silurian stratigraphic nomenclature for western New York State, including the lateral equivalents of the rocks dealt with in this study. Within that report, Brett et al. formalized the elevation of the Lockport to group-level status, the elevation of the Eramosa to formation-level status (re-affirming the banks of the Eramosa River between Rockwood and Guelph, Ontario, as the type locality as originally defined by Williams 1915), and attempted to resolve the many correlation problems caused by the near exclusive reliance of past workers on the identification of a lithology-based "Eramosa facies". Based on lithostratigraphic evidence, they showed that Zenger's (1965) "Eramosa" (and continued by Rickard 1975) was in fact a member of the Goat Island Formation (which they named the Vinemount Member), and that the lower portion of Zenger's (1965) Oak Orchard and Rickard's (1975) Guelph correlated with the Eramosa type section.

The age of the Eramosa Formation is not clear, but evidence suggests a Late Wenlock or Early Ludlow age. Berry and Boucot (1970) assign it a Ludlovian age. LoDuca and Brett (1991) suggest an Early Ludlow age for the lower member of the

underlying Goat Island Formation, but the graptolite data they use are somewhat uncertain (LoDuca, pers. comm. 2000). Kleffner (1991), using conodont data, assigned a Wenlock age to the Eramosa, but it may be that his "Eramosa" samples came from the upper member of the underlying Goat Island formation (which had been improperly designated as Eramosa by Zenger 1965). Using the same conodont data, Brett et al (1995), assign a Ludlow age to the Eramosa. Resampling based on the newly revised stratigraphy again suggested a Homerican (late Wenlock) age (Kleffner, pers. comm. 2000), although there is still a large amount of uncertainty with interpreting a conodont fauna that is dominated by long-ranging and endemic species. Conodont samples taken from the Eramosa in the Bruce Peninsula region have thus far revealed only non-diagnostic cones (Uyeno, pers. comm. 2000). Within the *Lagerstätte* described in this study, the complex dasyclad alga *Palmatophycus* was found. The only other occurrence of *Palmatophycus* is within the Motol Beds of the Czech Republic (Boucek 1942). This unit is Wenlock in age, but so little is known about the temporal distribution of non-calcified dasyclads (because they are so rarely preserved), that their dating potential is unknown. Conflicting conodont data and the absence of diagnostic graptoloid graptolites in the Eramosa mean that the unit can only be assigned a Late Wenlock-Early Ludlow age

The Eramosa Formation in the southern Bruce region

Previous interpretations of the Guelph Formation (which included the Eramosa as a member) in the Bruce Peninsula divided the rocks into three main

lithofacies: a biohermal facies which is present throughout the thickness of both the Eramosa and Guelph, a lower bituminous inter-biohermal unit (the classic "Eramosa"), and an upper non-biohermal Guelph unit (Liberty and Bolton 1971; Armstrong and Meadows 1988). The biohermal facies can be observed at numerous locations throughout the outcrop belt throughout the region (Figure 4); however, due to the discontinuous nature of outcrops, destruction of possibly diagnostic fossils by intense dolomitization, recurring temporally and laterally discontinuous lithologies, and the highly undulatory nature of the reef-interreef topographies, workers have often been unable to assign specific bioherms to any of the Amabel, Eramosa, or Guelph Formations. The paleo-topography, and thus sedimentation patterns, during Eramosa deposition was strongly affected by earlier Amabel bioherms, many of which were probably the site of continued patch reef development throughout the deposition of the Eramosa, and possibly into the Guelph (Figure 5). Variation from outcrop to outcrop, and the complex interplay of sedimentation patterns between the numerous reefs (both active and temporarily subaerial, inactive examples) and interreef regions makes a composite stratigraphic section representing the Eramosa impossible.

One of the larger reefs exposed in section can be seen in a roadcut at the intersection of Highway 6/10 and Grey Road 18 at Rockford (Figure 6). Although this example is probably upper Amabel, it is representative of the type of reef morphology common throughout the Amabel, Eramosa and Guelph sequences. Within this particular exposure, dolomitization is less intense than in most other examples, and thus the nature of the reef-structure can be observed. The reef core consists of a

Figure 4. Guelph, Eramosa and Amabel Formation lithofacies distribution on the Bruce Peninsula. (modified after Armstrong and Goodman 1990)

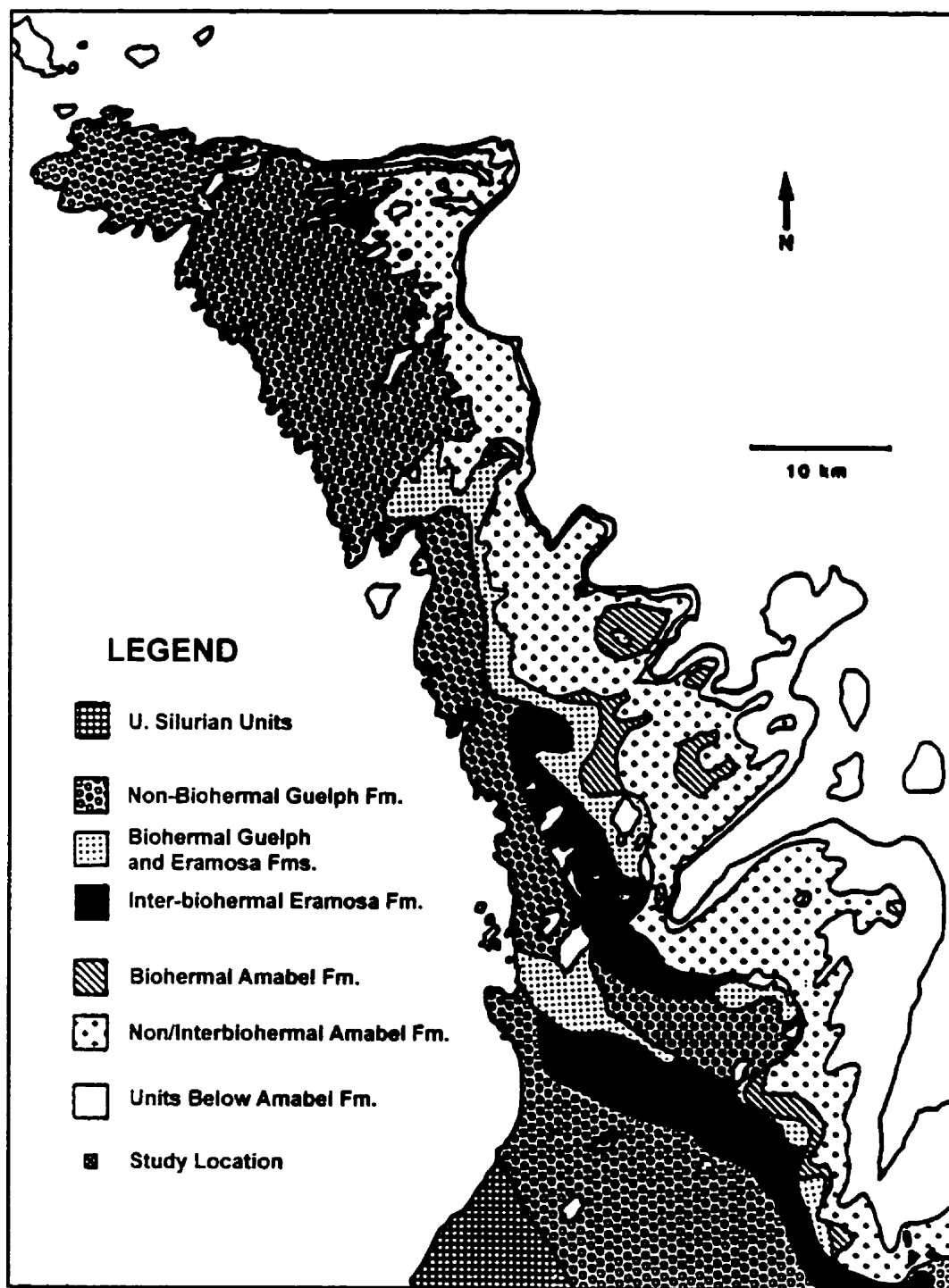
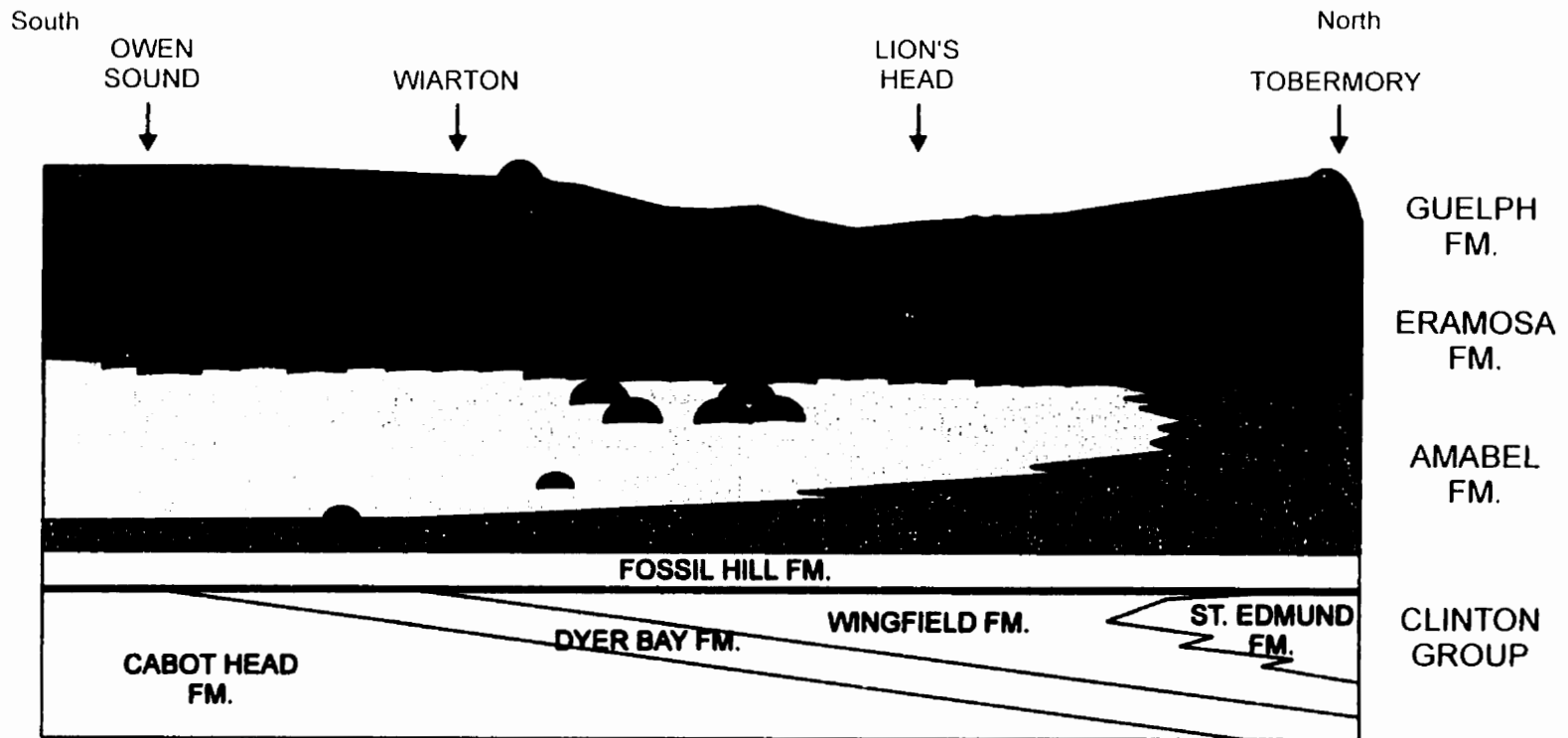








Figure 5. Schematic stratigraphic cross-section of the Clinton and Lockport Group formations on the Bruce Peninsula. (modified after Armstrong and Goodman 1990)




Amabel Fm. Lithofacies

-  Biohermal
-  Non-Biohermal (Wiarton/Colpoy Bay member.)
-  Non-Biohermal (Lions Head Mb.)

Guelph and Eramosa Fms. Lithofacies

-  Biohermal Guelph and Eramosa Fm.
-  Non-Biohermal Guelph Fm.
-  Inter-Biohermal Eramosa Fm.

 Ledgerrock Quarry Section

after Armstrong and Goodman 1990

Figure 6. Roadcut exposure of an upper Amabel reef at the intersection of Highway 6 10 and Grey Road 18 at Rockford, Ontario.



massive coral-stromatoporoid framework (Figure 7a), often with rather large, broken and overturned coral heads. The reef flanks consist of bedded crinoidal grainstones (Figure 7b). An example of an underlying reef with only the top exhumed can be seen just west of Owen Sound, approximately a kilometer north of the intersection of Highway 6/21 and Highway 6/70 (Figure 8).

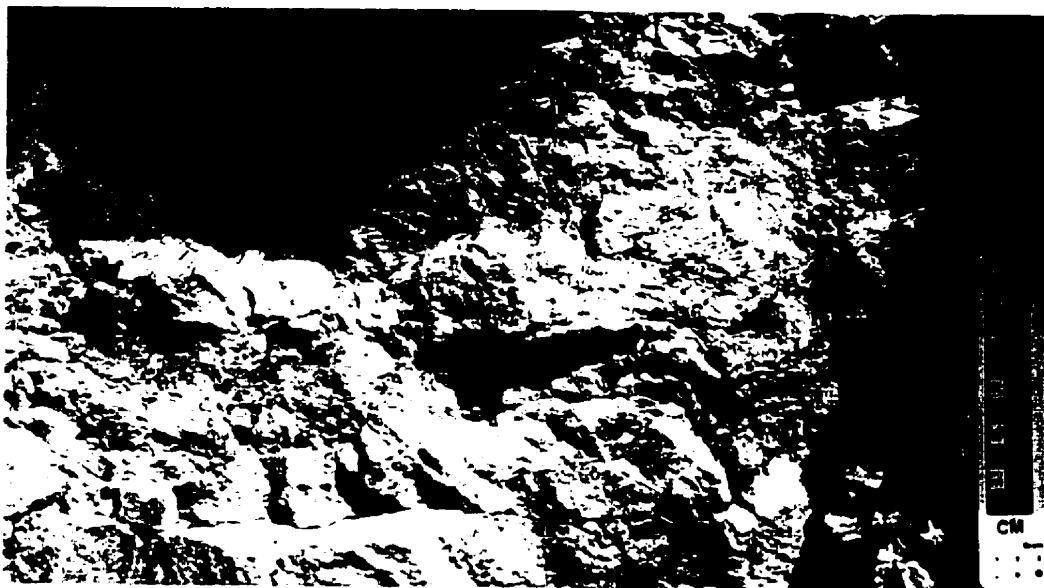
To the north of the study area, numerous distinct reef "ridges", on the order of 10 m wide and 100 m long, occur within the Eramosa. These have, in places, been exhumed by erosion and are clearly visible on both aerial photographs (Figure 9, intersection of Highway 6 and Albemarle Section Road 5) and 1:50,000 scale topographic maps. They trend northwest-southeast (glacial erosion features in the region trend northeast-southwest) and continue south into the study area. If shallow enough, these closely packed ridges would have served to greatly reduce water flow between the numerous interreef lagoons during the Silurian.

The Owen Sound Ledgerock Ltd. Wiarton Quarry lies almost entirely within the Eramosa Formation (Figure 5). Though no one location exposes the entire Eramosa, a simplified composite section (Figure 10) has an total approximate thickness of 15 meters. The Eramosa - Amabel contact is not exposed in the area. The Guelph - Eramosa contact shows a marked change from very dark brown, fine-grained, laminated dolostone to a coarse grained, light tan, relatively porous, blocky dolostone. Previous workers have subdivided the section into one Guelph unit and four distinctive Eramosa subunits (lithofacies as described by Armstrong (1988); Armstrong & Meadows (1988); and Armstrong & Goodman (1990).

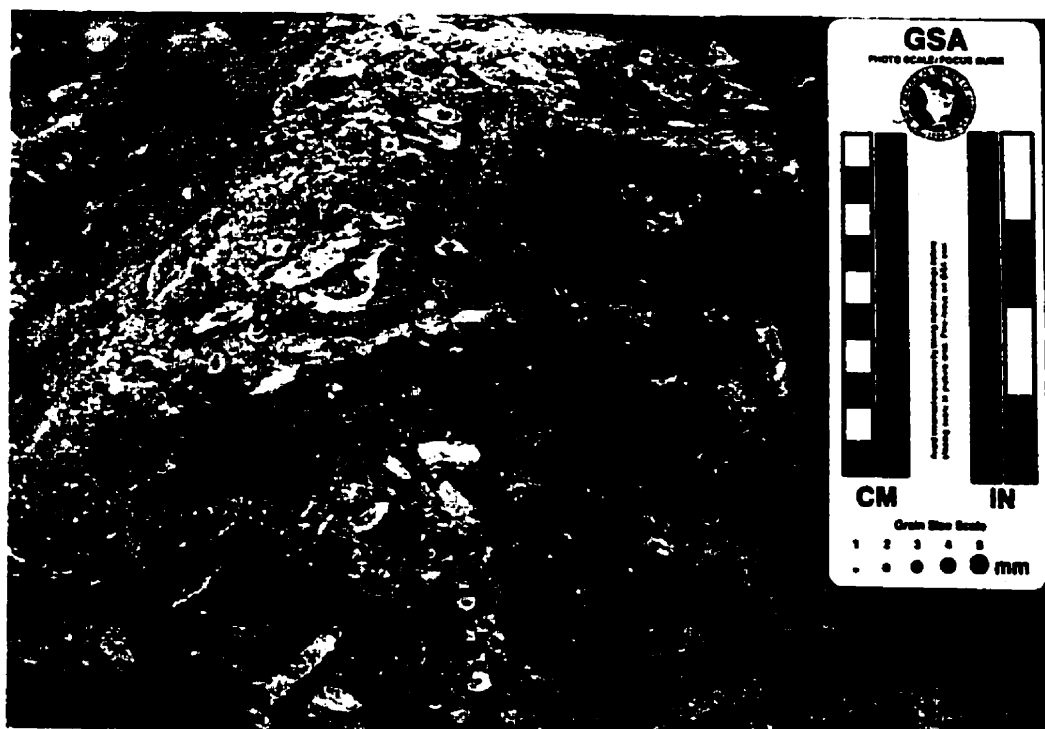
Figure 7. Biofacies of an upper Amabel reef exposure at the intersection of Highway 6-10 and Grey Road 18 at Rockford, Ontario.

A. Large overturned *Favosites* coral from the coral-stromatoporoid reef core.

B. Crinoid grainstones of the reef flanking beds.



A



B

Figure 8. Partially exhumed reef top, 1 km north of the intersection of Highway 6/21 and Highway 6/70, just west of Owen Sound, Ontario.



Figure 9. Airphoto showing northwest-southeast trending reef ridges within the Eramosa Formation, intersection of Highway 6 and Albemarle Section Road 5, northwest of Warton, Ontario.

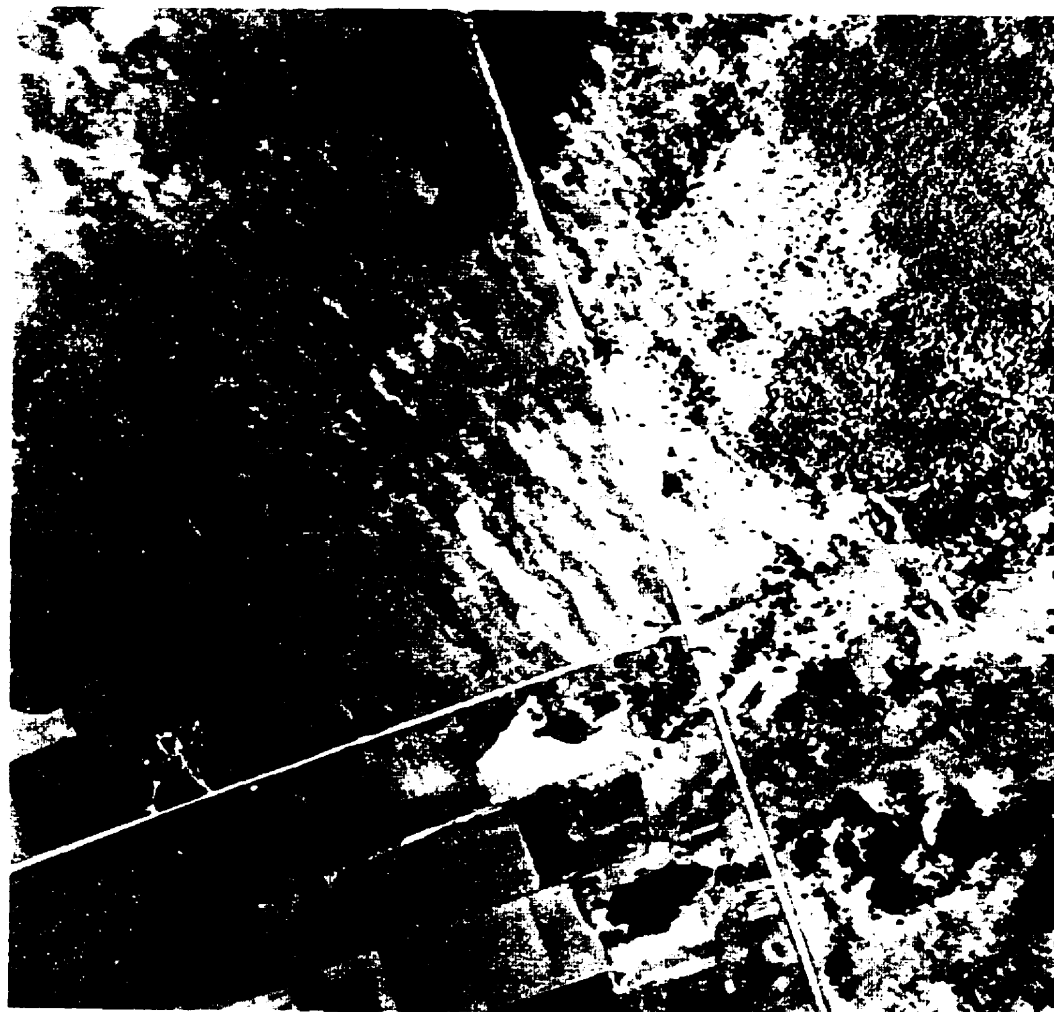
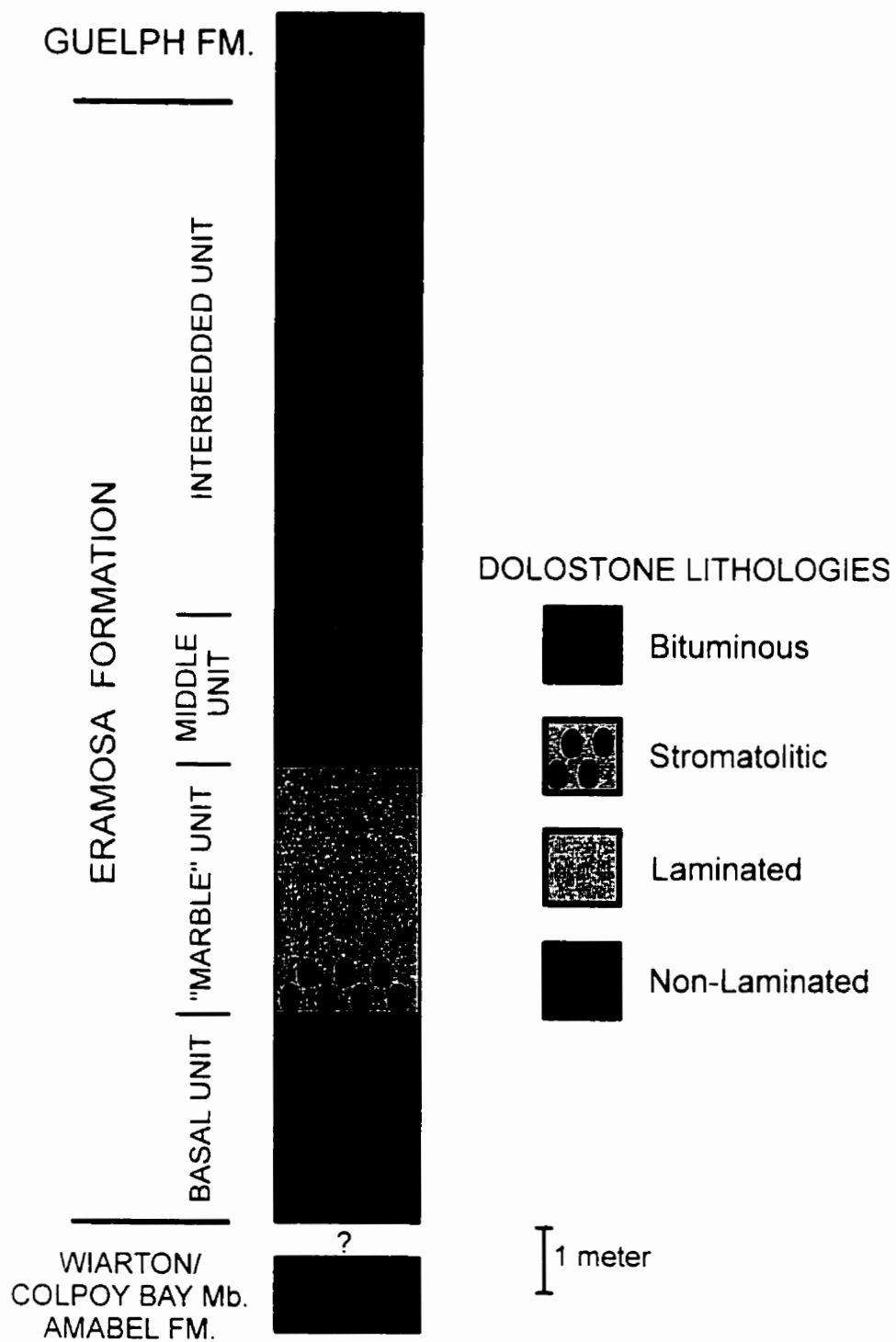


Figure 10. Composite stratigraphic section of the Eramosa Formation in the study area. (modified after Armstrong and Meadows 1988)



after Armstrong and Meadows 1988

Guelph Dolostone

"Guelph Formation Upper Unit" of Armstrong - moderate to thick bedded (10 to 30 cm) light tan to brown, fine- to medium-crystalline dolostone; sparsely to moderately fossiliferous; fossils are generally moldic echinoderm fragments, brachiopods, corals, bryozoans, stromatoporoids (~ 3 meters). Lower contact gradational over several centimeters into dark, laminated dolostone.

Eramosa Dolostone

Interbedded Unit - dark grey-brown to black, laminated & unlaminated bituminous dolostones interbedded with unlaminated and less-bituminous beds; nodules and extensive sheet-like masses of chert seen; particularly prominent in a few thin intervals within the upper part of the subunit; diverse fossil content (~7-9 meters)

Middle Unit - unlaminated, medium-bedded, tan-coloured dolostones (~1-2 meters, thinner on the west side of the quarry, but apparently thickening to the east)

"Marble" Unit - dark, laminated, moderately bituminous dolostones; some exposures towards south of quarry show development of stromatolitic (LLH) beds and fenestral textures in lower meter (~3.5 metres)

Basal Unit - unlaminated, medium-bedded, tan coloured dolostones, calcite filled fractures (~3 metres)

The lower contact of the Eramosa Dolostone with the Amabel is not exposed anywhere within the quarries.

Exposures in the Ledgerrock quarries property occur in three main areas. The main pit south of Oliphant Road is the largest exposure areally, and exposes rocks from the LLH bed at the base of the "Marble" Unit (seen when water in the pit is low) up to the basal 2.5 meters of the Interbedded Unit. Much of the extraordinary fauna collected for this study occurs in the base of the Interbedded Unit. Immediately north of Oliphant Road, along an access road, is a smaller pit exposing approximately 3.5 meters within the Interbedded Unit. At the end of the 600 m long access road, a third pit exposes the upper one-meter of the Interbedded Unit and approximately 3 meters of the overlying Guelph Formation. The contact between the dark laminated dolostones of the Eramosa, and the massive, tan, sugary dolostone of the Guelph appears to be gradational over several centimeters.

Local microstratigraphy by the use of Ground Penetrating radar

Due to the very irregular paleo-topography, the local strata is highly undulatory and variable over distance, making the tracing of beds between the three pit exposures impossible. Underlying reef ridges (some of which may have even been subaerially exposed periodically during the Silurian) and onlapping swale beds extend out into the lagoons. Planar and continuous bedding surfaces change in sedimentary, faunal and taphonomic characteristics over only tens of metres. In an attempt to link the sections exposed in the three Warton pits, Ground Penetrating Radar (GPR) was used to image the subsurface.

An early attempt at resolving the stratigraphy of carbonates using GPR (Pratt and Miall 1993) met with limited success, chiefly because previous GPR studies equipment were carried out by less sensitive or sophisticated equipment. Generally, the use of GPR to resolve bedrock stratigraphy in this manner is an untried and novel technique. GPR tends to have rather shallow penetration in most types of bedrock, and thus perceived to be not very useful for stratigraphic problems. GPR has most often been used to resolve stratigraphic relationships in unconsolidated sediments where there are great differences in subsurface composition. As the study area consists of an all-dolostone stratigraphy, expectations were not great.

Ground penetrating radar exploits the wave propagation characteristics of electromagnetic fields, and in many respects resembles more commonly used seismic reflection techniques. The frequencies used in GPR are much higher than used in seismic studies, and thus the resolution is much higher, although penetration is relatively shallow. Typically frequencies from 50 to 1000 MHz are used, enabling resolutions of tens of meters to tens of centimeters. The equipment uses a dipole antenna, Tx (the transmitter) and Rx (the receiver), both identical and interchangeable. The electrical conductivity of the host material controls depth of penetration. Depth penetration also decreases with higher frequencies. The EM wave is both reflected and refracted by changes in electrical character between the reflector and the surrounding host material. Even very minor changes in material composition or water content give rise to changes in electromagnetic impedance which, in turn, cause radar reflections. Data are converted from analog to digital and stored on a laptop. Modern GPR equipment permits the operator to watch as data are collected.

enabling decisions to be made in the field, an advantage not normally enjoyed in geophysical data collection. For a more comprehensive introduction to the principles behind GPR, see a review article by Annan and Davis (1997).

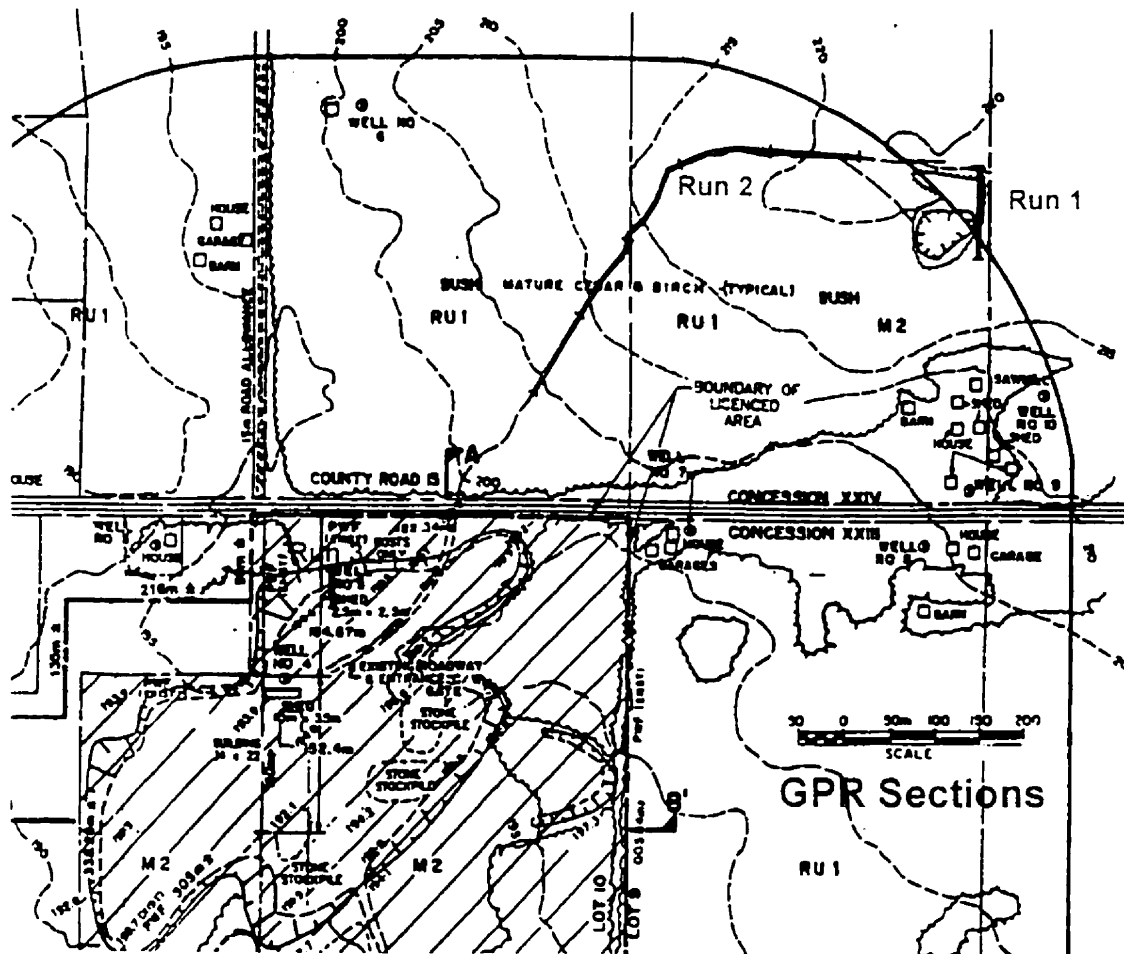
The GPR equipment used in this study was a PulseEKKO 100, produced by Sensors & Software Inc. (Figure 11). Three runs were completed around the Wiarton quarries of Owen Sound Ledgerrock. Run 1 was a 100m line perpendicular to slope in the northern pit, Run 2 was a 500m line along the north pit access road, and Run 3 was a 33m line next to a topographic high on the north side of the south (main) pit (Figure 12). A Common Mid Point survey was performed at the location of Run 1 to acquire velocity vs depth data. For the main runs, data points were 25 cm apart, and the operating frequency was 100 MHz. The topographic profile of the run paths were surveyed using a bubble level, so that elevation corrections could be made to the section profile. Data processing was performed by J. Hope using seismic analysis techniques - filtering, AEC gain processing, and topographic correction. Migration analysis was also performed, however it had negligible effect on the data.

The results exceeded expectations. Penetration depth was greater than anticipated, reaching 12 to 18 meters, and was limited only by the time window selected during program setup. A greater depth of penetration could have been possible with a longer time window. Numerous prominent horizontal reflectors traced quite clearly across the sample sections likely represent variations in water content (and hence electromagnetic impedance) within the rock. Water content, being a proxy for porosity, probably reflects the lithologic alternation between fine grained

Figure 11. The PulseEKKO 100 Ground Penetrating Radar equipment in the field.



Figure 12. Locations for GPR Runs 1, 2 and 3 in the Owen Sound Ledgerock Inc.
Warton Quarries.



laminated dolostone, and more porous, thick-bedded dolostone beds generated during storm events. Vertical joints can also be picked out using stacked hyperbolic reflections.

Run 1 shows a 100 meter transect extending from an present day elevated ridge, down a decreasing slope to almost horizontal bedding (Figure 13). Bedding tends to thin downslope in the upper portions of the section, while beds in the deeper half of the section appear to abut a large, unbedded structure (Figure 14).

Examination of the upper 3 meters, which are exposed within the pit wall, shows that the thinning beds are graded debris flows containing corals, brachiopods and rip-up clasts from the underlying laminated beds (Figure 15). The large massive structure is likely a buried reef ridge that, once submerged by rising sea level, became a site of rejuvenated reef growth. The main portion of the reef was removed by recent erosion, leaving the flanking beds as a ridge. A large displaced block approximately 1½ m by 5 m in size, apparently dislodged from the reef core and containing intergrown and oriented corals and stromatoporoids, lies within the lowermost Guelph beds, evidence of the presence of an actively growing reef adjacent to the present-day exposure.

Run 2 is a 500 meter long section along the road connecting the two pits north of Oliphant Road (Figure 16). The bedding in the southwestern half of the section tends to be horizontal and fairly consistent in thickness. In several places, bedding is draped over structures which appear to originate below the visible section, and may represent paleotopography of the original sea floor. Bedding begins to slope up and thicken towards the northeastern part of the section as one approaches the possible

Figure 13. Raw data for GPR Run 1, 100m in length, north pit of the Wiarton quarry.
Elevations in meters.

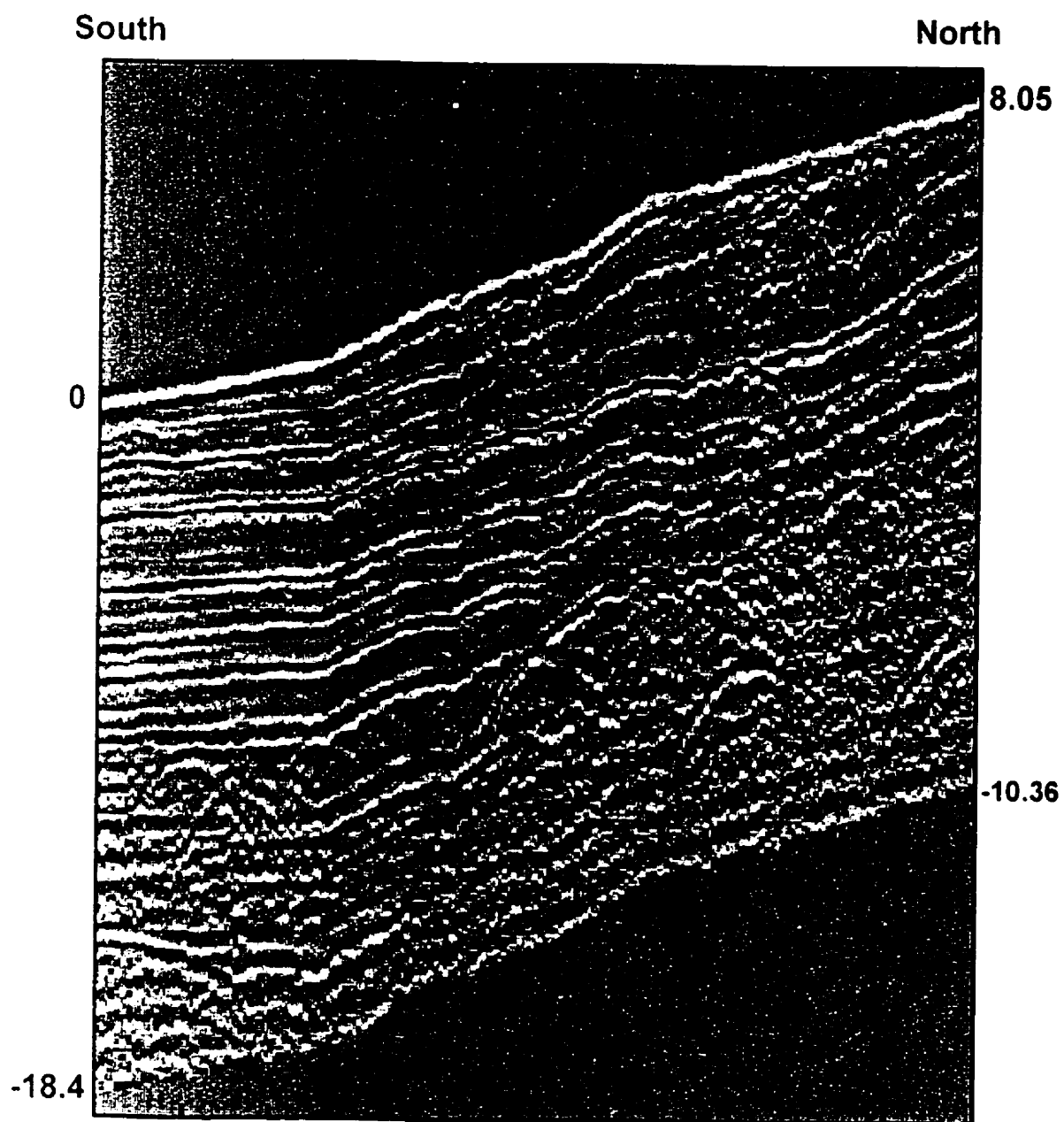


Figure 14. Interpreted data for GPR Run 1, north pit of the Warton quarry. Red - horizontal bedding surfaces, blue - vertical joints, orange - inferred buried reef. Elevations in meters.

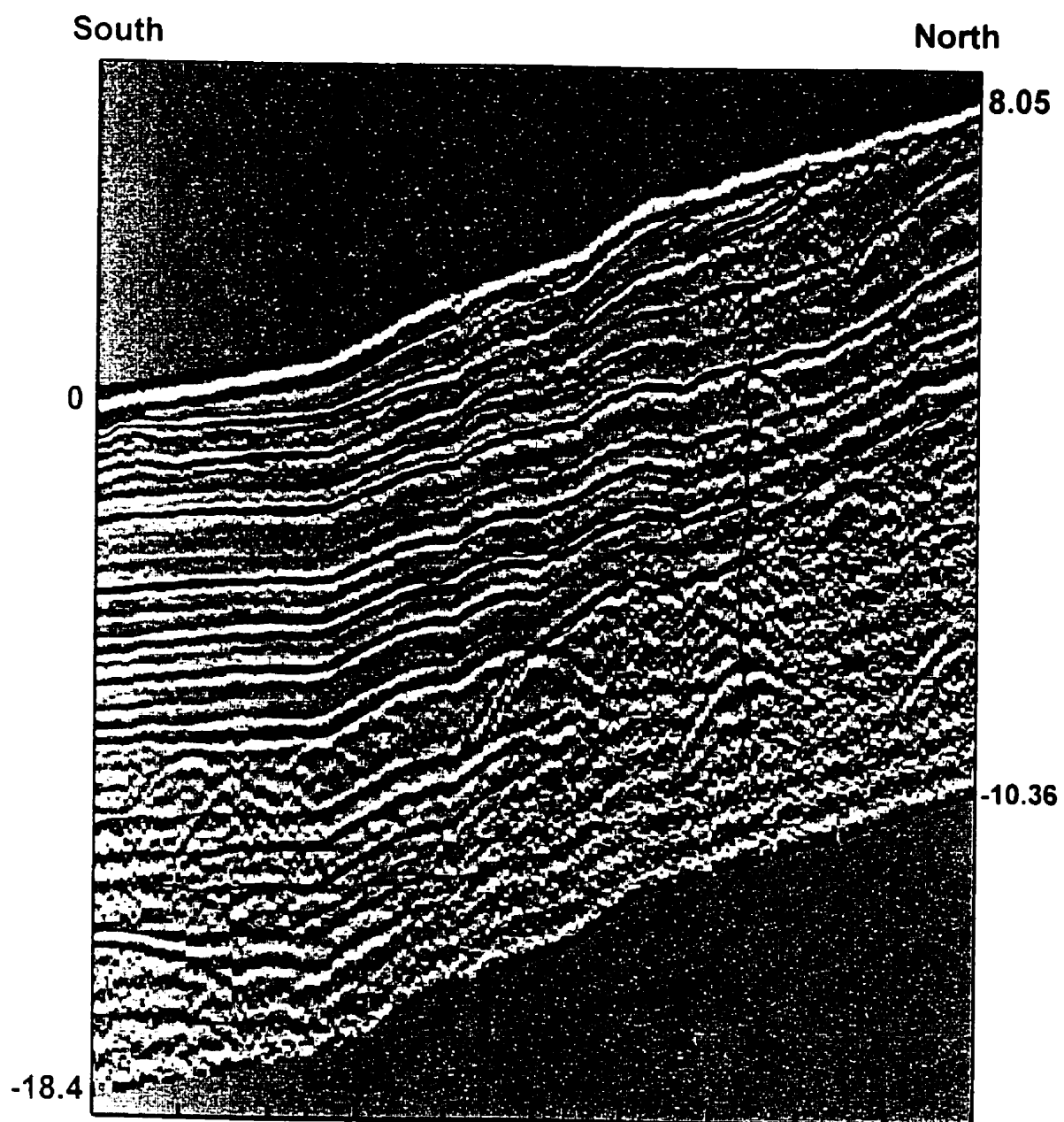
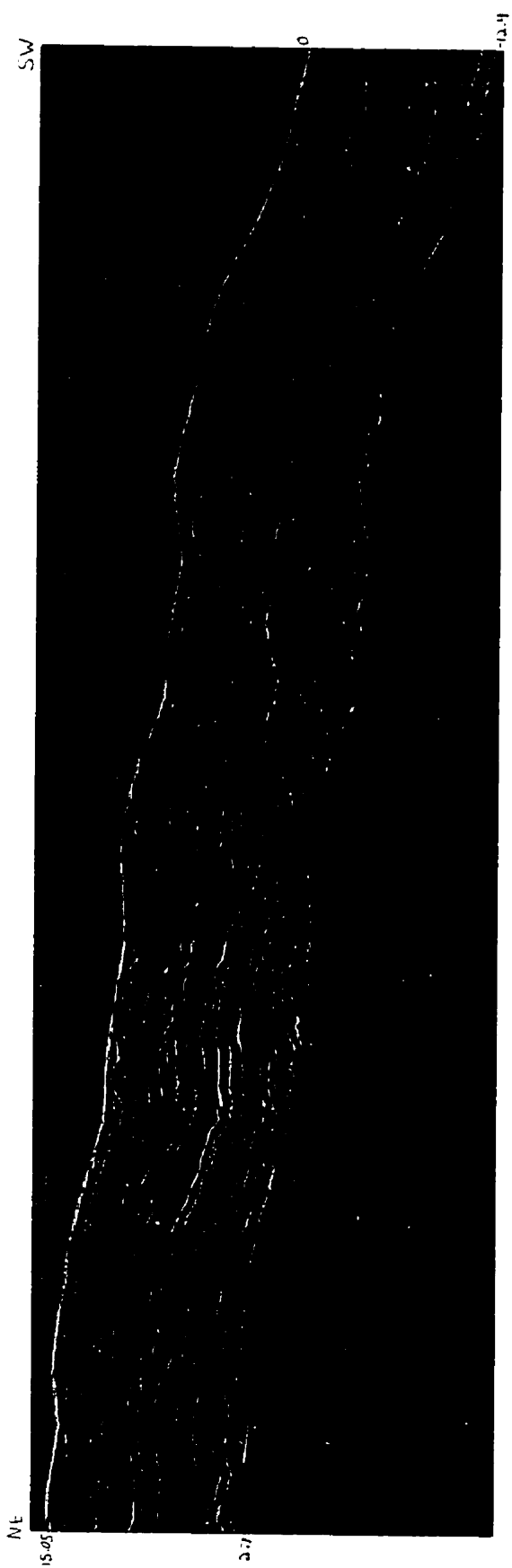


Figure 15. Debris flows, uppermost Eramosa Formation, north pit of the Warton quarry. Scale bar is sitting on the Eramosa - Guelph contact.



Figure 16. Raw data for GPR Run 2, 500m long, along north pit access road, Wiarton quarry. Elevations in meters.



reef structure described earlier. Numerous joints, only some of which have been traced, are visible along the section. This long section also enables the stratigraphy of the two quarries to be correlated (Figure 17).

Run 3 is a 33.5 meter transect on the northern margin of the main pit south of Oliphant Road (Figure 18). Part of the *Lagerstätte* biota lies adjacent to a topographic rise, against which the uppermost beds can be seen pinching out. Unfortunately this rise was buried by a thick berm (required by the Ontario Pits and Quarries Act to surround the property). The location of this transect just west of the berm was chosen in an attempt to image the edge of this structure. Unfortunately data acquisition in this run was extremely poor, possibly due to excessive water, and nothing useful can be seen in the resulting section.

On the whole, GPR imaging of the study area proved quite successful, with excellent depth penetration and surprisingly high bed resolution. Stratigraphic changes over both vertical and horizontal distance indicate the presence of a paleotopography representing multiple adjacent lagoons separated by small rises, some of which were probably reefs, others being older lithified sediments draped over buried reefs lower in the section. While many Silurian *Konservat-Lagerstätten* have been postulated to have been deposited in a lagoonal setting and often associated with nearby reefs (Kluessendorf 1994, LoDuca 1995), this is perhaps the first direct evidence for such a paleogeographic setting. Debris flows at the top of the Eramosa, described below in more detail, indicate that some of these rises were the site of active reef growth. With further section runs perpendicular to each other, a three dimensional image of the local stratigraphy to a depth of 20 meters could be

Figure 17. Interpreted data for GPR Run 2, 500m long, along north pit access road.
Wiarion quarry. Red - horizontal bedding surfaces, blue - vertical joints.
Elevations in meters.

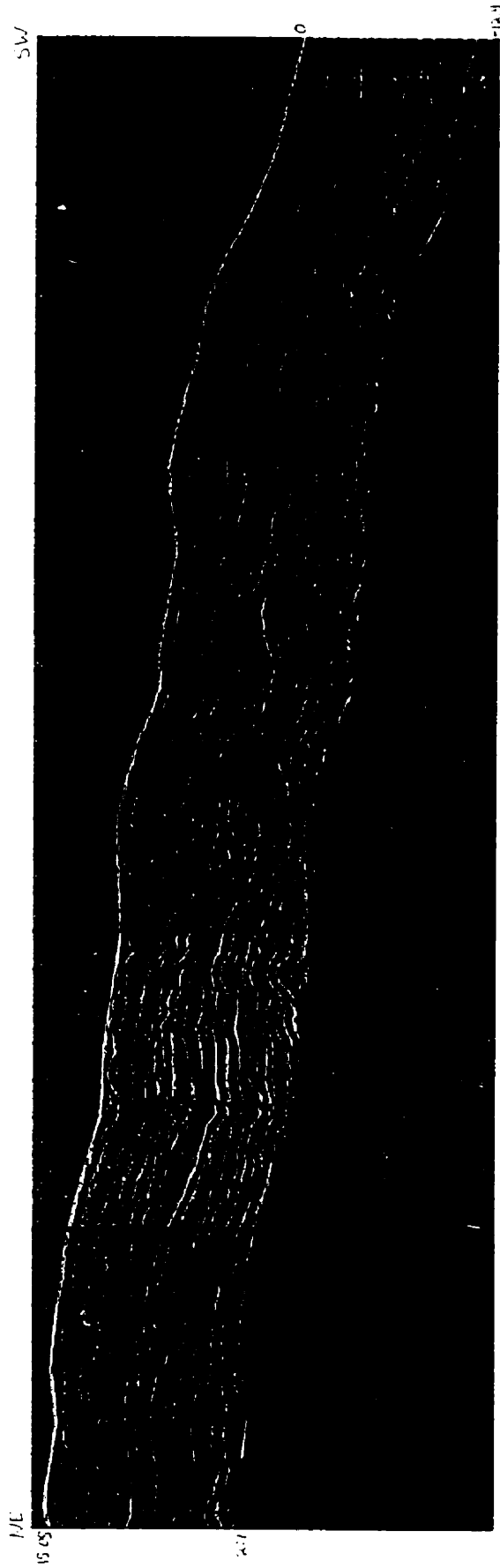
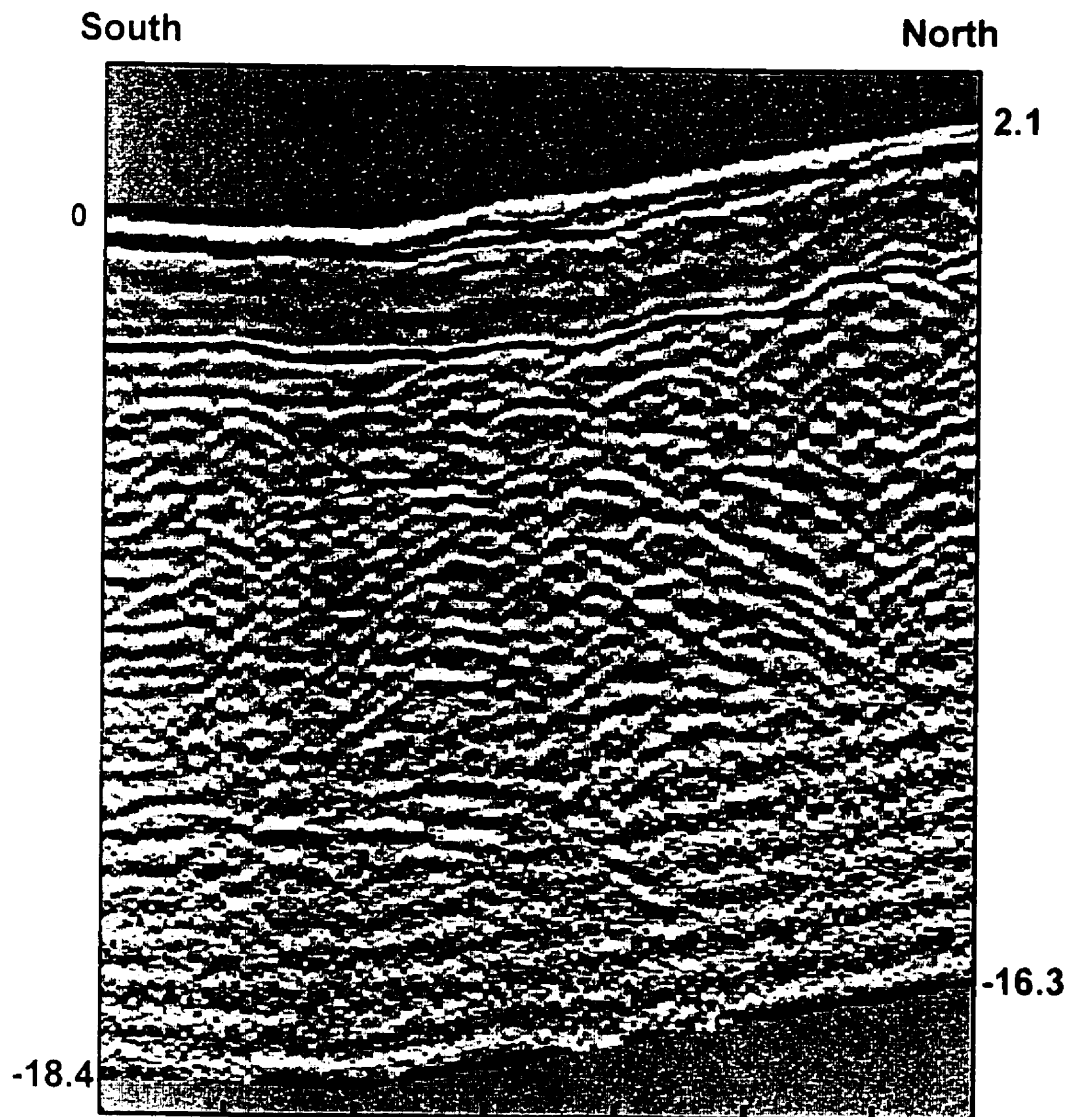


Figure 18. Raw data for GPR Run 3, 33.5m long, south (main) pit of the Wiar-ton quarry. Elevations in meters.



produced. Furthermore, using the GPR data to select optimum sites, drilling with core recovery is being planned for the property. Using core as a reference, specific lithology types can be assigned to individual reflectors and traced across the quarry property.

The success of this new technique shows the usefulness of GPR, not only in the imaging of near surface reefs, but also the resolution of complex small-scale stratigraphic features that are not in regions with conveniently exposed sections, or in dimensions other than what is visible, enabling researchers to "create their own roadcut". From a commercial viewpoint, this technique also has proven quite useful. Finished-stone quarries such as Owen Sound Ledgerock require specific stone types, and unfocussed excavating of poorly bedded rock is a significant waste of resources. GPR imaging has shown which areas have suitable rock, and at what depth. Natural joints and fractures are used to aid the excavation process, and these also can be located using the GPR data.

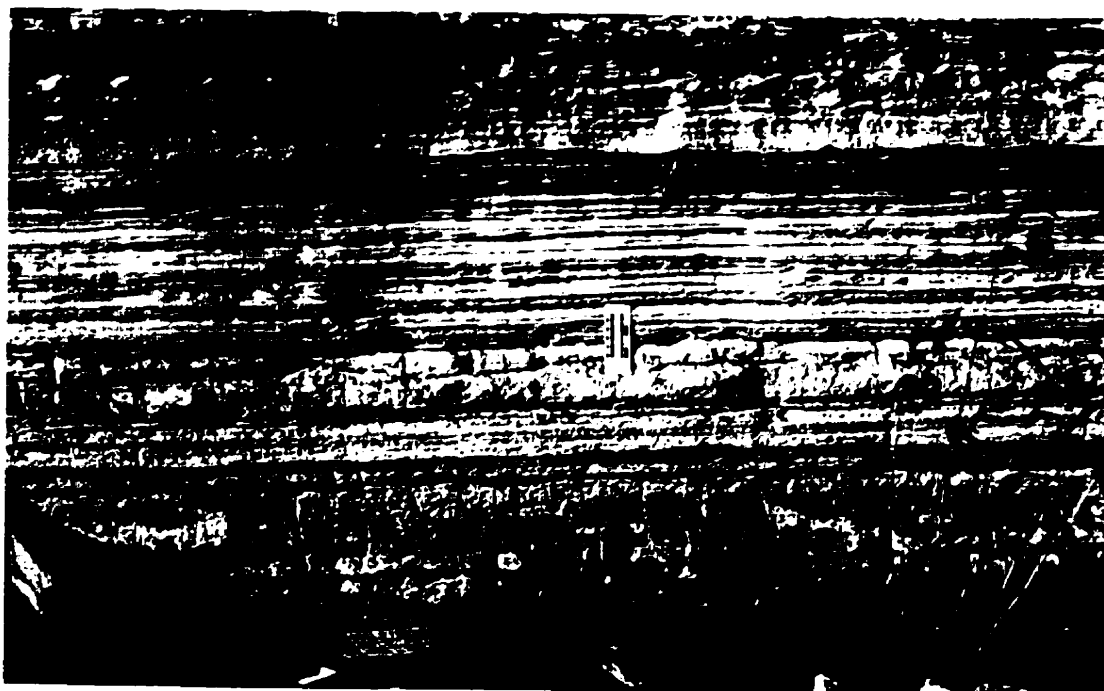
Lithology and Sedimentology

Deposition and Diagenesis

The Eramosa is composed chiefly of fine-grained dolostones that vary in nature from the medium brown-colored, very regularly laminated "Marble Unit", to the dark, organic rich laminated dolostones interbedded with lighter, non-laminated dolostones of the "Interbedded Unit". Particularly within the Interbedded Unit, the lithology alternates between dark laminated beds and lighter non-laminated beds at a cm, decimeter and meter scale (Figure 19 a, b). The Eramosa is also characterized by its high pyrobitumen content (TOC of 0.04-2.01% - Tworo, 1985, cited in Armstrong and Goodman 1980). Although the Eramosa has been identified as a potential source rock for Michigan Basin hydrocarbons, TOC's in exposed units here are below extractable limits.

Local topographic highs (as observed both in outcrop and in the GPR survey) were, at varying times, completely submerged (overlying beds are continuous, though may show some thinning) and may have been periodically subaerially exposed, with the overlying strata onlapping onto a corrosion surface (Figure 20). The intervening lagoons were periodically isolated from the open sea during low sea stands (possibly corresponding to periods of salt deposition within the basin), as evidenced by the presence of karstic surfaces (Figure 21), syn-sedimentary reticulate salt structures (Figure 22 a,b), and mudcracks (Figure 23).

Figure 19 a, b. Examples of alternating dark, laminated bedding and light-colored storm beds within the dolostones of the Interbedded Unit, Eramosa Formation, south (main) pit of the Warton Quarry.



A



B

Figure 20. Dark, laminated beds of the Interbedded Unit, Eramosa Formation.

onlapping the corrosion surface of a paleotopographic high, south (main) pit of the Wiarton quarry. (Note: this area of the quarry is currently buried by ongoing quarry operations)

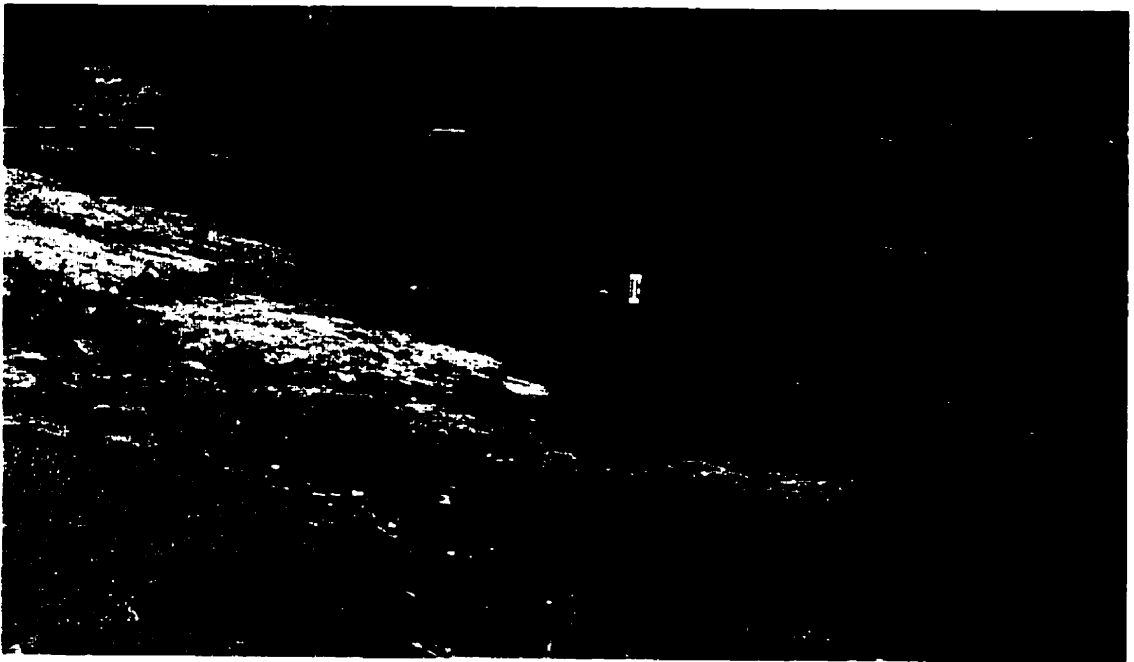


Figure 21. Contact between karstic surface and overlying bed, showing clay and interclast accumulation in depressions.

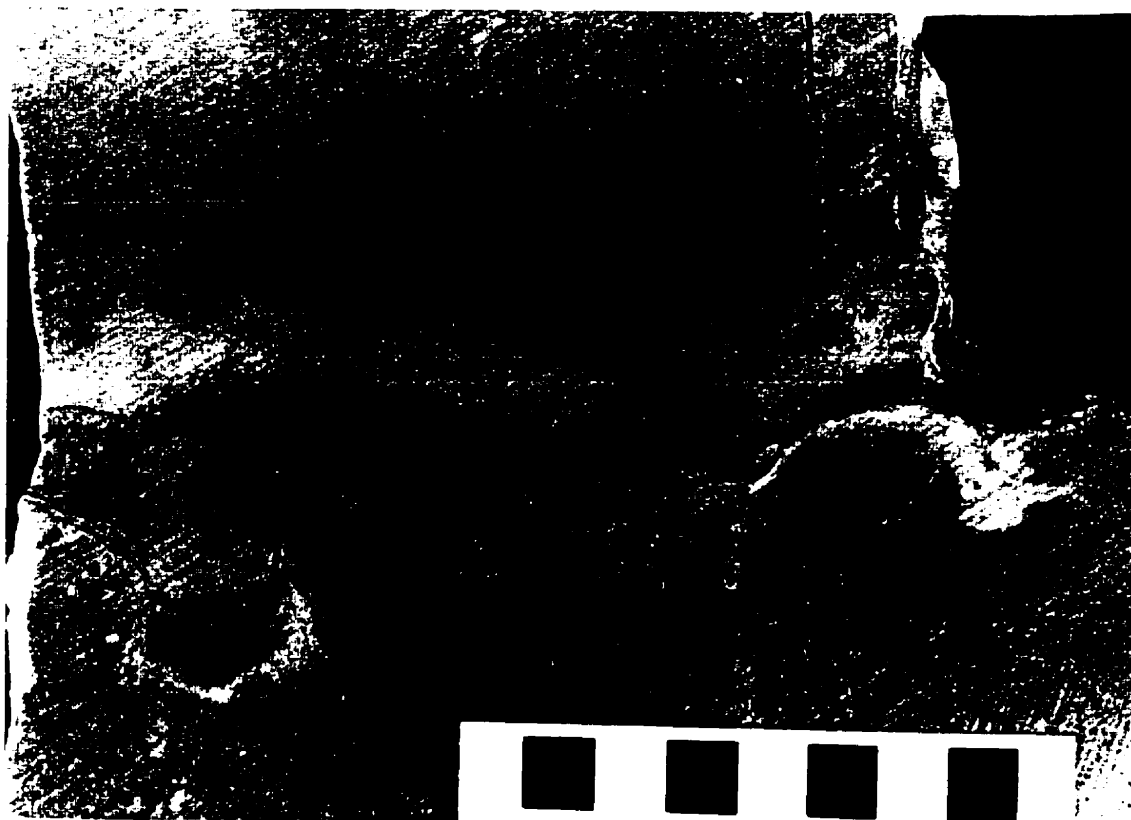


Figure 22 a,b. Two different styles of syn-sedimentary reticulate salt structures on bedding surfaces from the Eramosa Dolostone, Wiarion quarry.

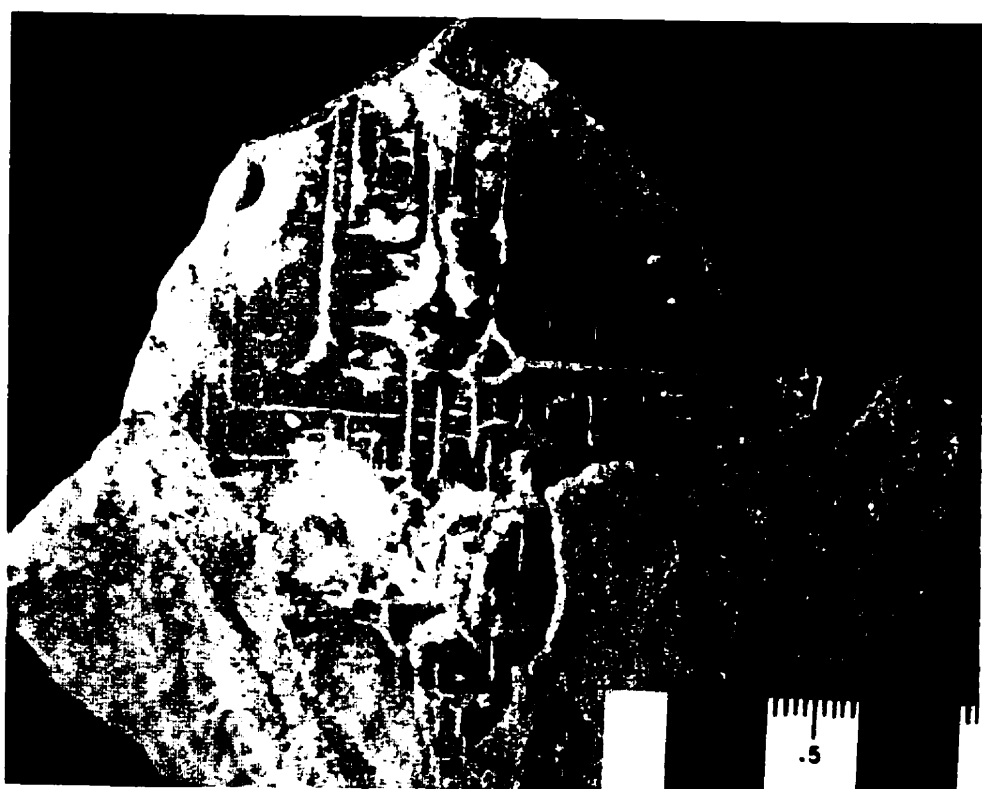
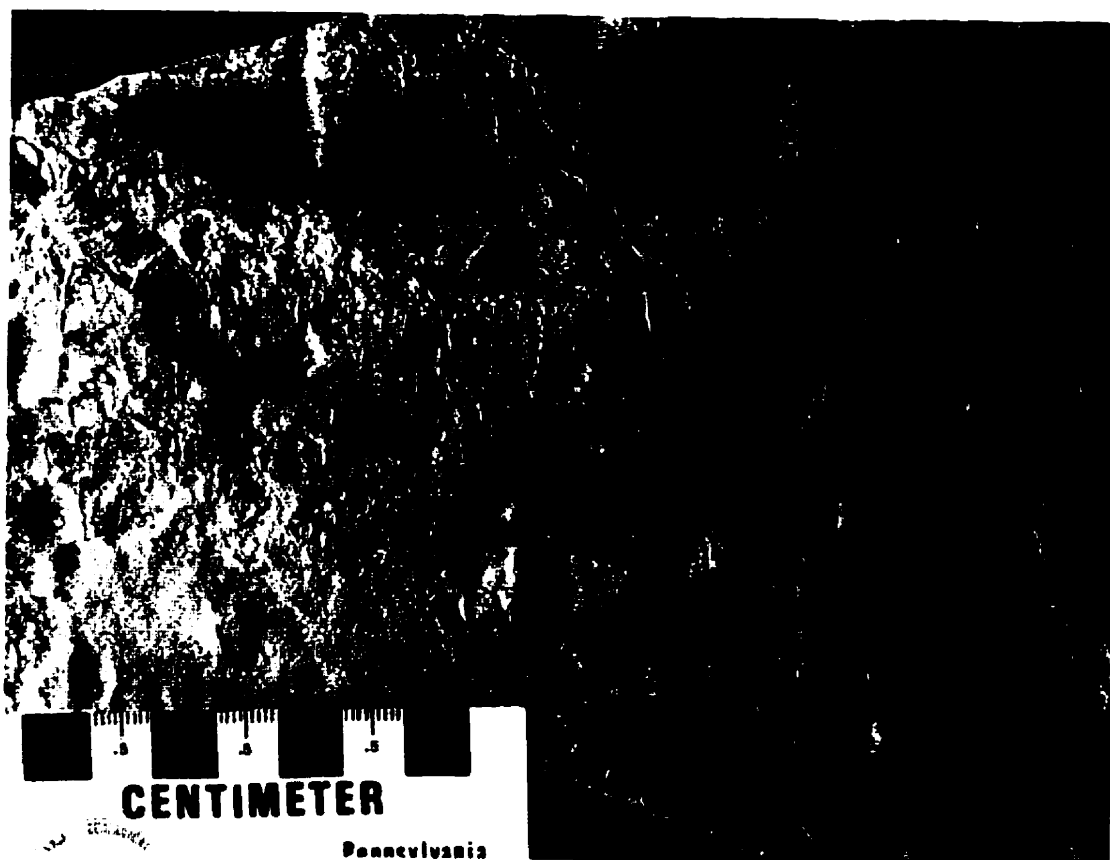
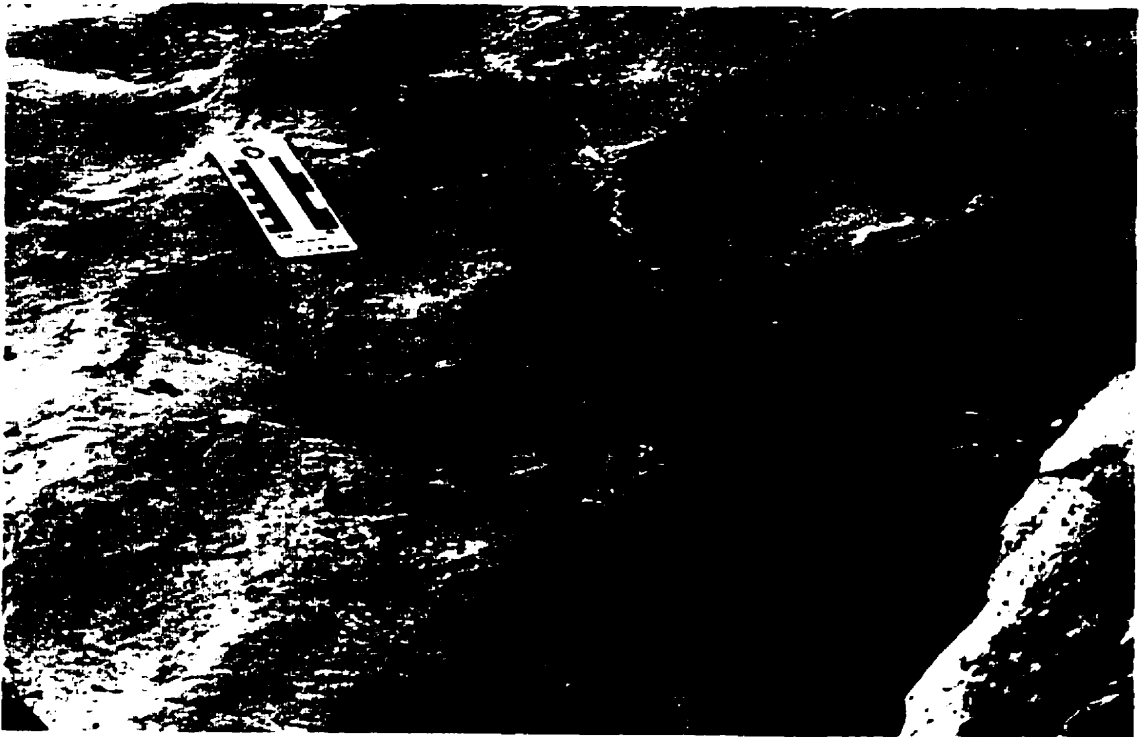


Figure 23. Desiccation polygons in algal mat material, some edges showing curling.
South (main) pit, Wiarton Quarry.

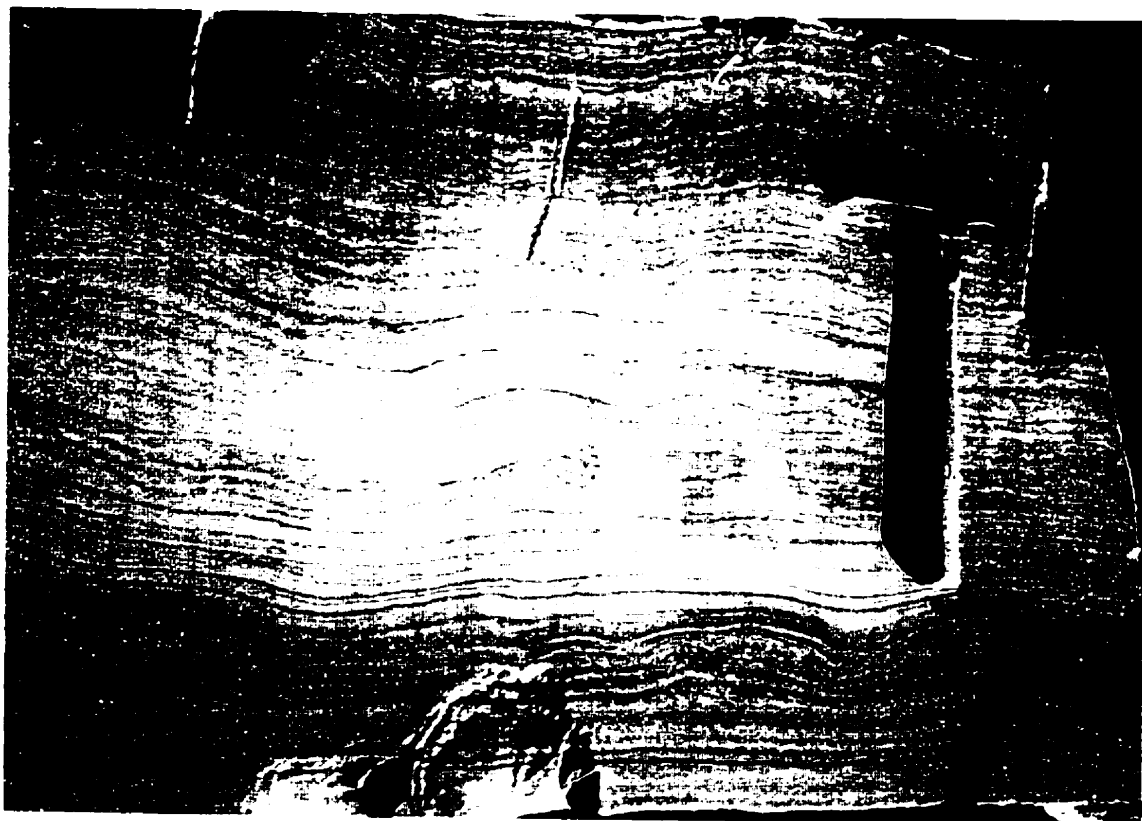


The origin of dolostone is an often-debated problem, and the answer, particularly for the Eramosa, is probably a variety of sources. Numerous patch reefs throughout the area, some of which were likely actively growing, can produce carbonate silt by the physical breakdown of the skeletons of organisms such as corals, stromatoporoids, crinoids and brachiopods. This may account for some of the carbonate brought in during storms and deposited as carbonate silt. The breakdown of the skeletons of calcareous algae, common within modern shallow water carbonate environments, can provide large amounts of carbonate. Both these sources supply calcite, rather than dolomite. Dolomitization can occur by evaporative reflux of marine waters (Deffeyes et al. 1965, Blatt et al. 1980) during times of low sea levels and subaerial exposure. The higher porosity of some of the dolostone beds, and the euhedral nature of dolomite grains as seen in thin section, may be evidence for the conversion of calcite and aragonite to dolomite. Dolomitization also resulted in vug-producing dissolution of fossils. Later stages of diagenesis produced fracture-filling calcite deposition.

High percentages of dolomite within modern marine carbonate environments can be deposited directly as detrital grains (Al-Bakri et al. 1984). Subaerial exposure of pre-existing dolostones within and adjacent to the study area (the dominant lithology throughout the region) could provide a source for these detrital grains.

Carbonate was also possibly deposited directly as an algal or cyanobacterial precipitate. Carbonate laminae of the "Marble" Unit grade directly into laterally-linked hemispherical (LLH) stromatolites (Figure 24). These small domal structures

Figure 24. Laterally linked hemispherical (LLH) stromatolites, near the base of the "Marble" Unit, Eramosa Formation, South (main) pit, Warton quarry.



appear to have intergrown directly with (now dissolved) gypsum crystals of a few millimeters in size. The salinity of the lagoon at that time may have been high enough for dolomite to precipitate directly.

Nature of Laminations

Throughout the unit there is ample evidence of sediment-laden microbial mats. Spectacular "crinkled" beds (Figure 25) characteristic of the cohesive properties of microbially bound sediments (Schieber 1999) appear to represent the disturbance of the uppermost, non-lithified layers of microbial mats by waves. Fragmented and redeposited laminae, often with an overlying layer of carbonate mud (Figure 26) represent the disturbance of partially lithified mats during storm events.

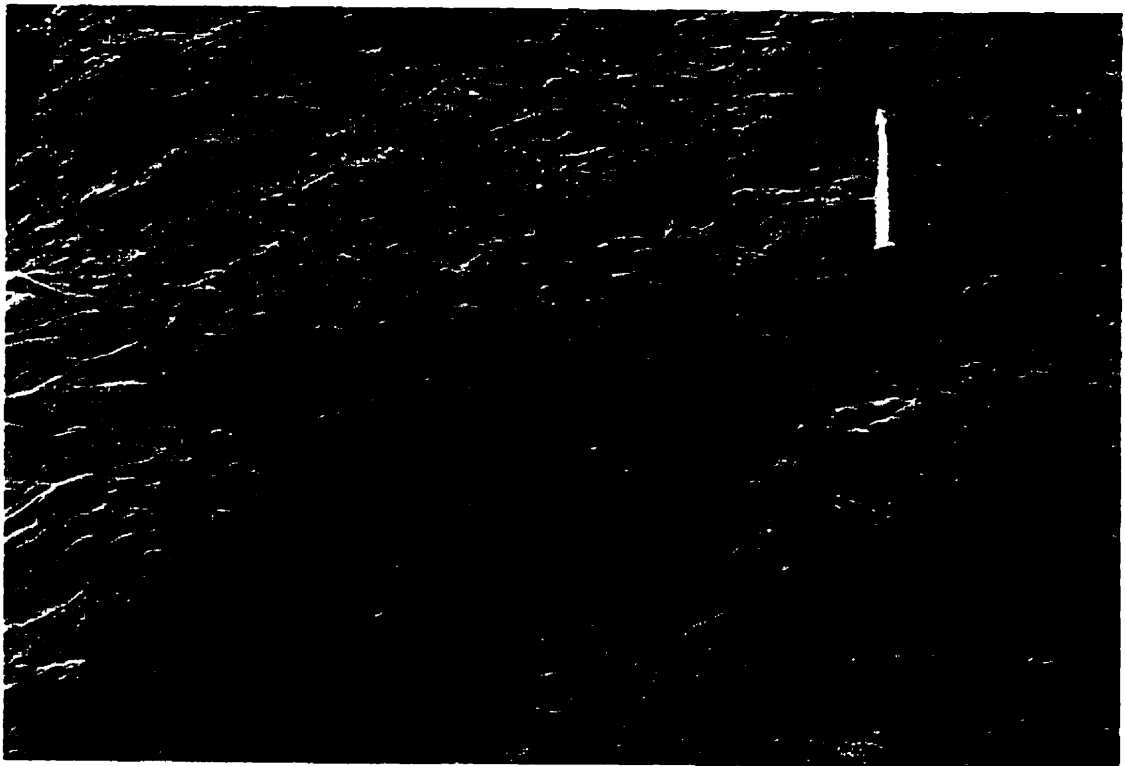
Within the "Marble" Unit, spacing of laminae can be quite regular (Figure 27a), suggesting that deposition of carbonate was controlled by the daily metabolic activity of the microbial mats. Some of the laminae within the Interbedded Unit show a clear, repetitive variation in lamina thickness (Figure 27b) resembling neap to spring tidal variations in sedimentation (Feldman et al. 1993). This would suggest that these latter laminations were produced by the tidal transport of detrital carbonate grains, rather than direct precipitation, with the organic-rich cap of each lamination produced by microbial colonization of the new surface.

Laminae can be accentuated by low amplitude stylolite formation during burial and compaction.

Figure 25 a,b. Examples of "crinkled" bedding surfaces formed by the disturbance of unlithified microbial mats. "Marble" Unit of the Eramosa Formation. Southern (main) pit of the Wiarton quarry.



A



B

Figure 26. Event bed composed of ripped up microbial mat fragments with a fine grained, carbonate mud cap. "Marble" Unit of the Eramosa Formation. South (main) pit of the Warton quarry.

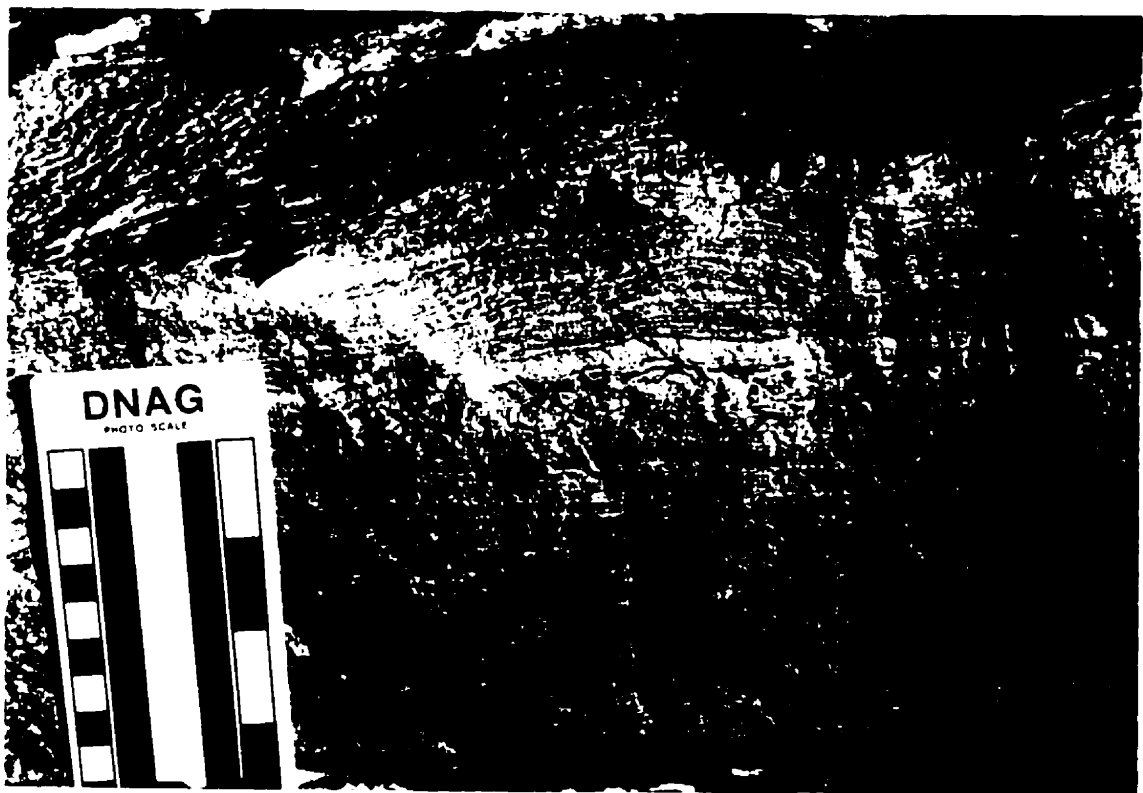
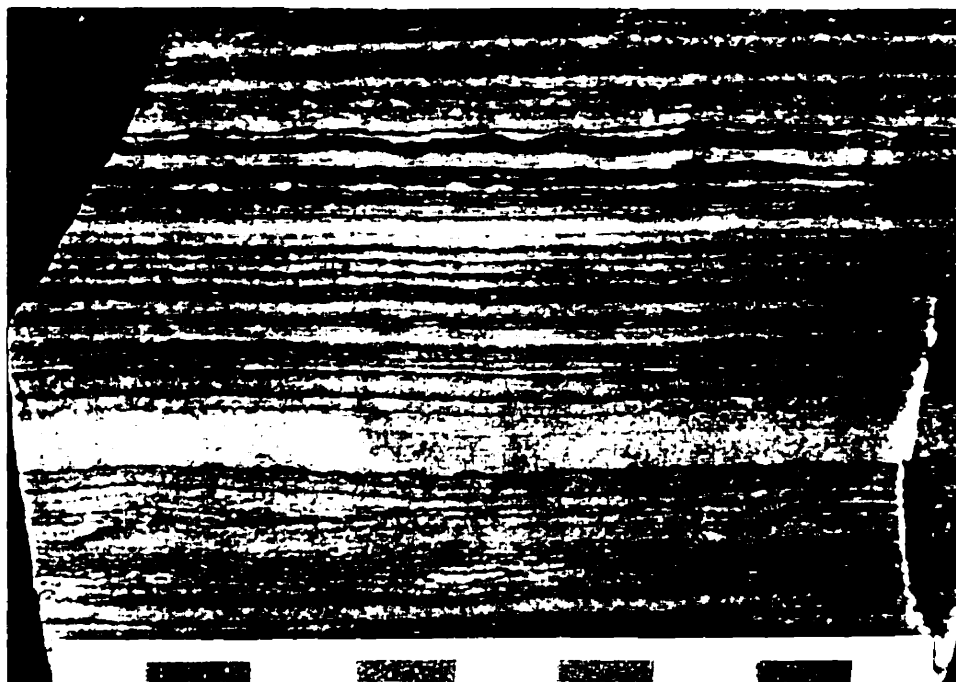


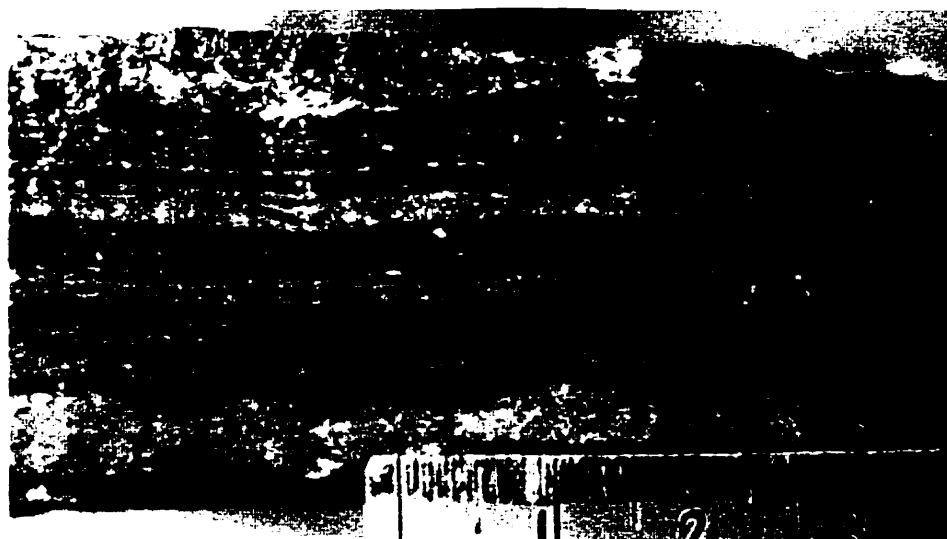
Figure 27. Laminations within Eramosa Formation dolostones. South (main) pit of the Wiarton quarry. Scales in centimeters.

A. Laminations of the "Marble" Unit.

B. Bundled thick and thin laminations of the Interbedded Unit, possibly related to spring to neap tidal variations.



A



B

Event beds

Numerous buff-colored, carbonate silt beds of varying thickness occur throughout the section. They range from one to 70 cms in thickness, and sometimes can be traced laterally into several beds. Some show evidence of homogenization by bioturbation, though burrowing rarely penetrates into the underlying laminated sediments. These represent storm event beds, the merging of beds representing amalgamation during multiple storm events.

In contrast to surrounding dark, laminated dolostones, these sediments would have been oxygenated during suspension by storm waves, resulting in the decomposition of organic matter within the original sediment by bacterial action and, hence its lighter color. One particular event bed within the south quarry contains structures that resemble collapsed voids (Figure 28a) with bed-surface ruptures (Figure 28b). This may represent storm redeposition of particularly organic-rich sediment, after which decomposition of the organics produced enough gas to form bubbles sufficient to burst through the sediment surface. A fine-grained lining of the collapsed structure is consistent with that caused by particle settling within the gas void and subsequent rupture observed during organic-decay experiments (Zangerl 1971).

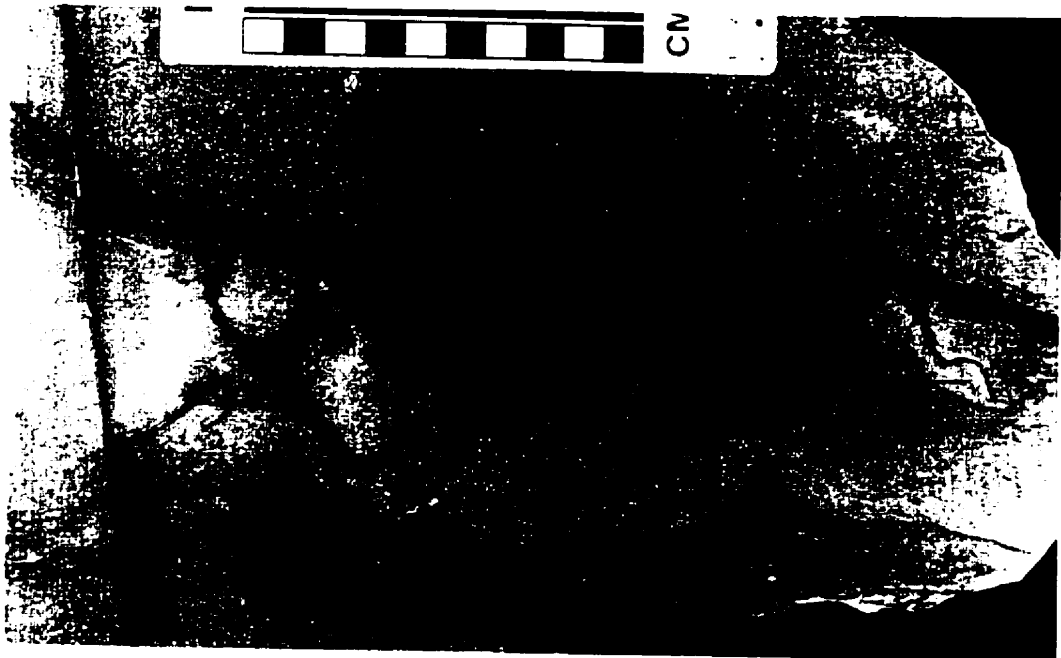
In the uppermost part of the Eramosa within the study area, storm-generated debris flows described earlier (from 10 to 30 cm in thickness) contain material carried from a nearby patch reef (Figure 15). Unlike those of the lower Eramosa, these

Figure 28. Gas-release structures within storm bed, Middle Unit, Eramosa Formation.

South (main) pit of the Wiarton quarry.

A. Vertical section showing collapsed voids (left) and escape fissures (right).

B. Bed surface showing possible gas escape ruptures.



A



B

graded event beds contain much fossil material, including coral, brachiopod, and crinoid debris (Figure 29). Unfossilized coral skeletons, particularly living coral, have a much lower density than lithified material, and behave hydrodynamically like particles of a much smaller size when moved, hence some of the coral material lies conspicuously high in the graded bed. Between these larger debris flows, smaller events produced carbonate silt beds of only a few millimeters in thickness, and which gently covered and smothered a dasyclad algal community.

An unusual bed traceable for some distance in the south quarry shows highly contorted beds and ball-and-pillow structures, sometimes with secondary chert formation developed around particularly tight "knots" (Figure 30). This may represent soft-sediment deformation triggered by a seismic event. The region does have several faults, some of which are still active today. One such fault, the Clarendon-Lyndon structure west of Rochester, NY, has a vertical displacement of several hundred feet and shows evidence of movement during Silurian times.

Silica

Thin, often fairly continuous chert beds occur periodically through the Interbedded Unit, particularly in the lower several meters. The beds often grade horizontally from nodular zones to sheet-like masses (Figures 31 a,b illustrate the same bed over a distance of 5 meters). The edges of chert nodules often cut across laminations. These beds are often associated with surfaces containing oriented

Figure 29. Storm-generated, graded debris flow containing corals and disarticulated crinoidal material. Uppermost Interbedded Unit of the Eramosa Formation. North pit of the Wiarton quarry.



Figure 30. Composite photograph of bed exhibiting soft-sediment deformation,
possibly caused during a seismic event. South (main) pit of the Warton
quarry.

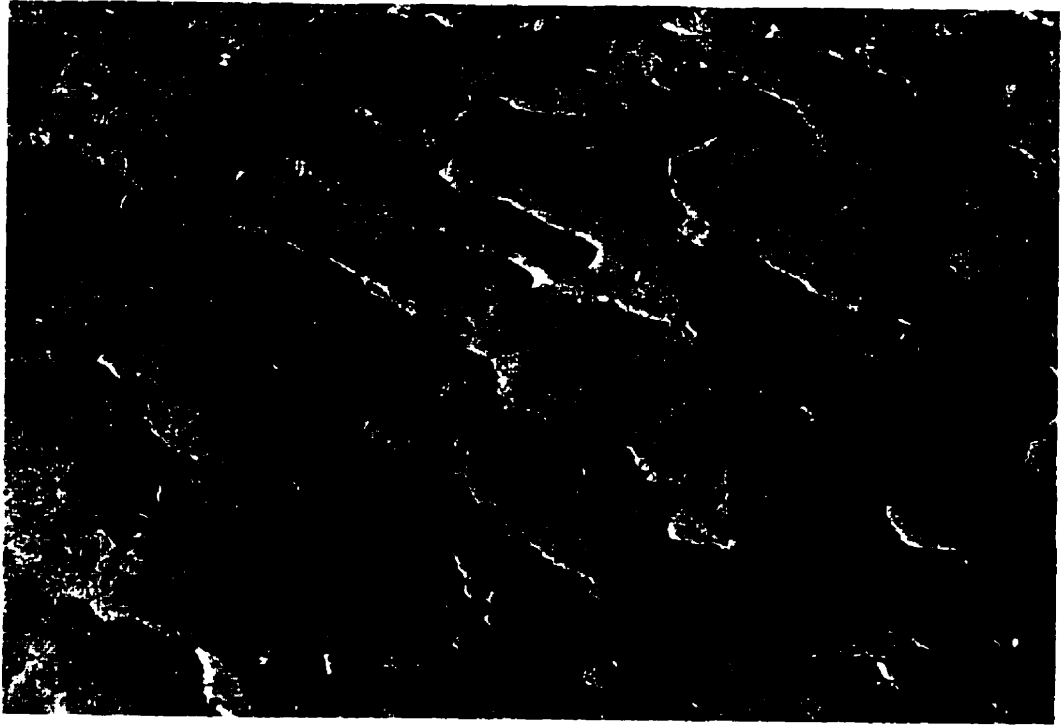


Figure 31. Bedded chert within the lower Interbedded Unit of the Eramosa Formation.

South (main) pit of the Wiarton quarry.

A. Discontinuous chert bed.

B. Sheet-like chert bed containing current-oriented cephalopods. This surface is the same bedding plane as A. Cephalopods are oriented in the same direction as the trend visible in A.



A



B

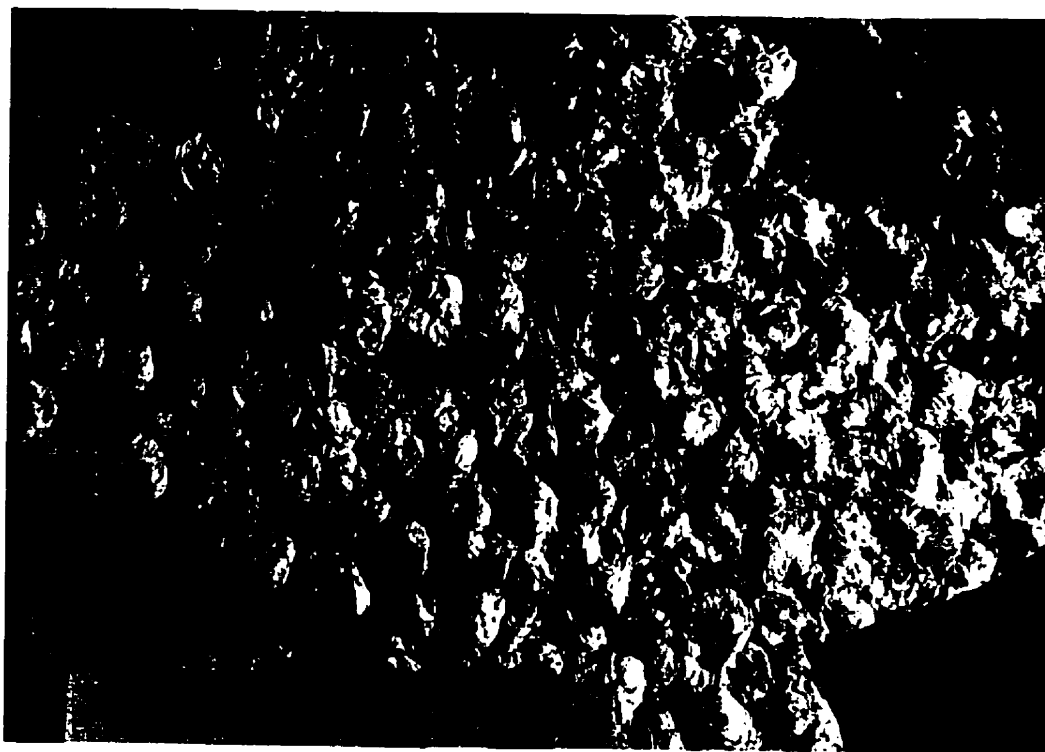
cephalopods (Figure 31 b), and rhynchonellid shell beds (Figure 32 a). The chert preserves the only uncompressed brachiopods (Figure 32 b) within the Eramosa, indicating very early silicification.

Dietrich et. al. (1963) concluded through petrologic studies that silica could be precipitated both before and during lithification and dolomitization. Siever (1962) suggested, based on experimental data, that adsorption of organic matter (whether originally deposited or produced as the metabolic products of bacteria) onto whichever siliceous organisms were present would slow dissolution of amorphous silica, whereas the siliceous organisms in the surrounding areas without organic adsorbates would be free to dissolve. A concentration gradient of dissolved silica would be set up, making possible diffusion from the surroundings into the site where organic material would continue to immobilize the silica by producing insoluble organic silica complexes. Decomposition of the organic matter produces CO_2 , lowers pH and dissolves carbonate at the reaction site, which diffuses in the opposite direction, precipitating in void space. The process continues, with carbonate dissolving and silica precipitating at the site until the organic matter was either completely oxidized by bacteria or complexed with silica, or until the bacterial activity that produced the CO_2 ceased.

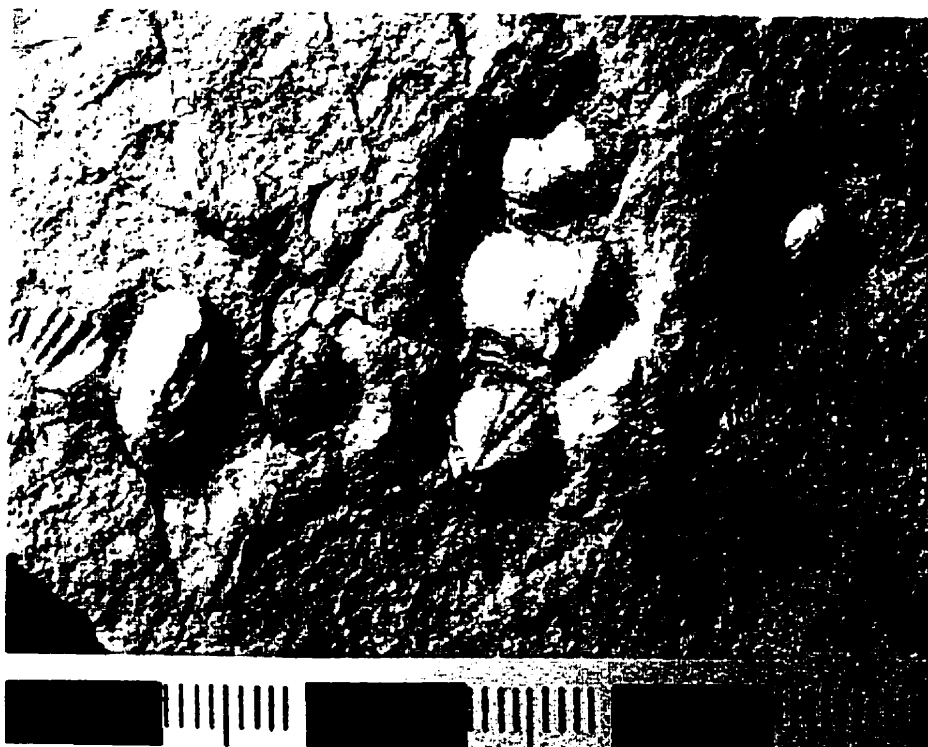
Within the context of the Eramosa chert beds, it would seem that the presence of demosponges in the lower Interbedded Unit would be a source of original amorphous silica, and the varying organic content of individual laminae and of the carbonate silt tempestites would produce gradients of variable organic decay rates.

The burial of dense shell beds would provide particularly high amounts of decaying organic matter within thin, yet continuous layers just below the sediment-water interface. Where chert is only sparingly present, it is often concentrated within articulated rhynchonellid shells alone, further illustrating the precipitation of silica at specific sites of organic decay.

Figure 32. A. Dense, rhynchonellid shell bed partially replaced by chert: x 0.85.
B. Silicified rhynchonelled brachiopods within a thicker chert bed: x 2.0.
Both from the lower Interbedded Unit of the Eramosa Formation, South
(main) pit of the Wiarton quarry.



A



B

The Biota

Overview

The biota recovered from the study area is unusually diverse, although it shows quite a varied distribution over the thickness of the Eramosa. The "basal unit" is unexposed within the quarry property, but a single block (as a test sample) lifted from below the LLH stromatolite bed during quarry operations, appears to be devoid of any trace or body fossils. The "Marble unit", extensively quarried in the south pit and the base of the exposed section, is an unfossiliferous algal laminated dolostone. No macrofossils have been recovered from these rocks. The absence of even trace fossils within this sequence suggests that a lack of body fossils is likely not merely a taphonomic artifact, but that the stromatolitic lagoon was perhaps too hostile for metazoan life.

The "Middle unit" contains few fossils, but rare orthoconic cephalopods do occur. On the rare occasion, when more than one is encountered, the cephalopods are usually aligned, indicating that empty shells were likely washed into the lagoon by wave or current action. Trace fossils are fairly common on some bedding surfaces, and mainly represent *Chondrites*- and *Planolites*-type traces. A few rare plant fossils were also found. The complete bioturbation of some otherwise unfossiliferous tempestite event beds indicates activity by macro-organisms.

The upper "interbedded unit" is, in places, very fossiliferous, and contains most of the fossil material recovered during this study. Fossil distribution within this unit is not homogeneous, however. The unlaminated tempestites tend to be unfossiliferous, with most fossils occurring within the dark, finely laminated dolostones. Fossil material tends to occur in low to medium densities, scattered on bedding surfaces. High density shell beds, mostly composed of rhynchonellid brachiopods, occur only rarely, and even these show relatively little evidence of reworking.

On a small scale, these fossiliferous bedding planes are irregularly distributed throughout the section every 0.5 to 2 centimeters, interspersed within otherwise poorly fossiliferous to unfossiliferous dolostone. The boom/bust colonization of the sediment surfaces is often by near-monotypic populations, the colonizer changing from bedding plane to bedding plane. While the most common colonizers were rhynchonellids, there are also bedding surfaces dominated by either dasyclad algae, pelecypods, gastropods, echinoids, ophiuroids, crinoids, sponges, phyllocarids, or *Serpulites* tubes.

On a larger scale, faunal composition changes significantly over the thickness of the Interbedded Unit. The lower meter of this sequence shows a progressive increase in diversity, particularly in those groups of organisms more commonly associated with normal marine conditions (e.g. brachiopods, crinoids, trilobites). Thin, light-colored beds representing probable tempestites are common, and occur every few centimeters. Above this are several meters of fairly lithologically monotonous, very unfossiliferous, dark, laminated dolostone containing rare

cephalopods and eurypterid fragments. The next few meters in the sequence are not well-exposed anywhere on the property, but the upper meter of the Eramosa (which can be seen in the northernmost pit) contains alternating storm-derived debris flows and dark, laminated dolostones. The organic-rich, laminated dolostones contain an autochthonous community of dasyclad algae and articulated scolecodont assemblages, while the light tan, graded debris flows contain an allochthonous reef community consisting of favositids, brachiopods, and crinoidal debris. The upper surface of one debris flow seems to have been colonized by large numbers of the brachiopod *Whitfieldella*.

Flora

The macroflora of any marine environment is a major component of the ecologic diversity, and significant element of any ecosystem. Warm temperate and tropical coasts (representing a variety of sub-environments) all have from 600 to 800 species among 200 to 300 genera of seaweeds (Lüning 1990). The several groups of calcareous algae have a reasonable fossil record, although the fragile nature of non-calcareous thallophytic algae ("seaweeds") normally makes their preservation virtually impossible. Among extant multicellular algae, only approximately 10% of benthic forms are calcified (Taylor and Taylor 1993). Hence the paleontologic record contains very little information concerning this very important aspect of community structure.

Early workers recognized that paleo-environments must certainly have contained a marine flora, and described many ichnofossils, animal remains, and even abiotic structures as plant remains ("fucoids"). As a deeper understanding of fossil preservation was reached, many of those same workers believed that algal material could not possibly be preserved in the marine environment, and paleontology entered a long period of "flora denial" where virtually nothing was assigned plant affinities. Ironically, many fossils assigned to groups like the graptolites, including genera that had been originally described as plant and later moved to other groups (e.g. Bouček 1957), are in fact again recognized as fossil plants (LoDuca 1990, LoDuca and Brett 1997).

In modern shallow water environments, algae can be responsible for significant biomass production. The death and decomposition of this material can contribute large amounts of organic matter to the sediment, contribute to anoxic conditions both above and below the sediment-water interface, and thus have a tremendous affect on the character of sediment deposits. This "invisible" component of the paleocommunity may form locally appreciable percentages of organic matter in petroleum source rocks (Dix 1990), and may be responsible for much of the organic content of the dark Eramosa sediments.

Throughout the Eramosa in the study area, there is ample evidence of microflora in the form of cyanobacterial films and stromatolitic structures, and one of the distinctive characteristics of the Eramosa *Lagerstätte* is the preservation of a diverse macroflora.

Non-dasyclad Algae

Many different forms of thallophytic algae were recovered (Figure 33); these include both branched and unbranched foliose forms, stick-like forms, bushy forms, radial forms, and tangled mats of filamentous algae. Very little can be done, however, towards classifying these algae. Modern high-level classification of algae is based on unpreservable, cellular-level characters, a primary one being the type of chlorophyll present, easily visible in a living example as color. Hence the algal divisions "Red Algae" (Rhodophyta), "Brown Algae" (Phaeophyta), "Green Algae" (Chlorophyta), etc. Complicating this is the tendency towards convergent gross morphologies within many of the groups. While some morphologies may be more commonly associated with particular algal divisions, meaningful assignment cannot be made with any degree of certainty.

Several unbranched foliose forms (Figure 33, a-c) show a simple elongated, blade with a median line on a stalk of varying length, and a small, simple holdfast. Among the larger branched forms, one specimen bifurcates symmetrically three times (Figure 33, f), resembling what is called "*Chondrites*" versus "*Chondrites*" versus closely resembles the modern chlorophyte *Codium* (Order Caulerpales) and may, in fact, be a green alga, though similar morphologies also occur in extant brown and red algae (LoDuca 1995). Another large form has a main stalk resembling the Silurian plant *Hostinella* (Figure 33, d). The stalks on the *Eramosa* specimen terminate in numerous, fine ramifications, a feature not observed in previous *Hostinella*

Figure 33. Non-dasyclad, thallophytic algae from the Interbedded Unit of the

Eramosa Formation.

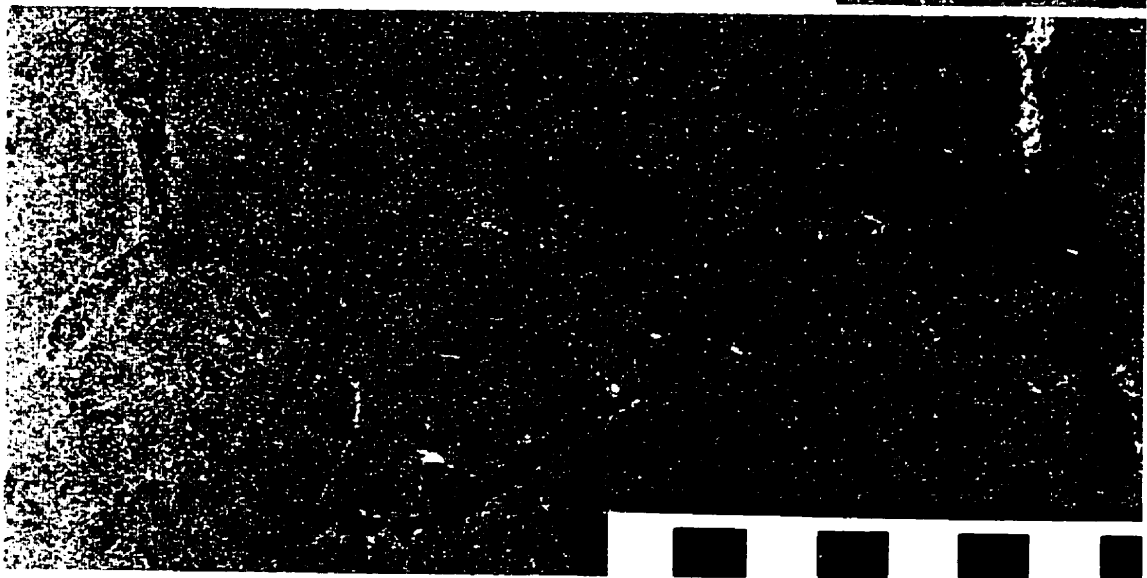
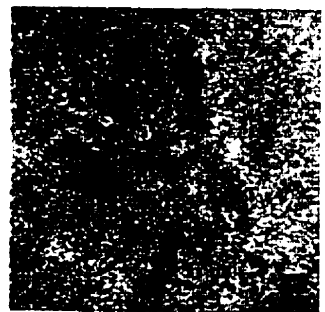
A-C. Simple, blade-like alga, under ethanol: A. x 2.0, B. x 1.6, C. x 2.7.

Note holdfasts present on B and C.

D. *Hostinella*-type alga; x 1.2.

E. Alga with a radial morphology, under ethanol; x 3.0.

F. "*Chondrites*" versus- type alga; x 0.9.



specimens, indicating little transport. Banks (1968) regarded *Hostinella* as a primitive vascular land plant and, if true, it probably colonized the small, exposed topographic highs dotted amongst the Eramosa lagoons. The remaining forms of algae found within the biota, but defying classification as dasyclads, show morphologies that are common amongst many of the algal divisions, but which cannot be ascribed to any particular group. These include mats of long, tangled, filamentous algae, and several circular forms of small, benthic algae with radially-arranged curved or branching filaments attached to a central point or stalk (Figure 33. e).

Dasyclad Algae

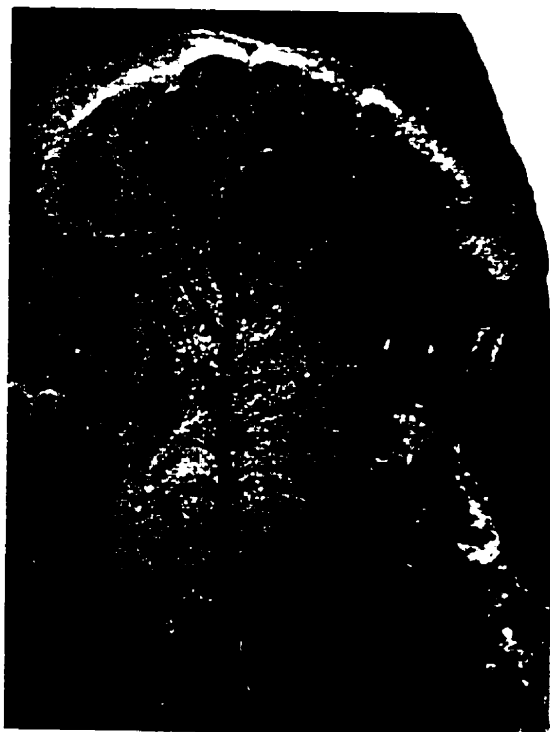
The Dasycladales, an order within the Green Algae (Chlorophyta), is unusual among the algae in that it has many unique morphological characteristics, enabling taxonomic assignment to be made. Coenocytic (single-celled), Dasycladales can reach up to 200 mm in length, are highly differentiated, and produce species-specific patterns at distinct sites (Berger and Kaeffer 1992).

At least two forms of algae with clearly dasyclad affiliation were found within the Eramosa *Lagerstätte*. Several specimens of *Palmatophycus* were recovered (Figure 34. a,b). This complex, highly branched genus has previously only been described from the Wenlock-aged Motol Beds of the Czech Republic (Bouček 1941). Originally described as an alga, it was later redescribed as a graptolite (Bouček 1957).

Figure 34. Dasyclad alga from the Interbedded Unit of the Eramosa Formation, all photographed under ethanol.

A. B. *Palmatophycus* sp.: A. x 1.5, B. x 2.4.

C. Enlargement of the terminal secondary and tertiary laterals on *Palmatophycus* illustrated in A.: x 7.5.



It consists of a thicker central axis approximately 1 mm in width, along which are attached secondary ramifications averaging 0.2 mm in width and up to 25 mm in length away from the growing apex and considerably shorter near to the apex. The secondary ramifications then give rise to numerous 1.5 mm long tertiary laterals, which in turn can be bifurcated (Figure 34 c). Arrangement of the secondary and tertiary laterals is not entirely clear, but it appears to be aspondyl (i.e. an irregular attachment pattern) rather than euspondyl (whorls). No reproductive structures were observed on any of the specimens, nor can the original length of the primary axis be determined..

The second form of dasyclad alga was sufficiently well preserved, and found in sufficiently large numbers showing different growth stages to be formally described below as a new genus and species.

Wiartonella

The dasyclad alga *Wiartonella nubbinophora* n. gen. n. sp. is preserved in 0.2 to 1.0 mm thick, dark, organic-rich, shaly laminae between 1 to 15 mm thick, light-colored, organic poor, carbonate silt beds. The dark beds are devoid of trace fossils, but contain numerous scolecodonts (both articulated and disarticulated jaw elements), faint impressions of decalcified brachiopods, and include a mixture of intact and fragmentary alga specimens, the latter typically consisting of dissociated laterals and denuded main axes. The varying level of articulation of the remains, combined with the sedimentological aspects of the beds, suggest a scenario in which standing crops

of algae, in varying stages of their life cycle and established in a normally low energy setting, were subjected to brief episodes of violent agitation as the result of storm activity. Some specimens of algae experienced immediate storm-induced obrution and were preserved intact, whereas others were buried only after prolonged exposure to wave agitation following uprooting and suspension in the water column, and are consequently much more fragmentary in nature. Large numbers of deciduous laterals shed during *Wiarthonella*'s normal life cycle also contribute to the volume of fragmentary material. Return to low energy, low oxygen conditions following storm events then insured that the entombed biota remained free of scavengers.

Like other material of noncalcified dasycladalean algae known in the fossil record (e.g. Banks 1968, LoDuca 1990, Kenrick and Li 1997), specimens of *Wiarthonella nubbinophora* are preserved as black carbonaceous residues, their carbon composition being confirmed by electron microprobe analysis. In many of the alga-bearing laminae, *Wiarthonella* is preserved as a thin carbon film. However compaction within some beds appear to have been minimal, possibly due to early lithification, and specimens consequently show 3-dimensionality. In some specimens, organic content seems to have been so high within the bed that secondary carbon has been deposited as a coating onto the fossil material.

SYSTEMATIC PALEONTOLOGY

Order DASYCLADALES Pascher, 1931

Family TRIPLOPORELLACEAE Pia 1920 (nomen translatum Berger and Kaever 1992)

Tribe UTERIEAE (sensu Bassoullet et al., 1979)

Diagnosis.— Thallus cylindrical, with or without annulation; distinct separation and alternation of sterile and fertile verticils; position of the fertile organs within the ramifications indeterminate. (Translated from the original French.)

Discussion.— Three of the five families of Dasycladales, namely Triploporellaceae, Dasycladaceae, and Acetabulariaceae, contain taxa with two types of laterals. Among Triploporellaceae, such a trait characterizes two tribes, Cyliroporellae and Uteriae, these being distinguished one from the other by the whorl positioning of the different lateral types: together in the same whorl in Cyliroporellae; segregated into alternating whorls in the Uteriae. In the Family Dasycladaceae laterals of two types occur only within the genus *Cymopolia*. Here, sets of 5 - 10 long sterile laterals alternate with sets composed of an approximately equal number of short sterile laterals. Finally, in the dasycladalean Family Acetabulariaceae, all tribes are characterized by two types of laterals, but instead of being inflated at just their distal ends, as is the case in the other examples considered, the fertile laterals are inflated along most of their length (instead of just the distal ends) thereby forming verticils with a distinctive cuplike (umbrellaphore) morphology that serves to define the family. The new genus *Wiarionella* bears laterals with a morphology and arrangement in precise accordance with the Uteriae body plan, and on that basis is assigned to this tribe. *Wiarionella* extends the range of the Uteriae by over 250 million years, from the Cretaceous back to the Silurian.

Genus WIARTONELLA new genus

Type species.— *Wiarionella nubbinophora* new species, by monotypy.

Diagnosis.— Noncalcified thallus comprising a narrow, cylindrical main axis with unbranched laterals in whorls (euspondyl). Laterals of two types: (1) hair-like with tapered ends (trichophore), and (2) cylindrical with ball-shaped terminations (phloiophore). Verticils of each lateral type alternate along the main axis.

Etymology.— In reference to the geographic origin of the material.

Discussion.— The Tribe Uteriaea includes, as well, the genera *Uteria* and *Angioporella*. *Wiarionella* differs from *Uteria* in the unbranched form of its fertile laterals, and from *Angioporella* in the shape of its fertile laterals, these being much less inflated distally and having relatively much longer tubular "bases". *Wiarionella* differs from both genera in its complete lack of calcification.

WIARTONELLA NUBBINOPHORA new species

Diagnosis.— As for the genus, by monotypy.

Description.— Thallus noncalcified, 25-40 mm long and 4-7 mm wide, with unbranched laterals in verticils (euspondyl). Main axis narrow, approximately 0.25

mm wide, cylindrical, without significant change of diameter at verticil junctions: apex blunt. Laterals of two types: phloiophore and trichophore. Trichophore laterals longer than phloiophore types, 3-5 mm long and 0.05 mm wide. Phloiophore laterals 1.2-1.5 mm long, each comprising a cylindrical shaft 0.06 mm wide and an inflated spherical termination 0.1 mm in diameter. Laterals segregated by type into alternating verticils along most of the length of the main axis, these spaced approximately 0.15 mm apart (Figure 35, a). Rhizoid globose, approximately 0.35 mm in diameter.

Etymology.— The trivial name refers to the conspicuously inflated terminations of the phloiophore laterals.

Types.— Holotype Figure 35, b; paratypes Figure 35 c-e.

Type locality.— Wiarton quarry of Owen Sound Ledgerock Ltd., west of Wiarton, Ontario. Approximately 1 meter below upper contact of the Eramosa Dolostone.

Occurrence.— Known only from the type locality.

Discussion.— Although no reproductive bodies (cysts or gametangia) have been observed in the phloiophore laterals of *W. nubbinophora*, such structures have been observed in similarly shaped laterals of other dasycladaleans (e.g., *Triploporella*, Barattolo 1982). Thus, the phloiophore laterals of this species are interpreted by analogy as gametophores: the lack of observed reproductive bodies is attributed to preservational limitations.

Figure 35. *Wiartonella nubbinophora*, a new dasyclad alga from the uppermost Interbedded Unit of the Eramosa Formation, North pit of the Wiarton quarry.

- A. Complete specimen of *Wiartonella* with holdfast, preserved as a thin carbon film: x 2.7.
- B. Holotype, with both trichophore laterals (vegetative, long, narrow) and phloiophore laterals (reproductive, short, thick and rounded, near upper third of specimen): x 5.8.
- C. Paratype with no phloiophore laterals: x 5.8.
- D. Paratype, with fully developed phloiophore laterals, trichophore laterals becoming deciduous: x 7.5.
- E. Paratype, only phloiophore laterals left: x 2.5.
- F. Paratype, phloiophore laterals becoming deciduous, leaving behind denuded central stalk: x 8.5.



By utilizing a number of complete specimens preserved in various stages of growth, it has been possible to reconstruct a fairly complete picture of the ontogeny of *W. nubbinophora*, outlined as follows. The earliest stages of thallus growth produced only verticils of short, sterile, trichophore laterals (Figure 35, b, lower part of specimen). This was then followed by "typical" growth consisting of verticils of sterile trichophore laterals alternating with verticils of phloiophore fertile laterals (Figure 35, b, remainder of specimen). The former concealed and perhaps protected the intervening verticils of fertile laterals and were retained until final growth height was achieved, whereupon they became deciduous (Figure 35, d), leaving the thallus composed largely of whorls of mature fertile laterals (Figure 35, e). Eventually, the fertile laterals also became deciduous (Figure 35, f), leaving behind a denuded main axis. In apparent contrast to the preceding, some specimens of *W. nubbinophora* of mature height appear to lack fertile laterals (Figure 35, c). A possible explanation for this may be found in the ontogeny of the extant dasycladalean *Acetabularia acetabularium*. Under natural growing conditions, the rhizoid of this species produces thalli with only vegetative (sterile) laterals during the summer months of the first two growing seasons, with reduction to the rhizoidal base occurring during the intervening winters. It is only during the third growing season that a thallus is produced with fertile laterals (van den Hoek et al. 1995). *W. nubbinophora* may have possessed a similar life cycle. The possibility that these sterile forms instead represent a phase of ontogeny which was then immediately followed by a phase of fertile verticil production through secondary outgrowths of the cell wall is considered highly

unlikely, as verticils in all living Dasycladales are only produced at the growing tip of the axis: in calcified forms, such secondary verticils, even if possible from a morphogenesis standpoint, would be blocked from development by the calcareous coat.

Among extant Dasycladales, the morphology of *Wiarttonella* resembles that of *Halycoryne*. In *Halycoryne*, as in *Wiarttonella*, verticils of inflated fertile laterals alternate with verticils of narrow sterile laterals along the length of the axis. The laterals of *Halycoryne* (both sterile and fertile), however, branch, and the fertile laterals form cuplike (umbrellophore) verticils, although this latter feature is mainly a consequence of the laterals of *Halycoryne* being inflated along most of their length, instead of just at the terminal end as in *Wiarttonella*, and thus does not present as great a difference as might first appear.

The tremendous range extension of the Utericae that results from the assignment *W. nubhinophora* to this tribe begs the question of whether this, instead, might represent a case of convergent evolution among two only distantly related groups. Were it not for the recent discovery of a number of other morphologically "advanced" dasycladalean taxa from the Lower Paleozoic (LoDuca 1990, LoDuca and Brett 1997, Kendrick and Li 1998, LoDuca et al. 1999) such an alternative explanation would be difficult to refute. However, these new taxa clearly indicate that considerable morphological innovation among Dasycladales had been achieved by the end of the Early Devonian, including all types of reproduction (endosporate, cladosporate, choristosporate and umbrelloporate). Therefore, the most parsimonious explanation is that all of the major dasycladalean clades can be traced back to the

early Paleozoic, and that the picture of dasycladalean evolution developed prior to the discovery of these taxa. The picture has been further clouded and distorted by the fact that the ancestral taxa of many, if not all, of the major dasycladalean clades lacked calcification.

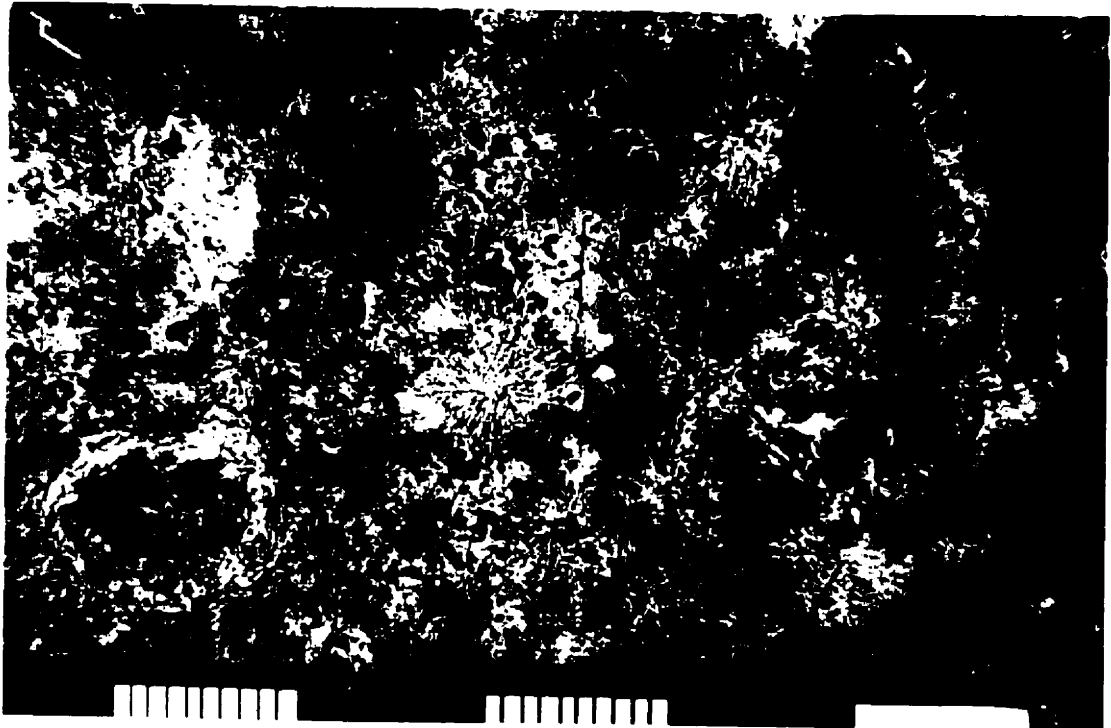
Fauna

Porifera

Within the reef facies of the Eramosa Formation and overlying Guelph, stromatoporoids are an important element in framework building. Bolton (1957) identifies *Clathrodictyon* and *Stromatopora* as occurring within the sequence. Unfortunately dolomitization usually destroys any identifying features. Within the study area, debris flows at the top of the section in the northernmost pit contain very poorly preserved possible stromatoporoids.

Although siliceous sponge spicules are often cited as a silica source for chert within sediments, there often is no direct fossil evidence for the presence of demosponges within a fauna, particularly within dolomitized facies. Within the Wiarton *Lagerstätte*, a single bedding plane contains numerous articulated disk-shaped demosponges with very long, apparently oxete spicules (Figure 36), possibly belonging to the Choiidae. The 1 cm disks occur on the same bedding plane as rhynchonellid brachiopods. While the brachiopods appear to have been dissolved

Figure 36. Choilid demosponges from the lower Interbedded Unit of the Eramosa Formation. South (main) pit of the Wiarton quarry. Photographed under ethanol: x 2.5.



before compaction and lithification (thus are represented by shallow, indistinct impressions), the sponges appear as molds partially lined with late-stage calcite druze. The original siliceous composition of the skeletal material enabled them to survive the early diagenetic processes that destroyed all calcitic skeletal material. After lithification of the sediment, the siliceous spicules were dissolved, leaving only void space.

Worm Phyla

Although there are more worm phyla than all other multicellular phyla combined, this group of organisms has perhaps the worst paleontological record. When worm fossils are found in exceptionally preserved faunas, preservation is rarely adequate to identify diagnostic characteristics, particularly anterior structures, though a few groups such as the polychaetes do have more obvious features that can aid in identification.

Numerous specimens of the problematic phosphatic worm? tube *Serpulites* occur on some bedding surfaces. Some specimens show multiple *Serpulites* tubes attached to each other (Figure 37 a).

Several long, annulated worms were recovered (Figure 37 b,c). Although anterior details are not preserved, and parapodia and setae appear to be absent, their overall morphology resembles that of *Protoscolex* and *Palaeoscolex*. Similar worms have been found in other Silurian *Lagerstätte* (most recently Mikulic et al. 1985, LoDuca and Brett 1997), and have in the past been variously assigned to either the

Figure 37. Worm phyla from the Interbedded Unit of the Eramosa Formation.

A. *Serpulites* tube, with several other attached tubes: x 1.7.

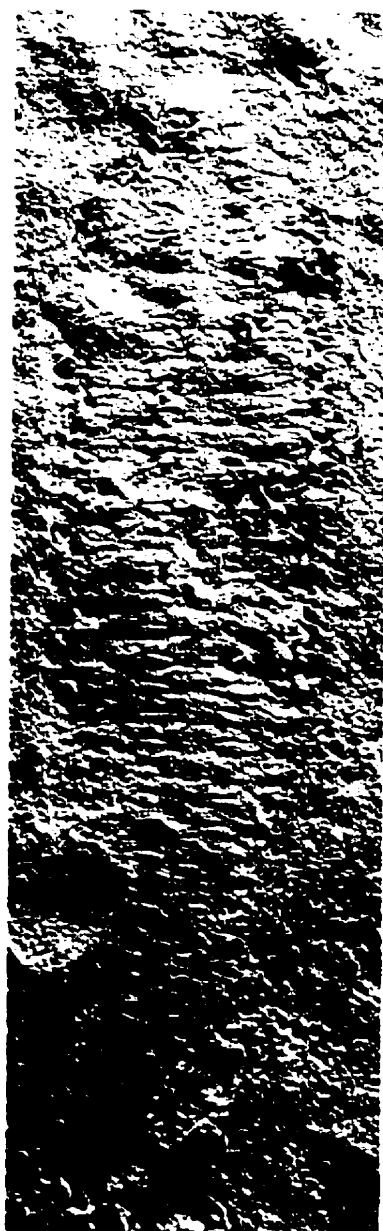
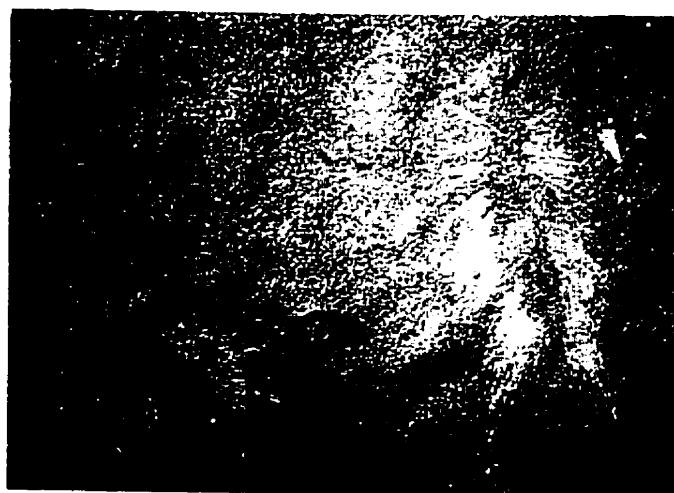
B, C. Annulated worms, both showing gut infills, both under ethanol:

B. x 2.5, C. x 1.8.

D. *Myoscolex*-type worm: x 1.6.

E. Amphinomid polychaete worms, preserving only the setae: x 1.4.

F. Amphinomid polychaete worm, with body outline and segmentation preserved, under ethanol: x 2.5.



Oligochaeta or Hirudinea. Conway Morris et al. (1982) indicate that such assignment is tenuous at best considering the state of preservation in even the best fossil examples; instead, these fossils may represent either group, or an entirely new group.

Several examples of a very large (up to 9 cm), segmented organism (Figure 37 d) that appears to closely resemble *Myoscolex*, described from the Cambrian Emu Bay Shale by Glaessner (1979), was recovered. *Myoscolex* attained similar sizes and shows an internally similar style of segmentation. The most striking similarity is the presence of highly unusual setae, which Glaessner (1979) describes as "uncommonly massive, smooth, gently curved, with blunt distal ends, about 3-6 mm long and 0.2 mm thick, and preserved as calcium phosphate". Glaessner goes on to say that the setae are unlike anything seen in living or fossil annelid worms but that there is some resemblance with *Echiura* setae.

The Polychaeta are perhaps the most readily identifiable group of worms, and several examples occur within the Eramosa *Lagerstätte*. In the laminated sediments between debris flows at the top of the Eramosa section, and associated with the well preserved alga *Wartonella*, were found numerous articulated scolecodont (polychaete) jaw assemblages. With the exception of a single specimen found with the faint outline of a long, sinuous body leading away from the jaw assemblage, the jaw assemblages show no evidence of the remainder of the animal. The presence of these articulated elements, however, indicate that the worms were probably buried alive with the algae.

Within the *Lagerstätte* beds of the lower Interbedded Unit were found examples of another polychaete with very long setae (Figure 37 e). A single specimen

preserves the outline of the polychaete body (Figure 37 f), but in most specimens only the setae are preserved, outlining the general shape of a 1.5 to 2 cm inferred body. The body shows a broad-banded segmentation that corresponds precisely with positioning of the setae bundles, and of the darker head region. No jaws are visible. The setae are short anteriorly (approx. 1.5 mm), and lengthen markedly posteriorly (up to 1 cm in length). One specimen (Figure x) is coiled such that the setae bundles are separated and clearly visible along the outer side. The "v-shaped" positioning of setae bundles indicates that the organism had biramous parapodia. This organism closely resembles *Rhaphidiophorus* from the Pennsylvanian Essex (Mazon Creek) fauna of northern Illinois. Thompson (1979) assigned *Rhaphidiophorus* to the polychaete family Amphinomidae, and observed that the Essex occurrence was the only Paleozoic record of the family. The Eramosa *Lagerstätte* extends that record into the Silurian. These body-fossils, along with a Wenlock volcanoclastic deposit from England (Briggs et al. 1996), represent the only occurrences within a 140 million year gap in the fossil record of polychaetes, from the Cambrian Burgess Shale to Devonian *Hunsrückshiefer*.

Cnidaria

Within the *Lagerstätte* beds occur several faint disk- and ring-shaped structures, some of which show indistinct radial structures. Though it is tempting to ascribe these to cnidarian medusae, their poor preservation prevents the exclusion of other possible affinities, including algal structures.

Conularids are fairly common within the lower Interbedded Unit, particularly within the *Lagerstätte* beds, and their preservation is generally good (Figure 38

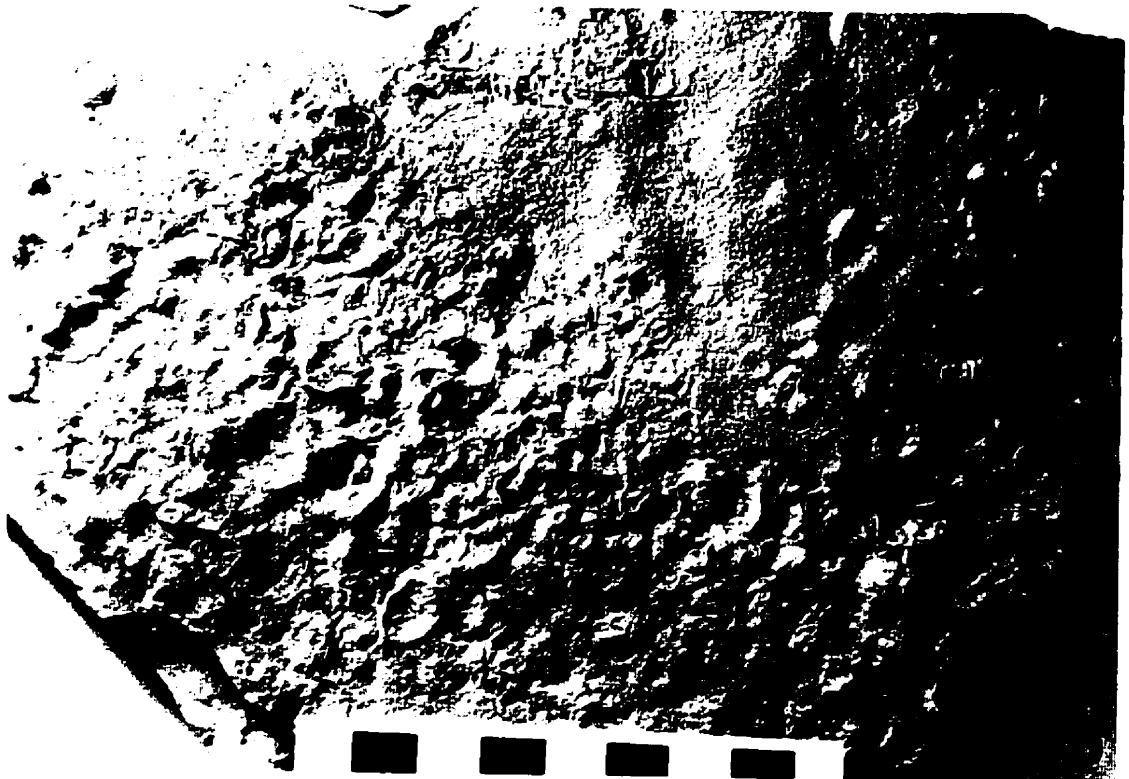
Figure 38. Cnidarians and brachiopods of the lower Interbedded Unit of the Eramosa Formation. South (main) pit of the Warton quarry.

A. Conularid; x 1.7.

B. Orbiculoid inarticulate brachiopod; x 2.8.

C. Articulate brachiopod *Leptaena* sp.; x 1.9.

D. Shell bed with numerous poorly preserved rhynchonellid brachiopods (note the phyllocarid *Ceratiocaris* at top center); x 0.85.



a). None of the specimens preserve soft tissue.

The debris flows at the top of the Eramosa contain the tabulate *Favosites* and the small rugosan *Enterolasma*. All appear to have been transported in from a reef community not represented within the present-day outcrops, though transport distance does not appear to be significant (Figure 29). The high position of *Favosites* specimens within the debris flow would suggest that they represent low density particles (and thus behave hydrodynamically like particles of a much smaller size), and were either living specimens or freshly killed corals.

Bryozoa

Bryozoa are generally absent from the Eramosa, although within the lowest portion of the Guelph Formation overlying the Eramosa in the northernmost pit, large numbers of broken trepostome bryozoans form a probable storm-derived bed. The sugary, recrystallized nature of the lower Guelph does not preserve fossils very well, and the small twiggy bryozoans are recrystallized, partially dissolved, and the resultant pore space partially occupied by bitumen.

Brachiopoda

Brachiopods are common in the biota, though their diversity is very low. The inarticulate brachiopod *Orbiculoidea* occurs throughout the lower Interbedded Unit.

and due to its originally phosphatic composition, is generally well preserved (Figure 38 b).

Large numbers of rhynchonellid brachiopods occur throughout the lower one-third of the Interbedded Unit, and to a lesser extent within the upper one-third. These brachiopods are usually preserved as faint, barely identifiable impressions (Figure 38 d), indicating that the shells were probably dissolved before compaction and lithification. Where early chert formation has occurred, shells can be relatively well preserved (Figure 32 b).

Leptaena (Figure 38 c) occurs rarely within the Interbedded Unit. Within the debris flows at the top of the unit, and within the immediately overlying basal Guelph, a more diverse allochthonous reefal fauna includes *Whitfieldella* and *Eospirifer*.

Mollusca

Bivalvia

Bivalves are generally rare in the Eramosa fauna, though a single bedding surface within the lower Interbedded Unit contains numerous disarticulated valves of a single species (Figure 39 a). The rarity of bivalves may be partly a taphonomic phenomenon. In normal marine environments, calcitic skeletons are well preserved, whereas aragonitic material often is not. The Eramosa Dolostone has a poor record of preserving calcitic material, and it would therefore be even less likely to preserve aragonite. However, the presence of similarly mineralized gastropods and

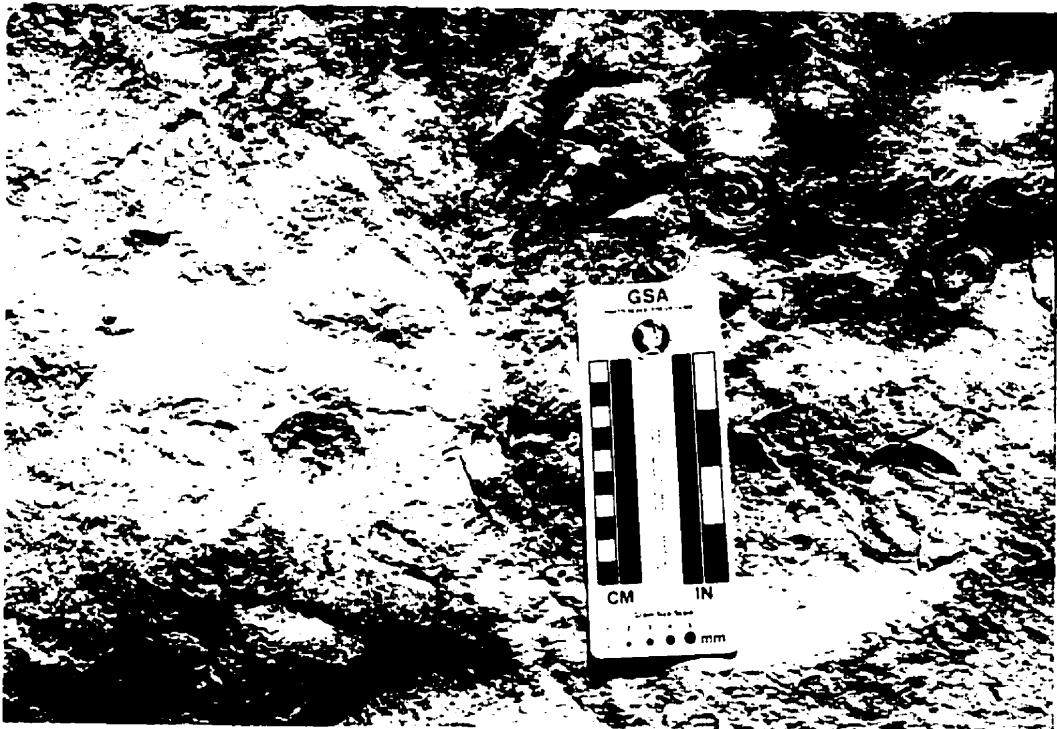
Figure 39. Mollusca from the Interbedded Unit of the Eramosa Formation.

A. Bivalves: x 0.95.

B. Low-spined and high-spined (top center) gastropods: x 0.3.



A



B

cephalopods would suggest that taphonomy is not the principal reason for the near total absence of bivalves. They were probably rare in the community to begin with. Bivalves commonly have an infaunal life habit and the anoxic lagoonal sediments would have prevented their colonization.

Gastropoda

Although gastropods are uncommon and very poorly preserved, several low-spined and high-spined varieties occur, often barely discernable on the bedding surface. Rarely, there may be bedding surfaces with a large number of individuals, usually dominated by single species (Figure 39 b). These may have been algal mat grazers. Mat grazing gastropods in modern environments often have large boom-and-bust populations (often dictated by fluctuations in salinity) in mono-specific communities (Bathurst 1971).

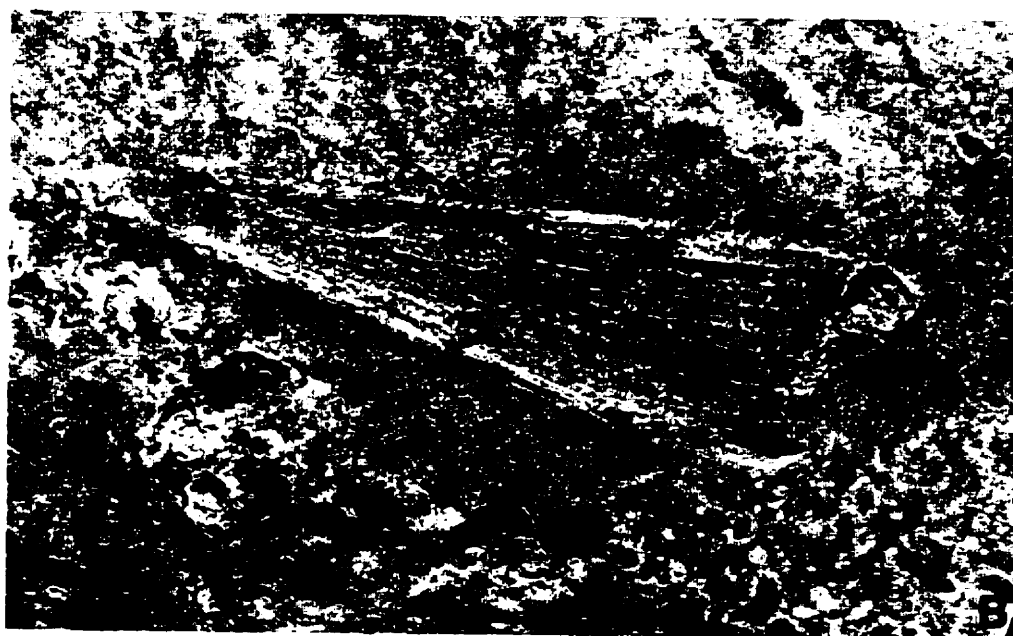
Cephalopoda

Like other molluscs within the biota, cephalopods are, as a rule, poorly preserved, though their larger size makes them easier to recognize. Silicification sometimes preserves portions of the shell, commonly the siphuncle (Figure 40 a). The only fossils generally recovered by quarry workers are orthocones such as *Dawsonoceras*, because of their large size (up to half a meter or more in length) and highly visible nature. Other genera occurring within the Eramosa include

Figure 40. Cephalopods from the Interbedded Unit of the Eramosa Formation.

A. *Geisonoceras* sp. partially replaced by chert, with numerous rhynchonellid brachiopods; x 0.62.

B. *Kionoceras* sp.; x 1.3.



Geisonoceras, *Kionoceras* (Figure 40 b), and brevicones such as *Amphicyrtoceras*. Orthoconic shells are often current-aligned (Figure 31 b), sometimes fragmentary, and were probably washed into the lagoons.

Arthropoda

Within most Paleozoic faunas, arthropods are normally represented by the heavily sclerotized members of the Trilobita. Though it is always assumed that other arthropod groups comprised important portions of any community, they generally are poorly represented or, more commonly, not present at all. Trace fossils of uncertain origin sometimes confirm the presence of this unseen fauna.

Within the Eramosa *Lagerstätte*, this faunal pattern has been reversed. Organisms with calcitic skeletal material, such as trilobites, are decalcified, while lightly sclerotized arthropods and other soft-bodied organisms (including worms) are preserved by the replacement of tissue with calcium phosphate (as confirmed by microprobe analysis). The gut tract is preserved in some specimens as well. Among the phosphatized organisms are several problematic organisms of uncertain affinity.

Trilobita

Trilobites occur infrequently within the biota and include *Dalmanites* (phacopid, Figure 41 a), a ceratarginid (lichid, Figure 41 b), a calymenid (Figure 41 c) and an encrinurid (Figure 41 d). Disarticulated sclerites and articulated specimens

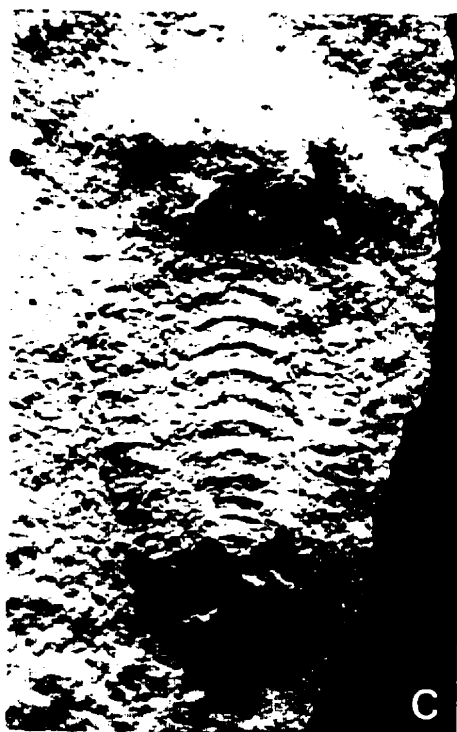
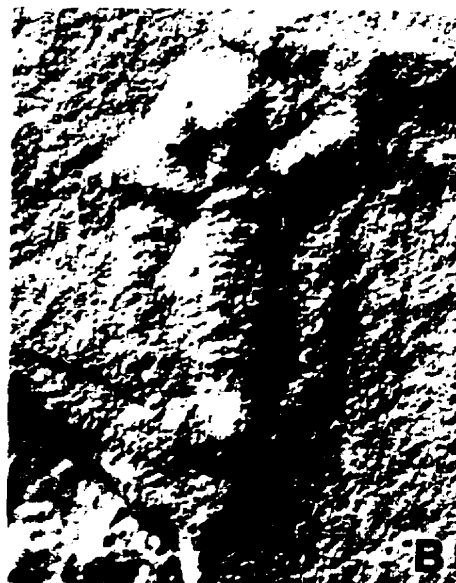
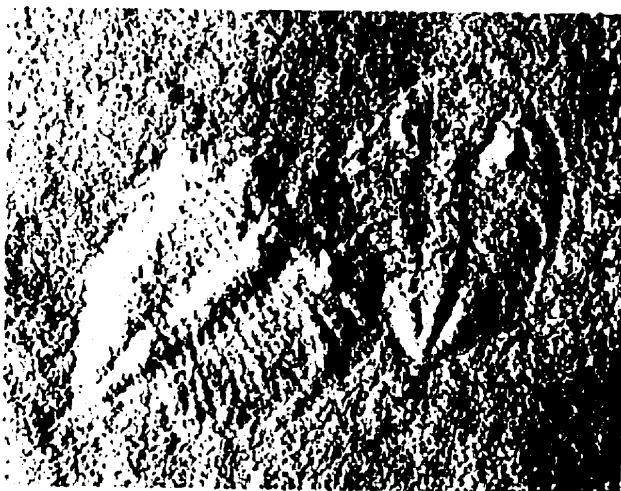
Figure 41. Trilobites from the lower Interbedded Unit of the Eramosa Formation.

A. *Dalmanites* sp.: x 2.6.

B. Ceratarginid lichid: x 3.3.

C. Calymenid: x 2.4.

D. Eocerinurid: x 1.9.



alike are generally preserved as faint impressions, making more accurate identification difficult to impossible. Articulated individuals probably represent carcasses (rather than molt ensembles) buried by storm events. These may have been killed when encountering inhospitable anoxic bottom waters and subsequently buried by sedimentation, or smothered by a storm event.

While calymenids as a group have a wide distribution, they tend to be facies-restricted at the generic- and family-level (Thomas 1979). Unfortunately such taxonomic identification is not possible with the very poorly preserved Eramosa specimens. Ceratarginids (such as *Trochurus* and *Acanthopyge*) and encrinurids commonly occur in Silurian shallow-water carbonate environments (Thomas 1979, Mikulic 1981, Mikulic and Watkins 1981). The ubiquitous phacopid *Dalmanites* occurs in an extremely wide variety of facies and water depths throughout the Silurian (Thomas 1979, Tetreault 1994).

Chelicerata

The largest organisms to occur within the Eramosa *Lagerstätte* are the eurypterids, and were likely the top of the food chain within the lagoons. Although exceedingly rare, they are (along with large cephalopods) one of the few fossils that quarry workers tend to notice. Over decades of hand-quarrying in the area, the many quarries have produced less than a dozen specimens. Occurring within the Eramosa are *Carcinosoma* (Figure 42 a), *Eurypterus* (Figure 42 b), and a stylonurid (possibly

Figure 42. Eurypterids from the middle Interbedded Unit of the Eramosa Formation.

A. *Carcinosoma* sp., from the Owen Sound Ledgerock (Wiar-ton) quarry:
x 0.28; ROM 49538.

B. *Eurypterus* sp., from the Georgian Bay Marble and Stone quarry, northwest
of Wiar-ton; x 0.6.

C. Stylonurid, from the Owen Sound Ledgerock (Cruikshank) quarry,
northwest of Owen Sound; x 0.36; ROM 49537.

D. Stylonurid, from disused pit near Amsen Quarry, northwest of Wiar-ton;
x 0.6; ROM 49536.



Kokomopterus, Figure 42 c. d). Preservation is normally very poor. Complete specimens have thus far not been recovered in situ (workers normally find them after rock has been removed from the quarry and partially processed), so there has been some question as to where in the section the eurypterids originated. During the course of fieldwork, fragments of *Carcinosoma* (walking and swimming appendages) and *Eurypterus* (telson) were recovered from the relatively unfossiliferous middle Interbedded Unit: a lithology that is similar to that of the complete specimens. Appendages possibly belonging to a stylonurid were retrieved from the uppermost Interbedded Unit.

Rarer yet than the eurypterids, scorpions also occur within the biota (Figure 43 a). Found within marine sediments, though their stratigraphic origin is uncertain, the new genera bear anatomical features that suggest scorpions may have already moved onto land (Waddington and Jeram 1997). This, in combination with the presence of a possible land plant within the biota (*Hostinella*), may indicate that the local topographic highs may not have been lifeless when subaerially exposed.

A probable xiphosure very similar to the xiphosure found in the Waukesha biota (Mikulic et al. 1985 a, b) occurs within the *Lagerstätte* beds of the lower Interbedded Unit. One specimen preserves the ventral surface of the prosoma and a portion of the post-abdominal segments (Figure 43 b), and has an outline reminiscent of the upper Silurian genera *Pseudoniscus* and *Bunaia* (which may be synonymous, Rolfe and Beckett 1984). A second specimen preserves the prosomal appendages, all of which appear to terminate in chelae (Figure 43 c.d).

Figure 43. Other chelicerata from the Interbedded Unit of the Eramosa Formation.

- A. Scorpion pre- and post-abdomen, under ethanol: x 3.8.
- B. Possible *Bunatia*-type chelicerate: x 2.7.
- C. Possible chelicerate with chelae, low angle lighting: x 3.1.
- D. Same, under ethanol: x 3.4.



Crustacea

Phyllocarida

The most common arthropods in the biota are the phyllocarid crustaceans *Ceratiocaris* (Figure 44 a) and *Caryocaris* (Figure 44 b). The most visible feature differentiating the two genera is the length of the terminal spine (referred to as the telson or style), where *Ceratiocaris* has an extremely long telson, while the telson of *Caryocaris* is short and approximately the same length as the furca (or "stylets"). Although there have been numerous Silurian phyllocarid taxa described, Rolfe (1969) synonymized all Silurian phyllocarids into *Ceratiocaris* and *Schugarurocaris* "pending revision". Under his classification, the specimens referred to as *Caryocaris* herein would be synonymous with *Ceratiocaris*.

Williams (1915) described the new eurypterid species *Eusarcus logani* from the type Eramosa locality near Guelph. Though the present whereabouts of the type specimens are unknown, the illustrated material appears to be fragments of *Ceratiocaris* (telson and mandibles). Collecting at the locality produced phyllocarid mandibles and other disarticulated remains. Pending the collection of better material from the Eramosa type section, it is possible that the long-telsoned *Ceratiocaris* from the Eramosa of the Warton area is the same species as the fragments Williams improperly assigned to the eurypterid genus *Eusarcus*, and thus should probably be redescribed and referred to as *Ceratiocaris logani* (Williams).

Figure 44. Phyllocarid crustaceans from the lower Interbedded Unit of the Eramosa Formation. All photographed under ethanol.

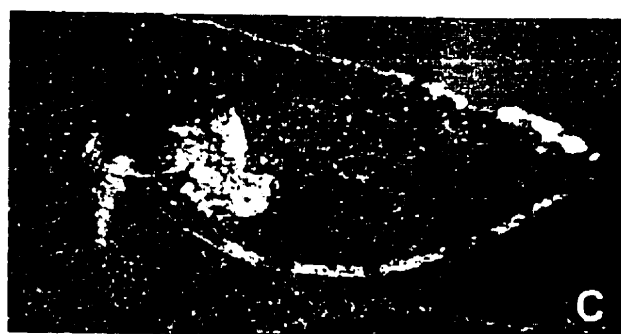
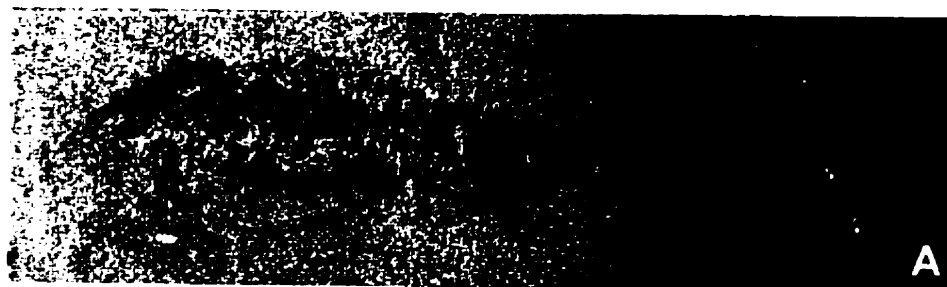
A. *Ceratiocaris* sp., with mandible and faint telopod preserved; x 2.1.

B. *Caryocaris* sp., with longitudinal thoracic muscles and partial pleopods preserved; x 2.7.

C. *Ceratiocaris* sp., preserving, mandible, anterior head region, and antenna and antennule bases

D. Enlargement of thoracic region of B, showing muscle fibers and pleopod bases; x 6.0.

E. *Ceratiocaris* sp., with displaced carapace preserving thorax and sediment gut-fill; x 2.4.



The Eramosa phyllocarids occur primarily within the lower Interbedded Unit, and show varying degrees of preservation. Bedding surfaces containing only disarticulated (and often current-aligned) phyllocarid telsons are common. Within the lower two meters of the Interbedded Unit, articulated individuals are common, preserving the abdominal and caudal segments and carapace. These often have intact jaw elements (mandibles) and probably represent carcasses rather than exuviae..

Within the phosphatized fauna of the *Lagerstätte* beds, preservation of the thoracic segments is common (Figure 44 b, e), sometimes with longitudinal muscle fibers (Figure 44 d), and possible short thoracic pleopod and long, narrow abdominal telopods appendages. One specimen preserves the anterior-most head segments, jaw, and the bases of the antenna and antennule (Figure 44 c). These structures compare quite favorably with those observed by Rolfe (1962) in *Ceratiocaris papilio*.

Though most specimens are preserved in a normal outstretched position, some individuals have a distinctively displaced carapace (Figure 44 e). These may represent individuals which had partially decayed and were displaced by gentle currents before burial, or may represent a *rigor mortis* position caused by contracting muscles. Although the individual in Figure 44 e contains a sediment gut fill and therefore is a carcass, other specimens do not and may represent exuviae in a "post-ecdysis" position.

Ostracoda

Large leperditid ostracods up to a centimeter in size occur within the Interbedded Unit, however they tend to be poorly preserved and difficult to identify.

Problematic Arthropoda

Preserved within the phosphatized Eramosa *Lagerstätte* are several organisms whose affinities are uncertain. Some are clearly arthropodan in nature, though in others it is difficult to distinguish between arthropodan-type or worm-type morphologies, chiefly because of their relatively poor preservation. Despite the difficulty in assigning these organisms, it is nonetheless useful to note their presence, as they represent an important portion of the community that normally is never preserved. Some have been found in other faunas (particularly the Brandon Bridge *Lagerstätte*), and variously ascribed to different groups.

The most common of these problematic organisms is a 1-2 cm segmented organism with a posteriorly tapering body and a relatively large, triangular tail or telson (Figure 45 a, b). The head region appears to have numerous small appendages, and projections from trunk segments may or may not represent appendages. The most visible and often only clear anatomical feature is a series of dark, rectangular, paired structures that begin near, or just behind, the head region, one pair per segment, and become progressively smaller in size posteriorly. It is unclear whether these structures represent an internal or external part of its anatomy. The organism may be a crustacean, and was an important part of the community within the lowermost, less diverse *Lagerstätte* beds in the lower Interbedded Unit, being outnumbered only by phyllocarid crustaceans.

A rarer organism within the lower Interbedded Unit is a relatively large arthropod with large grasping head appendages (Figure 45 c). This organism is very

Figure 45. Problematic arthropods from the lower Interbedded Unit of the Eramosa Formation. All photographed under ethanol.

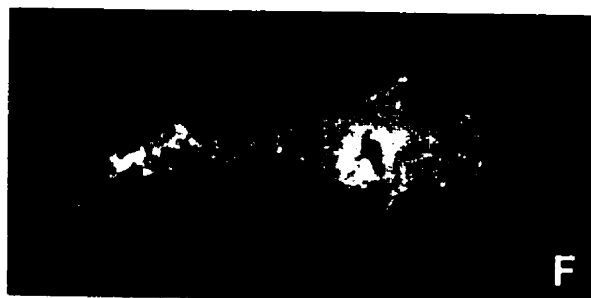
A, B. Possible crustacean: both x 4.1.

C. Possible remipede or branchiopod crustacean: x 2.2.

D. Unknown arthropod: x 2.1.

E. Unknown arthropod or polychaete: x 2.7.

F. Possible crustacean or chelicerate: x 3.0.



similar to one found within the Brandon Bridge *Lagerstätte* described by Mikulic et al. (1985 a, b), and equivocally assigned to the branchiopod or remipede crustaceans. Although the Remipedia have grasping head appendages (much smaller in size than the Eramosa and Brandon Bridge organisms) and a non-regionalized trunk (Schram 1986), many other arthropod groups have evolved similar raptorial appendages. Without better specimens that clearly show other head appendages and their relative positions and the structure of any trunk appendages, a definitive assignment is not possible. The Eramosa specimens differ from the older (Llandovery) Brandon Bridge specimens in having a smaller head region and a trunk which tapers less posteriorly.

Also found within the *Lagerstätte* of the lower Interbedded Unit is a relatively common, 2-4 cm segmented organism with no clear head region preserved (Figure 45 d). The ovate organism has approximately 12 or 13 dorsal segments, and lateral structures that may represent extensions of the primary tergites, or separate structures. The organism may or may not be a crustacean. A single specimen with a different preservation style (Figure 45 e) may represent the same organism, though this specimen appears to display polychaete-like features, with lateral projections possibly corresponding to paired parapodia.

A single specimen found within the lower *Lagerstätte* beds is a lateral view of a segmented organism with a large head region, several head appendages, an undifferentiated trunk, and tapered tail or telson (Figure 45 f). This specimen has some similarities to several organisms already described from dorsal views only (the xiphosure, Figure 43 b-d, and possible crustacean, Figure 45 a,b), or may represent another organism entirely.

One of the most spectacular organisms found within the Eramosa *Lagerstätte*, and another element common between the Eramosa and Brandon Bridge faunas, is a 3-6 cm, many-legged, organism (Fig 46 a-f). Described here because of the myriapodan arthropod assignment made by Mikulic et al. (1985 a, b), such assignment is far from unequivocal based on the specimens at hand. The record of Silurian myriapods is very sparse and poorly understood (Almond 1985). The organism is segmented, with an articulating annulation between each segment, implying a stiffened, arthropod-like integument. One specimen preserves a secondary segmentation, annulation or ornamentation (Fig 46 e). Each segment bears a pair of appendages, very thick at the base and tapering distally. The appendages of the Eramosa specimens show no evidence of segmentation, but rather appear flexible and annulated (Fig 46 b), much as is present in the Lobopodia. One specimen (Fig 46 b) shows evidence of post-mortem contraction of the appendages. The style of preservation varies from specimen to specimen, possibly indicating that mineralization occurred at different stages of decomposition, and illustrates the deformation of a possibly flexible integument (Fig 46 f). Some specimens (Fig 46 a, c) show what appear to be paired terminal claws, a feature more consistent with lobopods (Hou and Bergström 1995) than myriapods, though this may be a preservation artifact. If this organism is a lobopod, a taxon which is generally believed, through paleontological evidence (Dzik and Krumbiegel 1989, Hou and Bergström 1995) and molecular sequence analysis (Aguinaldo et al. 1997), to have not been ancestral to the arthropods (and myriapods in particular), then these organisms could not possibly have given rise to terrestrial myriapods.

Figure 46. Possible lobopod or myriapod from the lower Interbedded Unit of the Eramosa Formation.

A. Individual with possible claws, under ethanol; x 1.8.

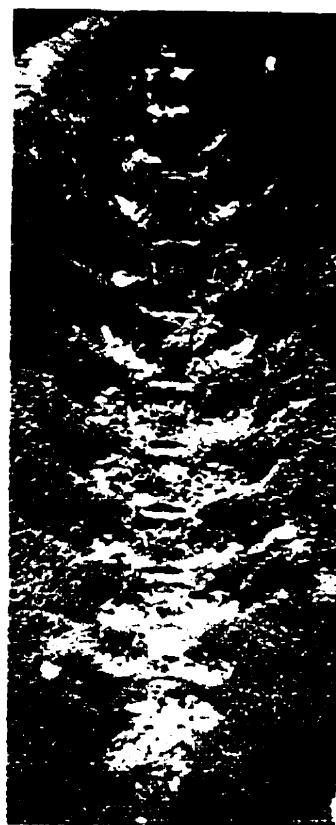
B. Same as A, photographed under low-angle lighting, showing annulations on appendages; x 1.8.

C. Another individual, under ethanol; x 2.3.

D. Another individual, showing curled appendages, under ethanol; x 2.2.

E. Specimen showing secondary annulation or ornamentation on body segments, under ethanol; x 2.1.

F. Partially decayed specimen, under ethanol; x 2.7.



Echinodermata

Crinoidea

Crinoids are rare, though present within the biota. A few rare beds of tangled mats of crinoid stems (sometimes partially silicified) and disarticulated columnals are found, though the stalks are quite thin (1 to 2 mm), and represent small species. Several articulated crowns were recovered, completely decalcified, indicating that they were not transported far, if at all. Positive identification is impossible due to the poor preservation, although one specimen represents an inadunate, and a second (Figure 47 a) is a pinnulated camerate .

Ophiuroidea

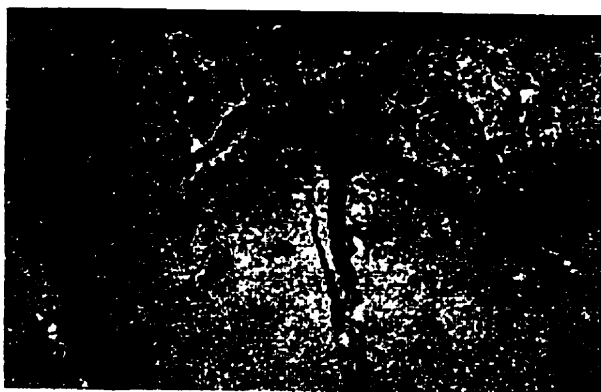
A single bedding surface in the lower Interbedded Unit yielded large numbers of ophiuroids (associated with rhynchonellid brachiopods and the trilobite *Dalmanites*) (Figure 47 c). Occurring in densities of approximately 20 per square meter, the ophiuroids are preserved as faint molds, some of which contain small amounts of bitumen (Figure 47 b). Recrystallization is such that the plate arrangement cannot be discerned, but they compare favorably with the gross morphology of the middle Silurian ophiuroid *Protaster*. Most individuals are of approximately the same size, and may represent a single generation.

Figure 47. Echinodermata of the lower Interbedded Unit of the Eramosa Formation

A. Pinnulated camerate crinoid: x 1.9.

B. Ophiuroid (brittle star), under ethanol: x 2.1.

C. Bedding surface with ophiuroids, poorly preserved rhynchonellid brachiopods, and a *Dalmanites* cephalon: x 0.8.



Echinoidea

One of the most interesting occurrences within the Eramosa *Lagerstätte* is a single bedding surface with a monospecific colonization of echinoids (Figure 48 a). With a density approaching 100 individuals per square meter, all the echinoids within this bed surface are preserved in living position as shallow depressions in the underlying sediment. As with so many of the other fossil occurrences within the *Lagerstätte*, most of the individuals are of a similar size and probably represent a single generation. Of the hundreds of specimens collected, every specimen without exception was found with the ventral side down. They have all been decalcified, with only the indistinct impression of the Aristotle's lantern and perignathic girdle (Figure 48 b). Some specimens preserve a faint impression of the ambulacral and interambulacral plates.

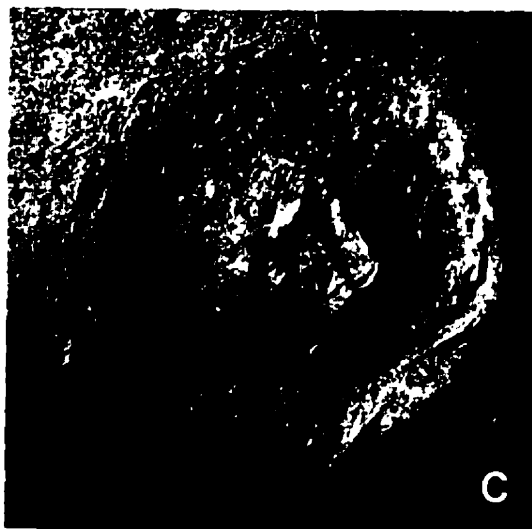
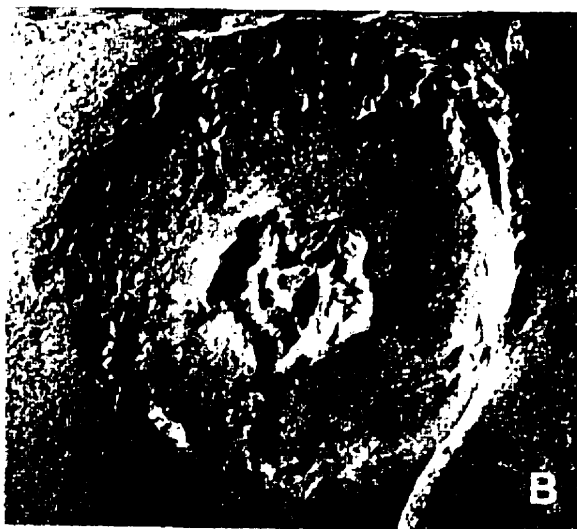
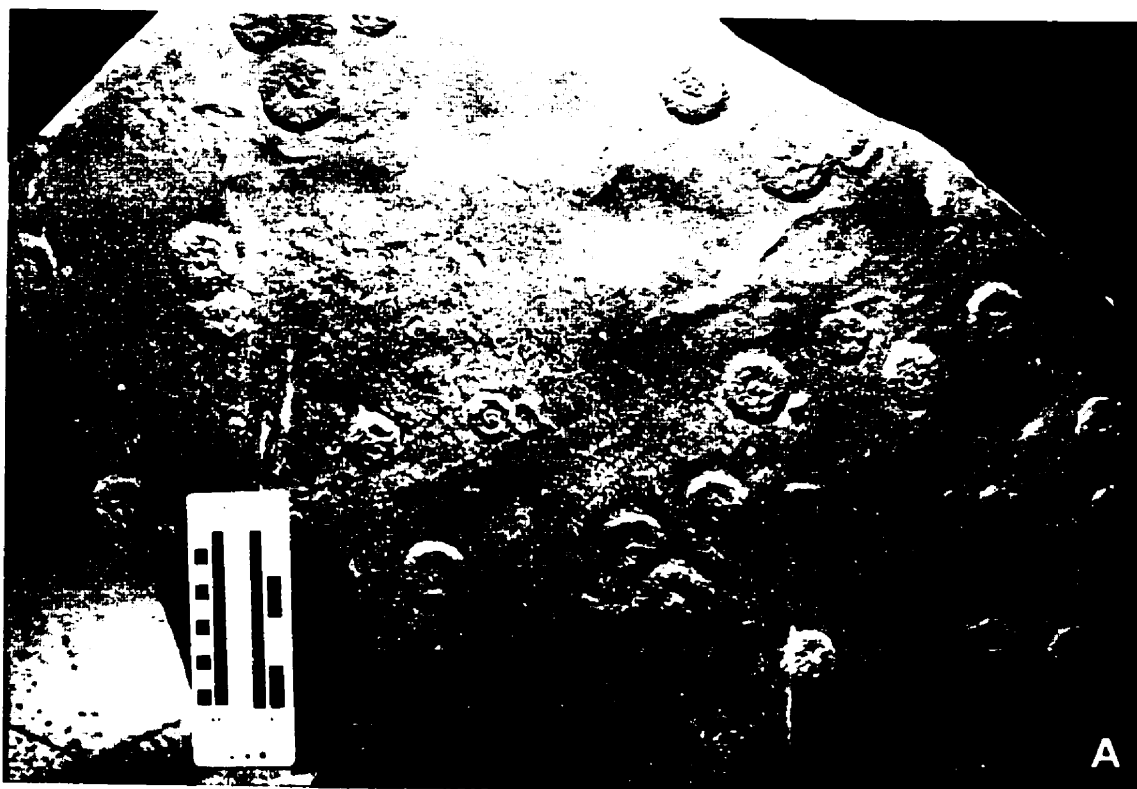
Poor plate fusion, which was common to all Silurian echinoids, has resulted in a rather pervasive taphonomic signature. In most figured specimens throughout the literature, there is evidence, often quite strong, of post-mortem or depositional distortion, if not fragmentation. Few preserve the original, presumably spherical, shape. This deposit is unusual taphonomically in that the lower 10 to 20 percent of the echinoid is preserved as a shallow 3-dimensional bowl set into a 1 cm thick tempestite. Lithology above and below this lighter dolostone bed is a dark, laminated shaly dolostone. Sometimes part of the echinoid test above the rim of the depression is preserved and has been flattened down onto the surrounding sediment, often

Figure 48. Echinoidea from the lower Interbedded Unit of the Eramosa Formation.

A. Bedding surface with numerous lepidocentrid echinoids; 0.23.

B. Internal view of echinoid oral surface, with jaws intact (aristotle's lantern);
x 1.6.

C. Internal view of echinoid oral surface with "unzipped" ambulacra at lower
left; x 1.3.



causing the ambulacra to "unzip" (Figure 48 c). The inside surface of the depression of some of the specimens contains only a partial sediment fill.

Figure 49 proposes a possible sequence of events to account for the taphonomy of this occurrence. The lagoon began as an anoxic environment, depositing dark, laminated sediment. A minor storm deposited a thin bed of carbonate silt and temporarily oxygenated the lagoon. Algae flourished in the warm, nutrient-rich lagoon, attracting the feeding echinoids. As the algae began eutrifying the lagoon, an oxycline formed just above the sediment. Virtually simultaneously, due to changes in the water chemistry, the echinoids died in place, and the carbonate-silt bed lithified, preserving their lower surfaces. The portions of the echinoid tests that were above the oxycline disintegrated, the poorly fused plates disarticulating and scattering, while the portion below the oxycline remained intact long enough, possibly with the help of a cyanobacterial film, to be buried by sediment. Very early lithification of the silt bed is further evidenced by the presence of a lantern in all specimens despite the complete disintegration of the upper 80% of the test, the lantern effectively being cemented into place before decay of the connective tissue.

Taxonomic Position

The early Paleozoic record of the Echinoidea is sparse, and there is little with which to compare the new discovery. The earliest "echinoids" are Middle Ordovician in age belonging to the Bothriocidarids. While superficially resembling echinoids in nature, bothriocidarids lack many features common to echinoids, and thus may be a stem to holothurians, rather than echinoids (Smith 1984). This leaves the

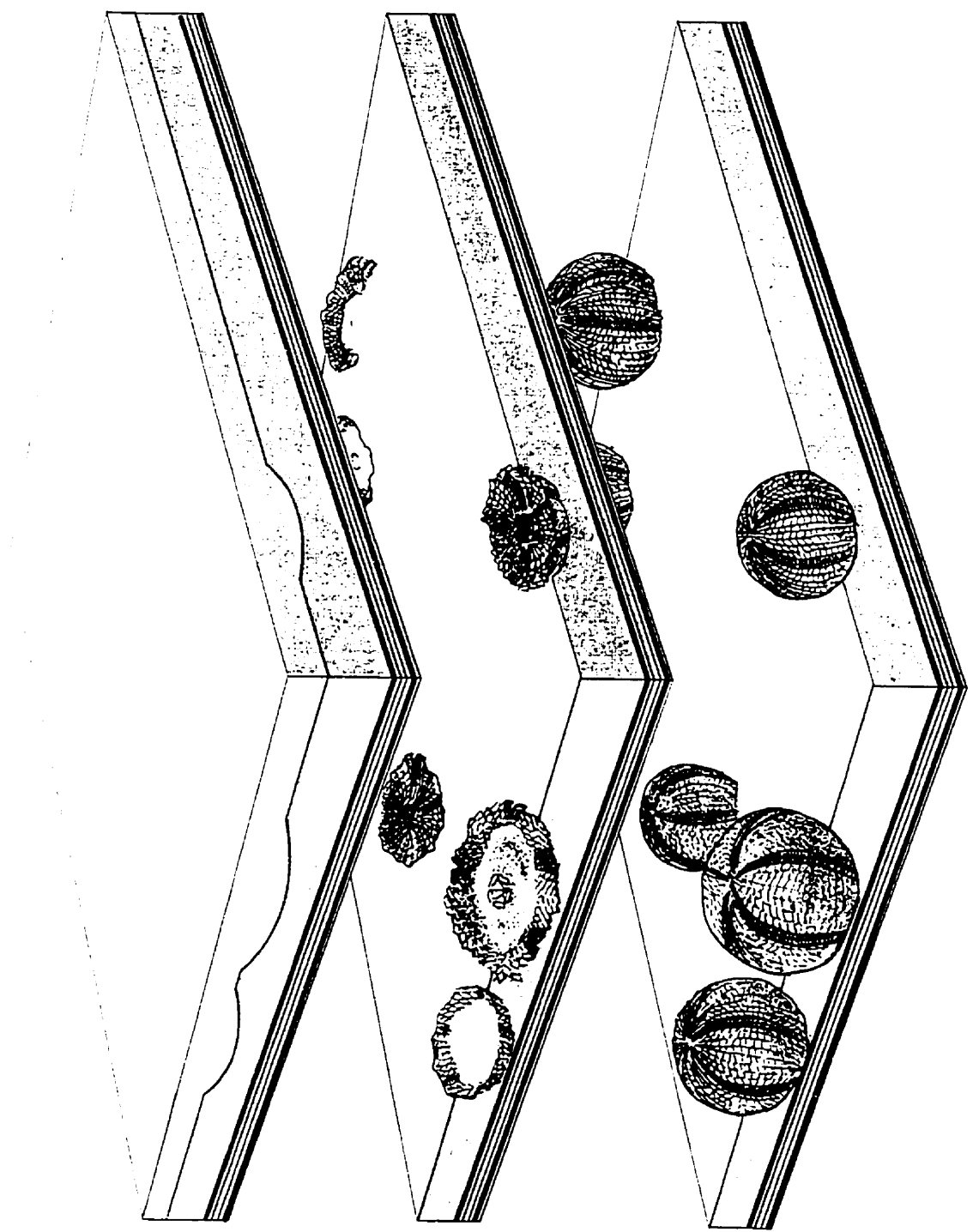
Figure 49. Reconstruction of the formation of the Eramosa echinoid bed. Drawing by C. Tsujita.

Bottom: Echinoids populate the surface of a thin carbonate silt storm bed.

Tests form depressions into unlithified sediment.

Middle: Death of echinoids, cementation of carbonate silt bed, and disintegration of upper portion of echinoid tests.

Top: Burial of surface.



lepidocentrids as the earliest group of true echinoids, with a record beginning in the Upper Ordovician. Lepidocentrids, as currently defined, are a heterogeneous group of all those echinoids whose only common feature is that they lack any of the more advanced characteristics of later groups and include the ancestors to several later lineages (Smith 1984). The only descendant group with a Silurian record is the echinocystitids.

The Wiarton echinoids are characterized by narrow, biserial ambulacra and at minimum a six-, perhaps seven-column interambulacral region. They most closely resemble *Koninckocidaris silurica* Jackson 1912. Although Jackson makes reference to the modern echinoid *Cidaris* in the naming of his new genus, the genus bears little resemblance to the true cidarids and is phylogenetically rather removed from that lineage, illustrating the danger of incorporating nomenclature from other temporally distant taxa into the naming of new taxa.

The type species of *Koninckocidaris*, *K. cotteauxi* Dollo and Buissert 1888, occurs in the Mississippian and is based on a fragment of a test and isolated plates that were never figured in the original description, and that "considering the great change that occurred in echinoid morphology between the Silurian and Mississippian, it is unlikely that the two forms are congeneric" (Kier 1965). It is likely, therefore, that *K. silurica* is a new genus. Unfortunately the repository of the only specimen of *K. silurica* is currently unknown. Watkins and Kuglitsch (1997) recovered small echinoid spines from a lower Silurian silicified fauna (Burnt Bluff Group of the western Michigan Basin), but taxonomic work on such fragmentary material is not possible.

Evolutionary and Ecologic Importance

The low preservation potential of echinoids most certainly has had an effect on the sparse Paleozoic fossil record of these organisms. Smith (1984) proposes that the principal cause of the low species diversity was probably that Paleozoic echinoids simply never adapted to a wide variety of habitats compared with those in which post-Paleozoic echinoids are found. Smith further states that "throughout the Paleozoic, echinoids seem to have been broadly restricted to quiet, off-shore habitats." The present new discovery would seem to counter both those statements, and suggests another possible reason for their absence from the paleontologic record. If early Paleozoic echinoids were living in near-intertidal environments, their preservation potential would be negligible considering the particularly fragile nature of lepidocentrids, and the low probability of preserving the very-nearshore environment because of reworking by waves, or storms. Looking at modern reef and near-reef environments within the Bahamas, Greenstein (1993) observed that the distributions of regular echinoids (which have far better plate fusion than Paleozoic echinoids) were not reflected in subfossil deposits in those same environments, unlike the burrowing irregular echinoids; thus their life habits contributed to a strong taphonomic bias against their preservation. Experimental studies on the decay and disintegration of modern echinoids by Kidwell and Baumiller (1990) show that disintegration of tests (despite good plate fusion) can begin within days of the organism's death, and predictions made from their study indicate that high temperatures and water depths less than 20 meters (which would be characteristic of

the Eramosa lagoons) contribute to the worst possible preservation potential. Furthermore, the tendency of near-shore carbonate environments in the lower Paleozoic to undergo severe dolomitization would limit preservation potential even more.

Chordata

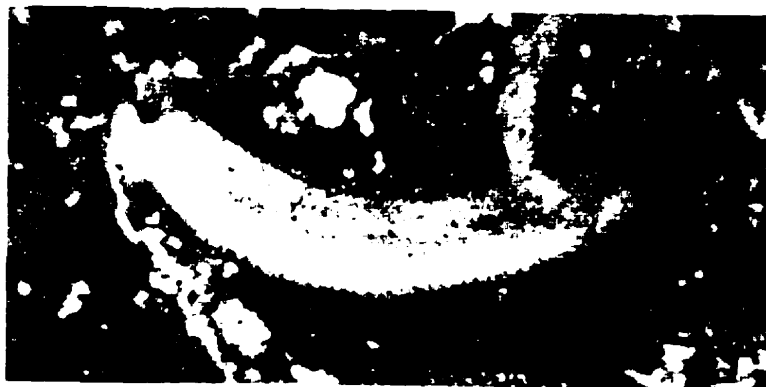
One of the smallest, yet most intriguing organisms from the Eramosa biota is a 1.5 to 2 cm segmented, worm-like animal (Figure 50 a, b). The organism has a clearly identifiable enlarged head region somewhat triangular in profile, and, on some specimens, a visible gut. If there were no further discernable features, the organism could be classified as an errant polychaete. Close examination reveals that the segmentation appears to have a zigzag pattern similar to the myomeres of modern *Amphioxus* and the Cambrian *Pikaia* of the Burgess Shale, and a thin linear structure running the length of the organism above the gut-trace may be interpreted as a notochord. It would seem possible, then, that this organism was a cephalochordate. Although the Burgess has generally been thought to represent a deep-water facies, *Pikaia* is quite rare in the deposit, and today, *Amphioxus* lives in very shallow coastal waters.

Trace Fossils

Though bioturbation is rare throughout the section, bedding planes within the lower Interbedded Unit can contain enormous numbers of *Planolites*-type burrows.

Figure 50 A, B. Possible *Amphioxus*-like primitive chordate, under ethanol.

A. x 3.4, B. x 2.9.

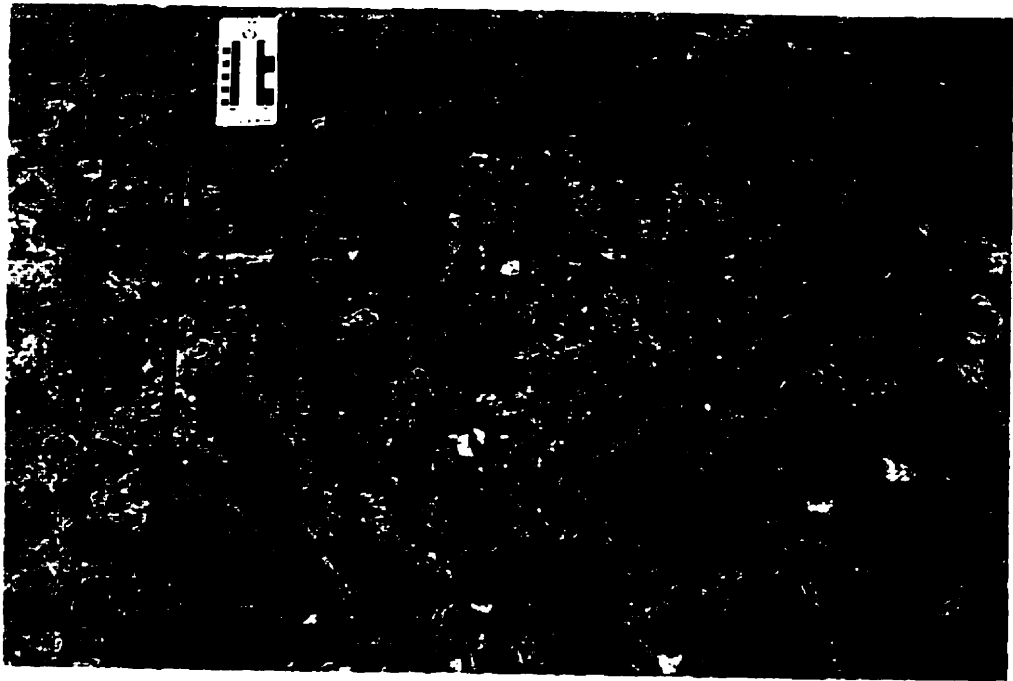


These usually consist of long, sinuous, horizontal burrows of varying sizes, ranging from a few millimeters up to 3 cm in width (Figure 51 a), and never penetrating very deeply into the sediment. The burrows on these bedding surfaces often are of the same size, with size varying from surface to surface. Rarely, branching burrows do occur and, in one particular bedding surface, can reach a fairly large size (Figure 51 b).

One particular type of burrow common on some bedding surfaces is unlike the previously described burrows in being unusually short and straight, and often showing almost angular tapering at both ends (Figure 52 a,b). Another unusual feature sometimes seen on these burrows is a very narrow single, rarely double, groove leading up to the larger burrow. The size of the main portion of the burrow varies from 10 to 25 mm in width, but like previously described burrows, burrow size on any particular surface tends to be relatively consistent.

The short, straight nature of these burrows combined with the unusual, narrow groove, is inconsistent with any structures that would be expected from the normal burrowing behavior of a worm. Phyllocarids are quite commonly found throughout the Interbedded Unit, and it is known that modern phyllocarids burrow in sediment (Vannier et al 1997), though as much smaller organisms. Recent nebuliid phyllocarids can burrow completely into the sediment with relative ease. Figure 53 illustrates how *Ceratiocaris* could produce the traces observed within the Eramosa. Most of the digging activity was done with the sturdy antennae, with the pleopods used for pushing back loose sediment and possibly assisting in forward movement. Once the elongated carapace of *Ceratiocaris* had begun making the groove-shaped furrow, it would have been more efficient to continue in a straight line.

Figure 51. Large unbranched (A) and branched (B) horizontal burrows from the Interbedded Unit of the Eramosa Formation, Wiarion quarry.

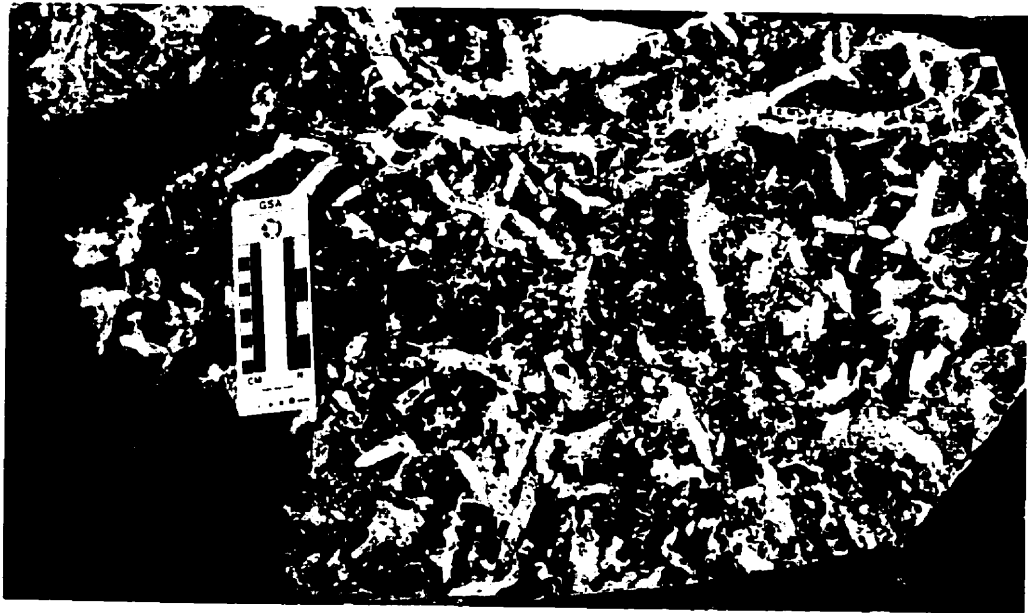


A



B

Figure 52. A, B. Relatively short, straight, burrows possibly attributable to the burrowing activity of phyllocarid crustaceans. Note double grooved trace at arrow.

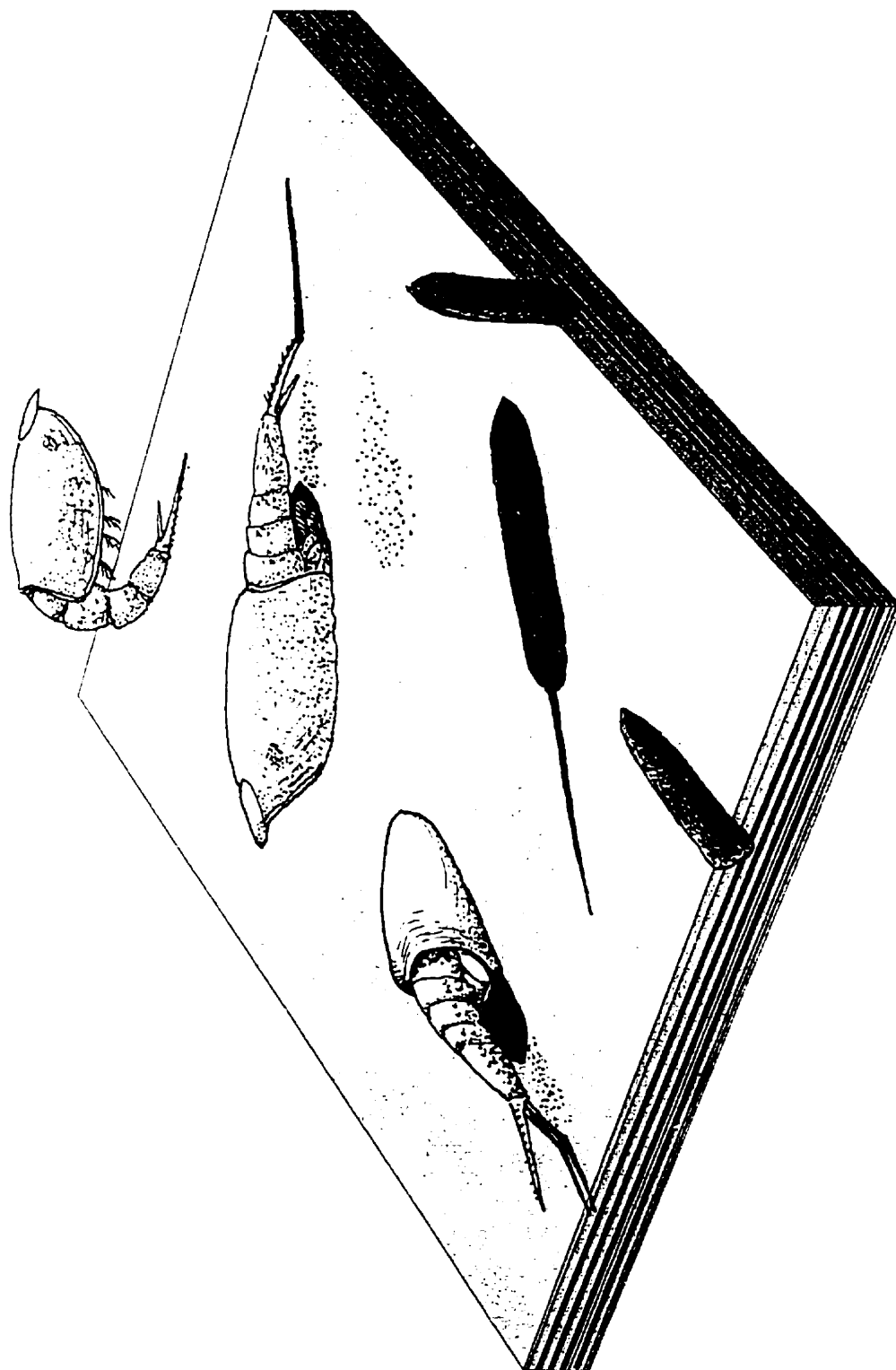


A



B

Figure 53. Reconstruction of the creation of traces by burrowing phyllocarid crustaceans. Drawing by C. Tsujita.



Though Paleozoic phyllocarids had generally large and massive mandibles, this does not necessarily indicate carnivorous habits (Rolfé 1969, Schram 1986). Modern phyllocarids (leptostracans) lack massive jaws, and derive a portion of their diet by filter-feeding using the thoracopod setae. *Ceratiocaris* may have been too large to feed microphagously, but interpretation is hampered by the fact that burrows possibly constructed by such a large crustacean have never been previously found in association with deposits containing their actual fossils (Rolfé and Beckett 1984). Larger *Ceratiocaris* were probably macrophagous, and may have fed on larger pieces of detritus. Rolfé and Beckett (1984) suggest that the absence of any raptorial limbs indicates that *Ceratiocaris* was not an active predator, and its detritus feeding habit is confirmed by sediment packed gut infills (Figure 44 e).

Paleoecology

While the diversity of the Eramosa biota as described above is quite high, the distribution of organisms throughout the section is not uniform, and varies as a result of both ecology (original populations) and taphonomy.

The lowermost Eramosa exposed in the study area, the "Marble" Unit, consists of a stromatolitic, non-fossiliferous facies. The lack of any fossil fragments and traces probably indicates that there were no other organisms inhabiting the lagoon at the time. As one rises in the section through the Middle Unit and into the Interbedded Unit, slight changes in water depth resulted in intermittent access to normal marine waters and therefore frequent and rapid changes in temperature, oxygen and salinity. This produces population boom-bust effects on a bed-by-bed basis, community composition often changing each time. However, some generalizations can be made.

A trace fossil association is the first evidence of animal life to enter the lagoons, consisting of bedding planes with large numbers of small or large horizontal *Planolites*-type and *Chondrites*-type feeding burrows. These burrowed surfaces occur with the event beds of the Middle Unit, and probably represent brief pulses of normal, or near-normal salinity waters brought into the lagoons during storms.

At the base of the Interbedded Unit, the first *Lagerstätte* beds occur, consisting principally of a phyllocarid association containing several types of soft-bodied organisms, the most common of which is the possible crustacean in Figure 45

a and b. Also within this zone is a single bedding surface containing a monotypic community of echinoids.

The next meter of the Interbedded Unit consists primarily of a rhynchonellid-phyllocarid association. Many bedding surfaces within this sequence contain only phyllocarids, only rhynchonellids (sometimes in the form of shell beds, Figure 32 a), or both. Occurring here also are rare trilobites, and a single bedding surface populated by ophiuroids (Figure 47 c). These surfaces, like most fossil beds, are communities that have gone through the "taphonomic filter", resulting in the preservation of organisms with robust exoskeletons. Through this sequence, however, are numerous *Lagerstätte* beds containing most of the soft-bodied organisms recovered during this study. One large bedding surface (approximately 1.2 by 1.2 meters) recovered from this sequence contained on average 50-100 rhynchonellids (their poor preservation makes it difficult to assess what is and isn't a brachiopod), 80 phyllocarids, 8 polychaetes (Figure 37 e,f), 8 problematic crustacea (Figure 45 d), and single examples of other organisms (the "remipede" crustacean and an annelid, among others) per square meter. This probably more accurately represents the composition of the community at the time. It should be noted that larger phyllocarids are slightly over-represented because their size results in exposure of individuals one lamina above and below the surface actually being counted. Most of the phyllocarids on this surface, however, are quite small and not represented at all in the non-*Lagerstätte* beds.

Rising up through the lower meter and into the second meter of the Interbedded Unit, rhynchonellid brachiopods become more common, as do trilobites,

while phyllocarids become much rarer. This change is real, and probably represents more normal marine waters affecting the lagoons, although the lack of any *Lagerstätte* beds prevents speculation on the changes to the soft-bodied portion of the community. The presence of bedding planes with horizontal burrows indicates that there certainly was an unpreserved fraction of the community.

Above the rhynchonellid-phyllocarid association is a recurrence of the trace fossil association, with bedding planes covered with horizontal *Planolites*-type traces (Figure 51 a,b). For the next several meters of section above this is a fairly unfossiliferous sequence of laminated dolostones containing rare cephalopods and eurypterids. The cephalopods were likely transported in by currents. The eurypterids are so exceedingly rare that they also may represent individuals that were brought in (though still living) or were merely part of a sparse fauna. It may therefore be inappropriate to assign this as a eurypterid association, since many eurypterid faunas normally have very low density populations.

In the uppermost meter or two of the Interbedded Unit occurs a thallophytic alga-scolecodont association, dominated by the dasycladacean green alga *Wiarionella*. Though only their jaws are preserved, the numerous articulated elements indicate that the scolecodont polychaetes must have been fairly common and autochthonous. Rhynchonellid brachiopods are also a minor part of the fauna.

The last major community, the reef association, is only represented by allochthonous material brought into the outcrop area by storm-generated debris flows and consists of *Favosites* corals and unidentifiable crinoid and brachiopod debris.

General Taphonomy

Due to the great variation in both environmental conditions and in community structure within the Eramosa lagoons, the taphonomic nature of the fossil beds also varies greatly. The Eramosa contains both concentration- ("*Konzentrat*") and conservation-type ("*Konservat*") *Lagerstätten* deposits, the former represented by storm-winnowed brachiopod shell beds and the latter by the soft-bodied fauna of particular interest to this report.

Many of the organisms preserved within the Eramosa *Lagerstätte* appear to have been buried rapidly by sediment, though the sediment layer is not always thick. Such obrution of the sea-floor community could smother smaller organisms, but would seem unlikely to be sufficient to kill larger organisms. The dark, organic-rich nature of these *Lagerstätte* beds would suggest anoxia below the sediment water interface. Disturbance of sediment during a storm could effectively poison the lagoon community, burying it under a thin layer of sediment as it settled out of suspension. The sometimes twisted body positions of organisms (such as some phyllocarids) suggests such current action could occur during these burial events. Conversely, other beds such as the echinoid community suggest that death occurred instantaneously across the sea floor, but without any disturbance whatsoever, evidenced by the life-position (oral side down) of 100% of 100's of specimens (and the rolling of a spherical organism would seem to be easily done). These community-kills may have been caused by the isolation of the lagoon from normal marine waters and a subsequent water temperature increase, or by a the changing water chemistry initiated

by resulting algal blooms. The very high organic content of the sediment, probably a result of high algal productivity (Dix 1990), produced rapid anoxic conditions below the sediment water interface, and during periods of poor water circulation the oxycline may have periodically risen above the sediment surface killing any organisms that were trapped in, or entered into that zone.

The importance of anoxia in the preservation of exceptional biotas is clear, as evidenced by the presence of anoxic conditions in many *Lagerstätten* (Seilacher et al. 1985, Allison 1988b). Anoxic sediments will, most importantly, prevent bioturbation and the consequent disturbance of a decaying buried carcass. However Allison (1988a) determined experimentally that anoxia alone is not responsible for the preservation of soft-parts, and that decay occurs quite effectively under anoxic conditions.

Within the upper thallophytic-alga *Eramosa Lagerstätte*, the flora is carbonized. The thin shale laminae that preserve this material is extremely high in carbon content, and buried by thick carbonate debris flows. The 3-dimensional nature of many of the *Wuartonella* specimens suggests that very early cementation of the sediment occurred, effectively sealing the alga before decomposition could occur. Organic diagenesis, particularly in the presence of clays, can assist in the preservation of structural tissues such as plant and animal cuticles (Butterfield 1990). Animal tissue, however, was not preserved, as evidenced by the numerous articulated polychaete (scolecodont) jaws. These worms were clearly present and caught up the the obrution event, although the *in-situ* jaw elements were preserved without any evidence of the organisms body.

Within the lower phyllocarid-dominated *Lagerstätte*, the soft-bodied fauna is preserved as phosphate thin-films, hence a different process must be responsible. Briggs et al. (1993) showed experimentally how phosphate could be deposited within the bodies of decaying organisms by bacteria. Such precipitation can preserve fine details, as seen in the Eocene Messel Lagerstätte from Germany (Wuttke 1983) and the Cretaceous Santana Formation of Brazil (Martill 1988). For phosphatization to occur, rate of burial should be low and organic content high (Allison 1988b). Algal production and decay within the lagoons could provide a source of excess phosphate, helping to initiate the process. Bacterially sealing the organism and its immediate surroundings is important for the process to proceed rapidly enough to precipitate phosphate before the organism decays (Briggs et al. 1993). Within the Eramosa, there is ample evidence for cyanobacterial films coating the lagoon floors, much as those seen in the Solnhofen (Barthel et al. 1978, Seilacher et al. 1985), and this could have facilitated the initiation of multiple nucleation sites for the phosphate mineralization of many carcasses over an entire bedding surface. The locally low-pH conditions required for the production of phosphate would be neutralized by any carbonate exoskeleton (dissolving the calcite in the process), perhaps explaining why soft tissue is not preserved in trilobites and molluscs present on these same bedding planes. These taxa appear to have undergone dissolution prior to sediment lithification, as they are preserved as faint impressions, and not casts. Some echinoderm material (mostly crinoid columnals), on the other hand is preserved as molds, and thus had undergone dissolution after lithification had occurred.

For the soft-tissue of an organism to be preserved, the process must occur very quickly over days or weeks, yet the fossils are preserved as thin films. Even at high rates of sedimentation, which is certainly not the case in the Eramosa, it would take decades to accumulate a sediment load high enough to begin compaction of an unlithified sediment (Weller 1959), and there is evidence for early cementation throughout the Eramosa. Zangerl (1971) suggests that flattening of fossils occurs as the collapse of void space left behind after the decomposition of the organism. Any disseminated phosphate would then be flattened along the plane of compaction, the thickness of the phosphate being determined by how much had been produced before complete decay of the carcass.

Lagerstätten Classification and Comparisons to other Exceptional Biotas

As can be seen above, the Eramosa actually preserves three different types of *Lagerstätten*. A phyllocarid-dominated biota in the lower Interbedded Unit, a eurypterid biota in the middle Interbedded Unit, and a dasyclad-algal-dominated biota in the upper Interbedded Unit. Kluessendorf (1994) statistically separated Silurian *Lagerstätten* into two primary groups: eurypterid-phyllocarid-dominated (EP) biotas and dendroid-graptolite-characterized (DG) biotas. LoDuca (1995) added a third *Lagerstätte* type, the thallophytic-alga-dominated (TA) biota.

The EP biotas, occurring mostly in the Late Silurian, show a high degree of similarity (Kluessendorf 1994). Diversity is generally quite low and consists almost exclusively of arthropods (mostly eurypterids, though phyllocarids and ostracods also commonly occur, and rare scorpions have been found). The Eramosa eurypterid fauna is exceedingly sparse, but it consists of at least three eurypterid genera and possibly two scorpions, and fits well within the EP classification. EP biotas occur widely, particularly around the Michigan Basin, and have been studied for some time because of their rather spectacular fossils (especially the Upper Silurian Bertie Dolostones in Western New York, e.g. Clarke and Ruedemann 1912, O'Connell 1916). Seilacher et al. (1985) contended that the extraordinary hydrographic, sedimentational and early diagenetic conditions required to preserve a *Fossil-Konservat-Lagerstätte* were such that their occurrence could be predicted. Specifically, Kluessendorf (1995) notes that the position of EP biotas in hypersaline peritidal environments surrounding the evaporitic Michigan Basin makes them highly predictable. In fact, the position of the Wiarton *Lagerstätte* fits within a gap in the predicted geographic belt.

The *Wartonella Lagerstätte* of the Eramosa likewise fits very well into the TA biota category. Thallophytic-alga-dominated biotas as defined by LoDuca (1995) may contain both dasycladalean and non-dasycladalean alga and worm phyla, in addition to a more diverse, normal-marine fauna than EP biotas, including dendroid graptolites, brachiopods, molluscs and corals. The *Medusaegraptus* epibole of the Gasport Formation in western New York (LoDuca 1990, 1995, LoDuca and Brett 1997) is an example of a TA biota. The Eramosa TA biota has more diverse algal flora preserved, and includes worms, brachiopods and molluscs, although there is a

notable absence of dendroid graptolites, generally a major component of other TA biotas. The proximity of the Eramosa TA biota to a nearby reef (represented by allochthonous coral and crinoid material) confirms a possible relationship to these types of faunas, however they are not a noticable component of the autochthonous Eramosa TA community.

The third Eramosa *Lagerstätte* biota is more difficult to classify. The DG biota, as defined by Kluessendorf (1994), contains a more diverse, normal marine fauna than EP biotas, but is generally dominated by dendroid graptolites - an element that is completely lacking from all of the Eramosa *Lagerstätten*. Phyllocarids, a major component of the fauna, are generally associated with EP biotas, while the phyllocarid-rhynchonellid association is clearly not, though they may also occur as a minor component of DG biotas. Examples of DG biotas include the Brandon Bridge of southern Wisconsin (described by Mikulic et al. 1985 a,b) and the Leclay Shale of northern Illinois (described by Weller 1925, Roy and Croneis 1931, Lowenstam 1948), all of which include dendroid graptolites as part of the fauna. With this exception, however, there are several unique organisms common to the Brandon Bridge and Eramosa, despite their different ages, of late Llandovery and Early Ludlow respectively. This would seem to suggest a close ecological relationship between the two biotas. Kluessendorf (1994) also placed the Mississinewa Shale *Lagerstätte* of northern Indiana (described by Erdtmann and Prezbindowski 1974) as a DG biota, though LoDuca and Brett (1997) suggest that the presence of dasycladalean alga would more properly indicate a TA-type biota.

Paleoenvironmental Interpretation

The Eramosa is interpreted as being deposited on a wide carbonate platform on the margin of the Michigan basin. Major biohermal development during deposition of the underlying Amabel formed a partial barrier system, affecting open circulation during Eramosa deposition. The platform was dotted with often subaerially exposed low topographic rises formed by the burial of underlying patch reefs, which, during times of normal marine salinity and higher sea levels, were sometimes the site of active reef growth. Between the topographic highs were shallow lagoons which periodically were cut off from open marine circulation, and, in the warm, tropical climate, may have experienced wildly fluctuating salinities.

During the deposition of the lowermost Eramosa (the "Marble" Unit), water salinity was high, making the lagoons rather inhospitable to all metazoan life. This may have been a time of basin-wide increased salinities when salt deposits were forming in the Michigan Basin. Cyanobacterial mats formed within the lagoons, directly precipitating very evenly-laminated stromatolitic carbonates that underwent rapid lithification. Storms would disturb only the uppermost still-living mats, creating crinkled features and thin laminae-breccias. Sediment transport was probably minimal during this period of lowered sea level as each lagoon would act as its own sediment trap.

As normal salinity began returning to the lagoons, either as a result of a slight sea level rise or a basin-wide change in salinity, shallow burrowers moved in and began disturbing the mats. Lithification may not have been as rapid, providing a more

transportable source of carbonate sediment. Also, if sea level began to rise, fetch would be increased and thus also storm wave amplitudes, enabling the transport of carbonate silt and mud between lagoons, producing the thicker event beds of the Eramosa Middle Unit.

During deposition of the Interbedded Unit, circulation patterns in the lagoons would rapidly alternate between open and restricted, controlled by minor changes in sea level. When circulation was good, normal marine organisms would populate the sediment surface for a short time. Often these populations would be monospecific, and determined by water depth, temperature, and oxygenation of any particular lagoon, or even "who got there first" as possibly determined by a species' breeding cycle. Storms would periodically smother bottom communities. Any slight drop in sea level would cut off water circulation to some lagoons, after which temperature would rise, stagnation and excessive algal productivity would decrease oxygen levels, and eventually salinity would increase, killing the normal-marine fauna. Sedimentation during these times would produce algal laminae devoid of macrofossils, until the next sea level rise brought normal-marine waters to the lagoon.

During late Eramosa times, sea level rose more significantly, flooding the exposed topographic rises and bringing more consistent normal-marine conditions. Reef growth became more common on rises within the study area, and dasyclad algae colonized the interreef lagoons. The abundance of dasycladalean algae within the biota indicates a clear, shallow (almost certainly less than 30 m and more probably less than 10 m), low energy marine setting (Elliott, 1968; Berger and Kaever, 1992). By Guelph times, water depth had increased significantly, changing the nature of

water circulation, and sedimentary and ecologic patterns. While precise dating of the Eramosa has thus far not been possible, the lithologic evidence corresponds well with a global eustatic sea level rise in the Early Ludlow reported by Johnson and McKerrow (1991).

It has been suggested (Kluessendorf 1994, LoDuca 1995, LoDuca and Brett 1997) that North American Silurian *Konservat-Lagerstätten* have several characteristics in common. They are relatively shallow, restricted, low-oxygen, marine carbonate environments, involve obrution, occur in proximity to reefs (living or buried), and often occur at the beginning of a marine transgression, thus making them predictable in nature. The Eramosa *Lagerstätten* also fits within this pattern.

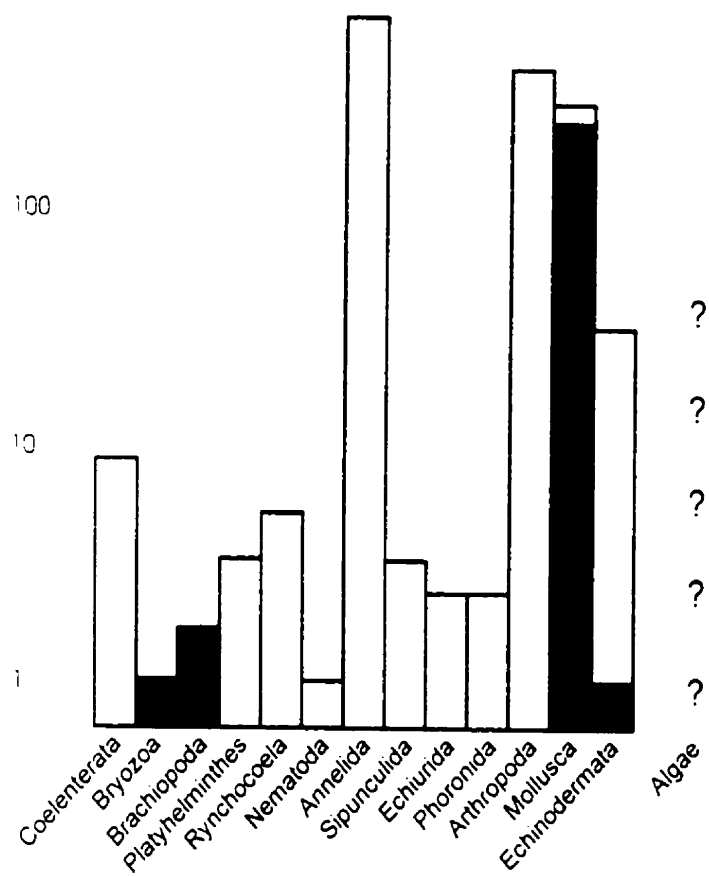
The proposed irregular and restricted nature of the carbonate platform during Eramosa times is similar to that which has been proposed for the Jurassic Solnhofen limestone of southern Germany (Barthel et al. 1978). Two competing theories have been proposed to explain Solnhofen carbonate deposition. Barthel (1970, 1972) believed that reef-derived allochthonous carbonate sediment became suspended in the water column during storm events, washed over coral patch reefs and flooded into the salt-stratified lagoons, settling out afterwards. Keupp (1977a,b, as translated in Barthel et al. 1978) believed that the Solnhofen was an autochthonous carbonate deposited by cyanobacteria living in the salt-stratified lagoons. Barthel's argument against Keupp's model was the lack of irregular and wrinkled surfaces within the Solnhofen commonly associated with algal/cyanobacterial deposition of carbonate: a feature that is pervasive throughout the Eramosa's "Marble" Unit.

The Upper Triassic Steinplatte reef complex of Austria, although much more extensive in thickness and areal extent, also provides a good environmental parallel to the Eramosa. Sequences of intertidal laminar algal stromatolites, with algal-crust intraclast conglomerates and evidencing frequent subaerial exposure, were deposited over a wide carbonate platform between barrier reefs (Pillar 1981).

Summary (including General Comments on *Konservat-Lagerstätten*)

It is the nature of the fossil record that we must view the history of ancient life through the highly biasing taphonomic filter. In most cases, any study of paleocommunities must necessarily be restricted to that portion which has a preservable skeleton. Stanton (1976) enumerated the preservable versus total fauna composition of the shallow Southern California shelf and found that 70 to 90% of the fauna had no chance of being preserved under normal circumstances (Figure 54). The marine flora was not examined in that study, yet it represents another major component of the marine community just as important as the fauna, yet with virtually no chance of preservation. This must certainly have been true throughout all of geologic time. Most phyla have a low probability of appearing in the fossil record. Any paleoecologic study, whether it be an analysis of an ancient community, or the change in paleocommunities through time is therefore flawed and incomplete. For example, the absence of any preserved flora means that the entire autotrophic tier

Figure 54. Taxonomic composition of total (white) and shelled (black) faunas on the shallow Southern California Shelf. (modified after Stanton 1976).



(with the exception of diatoms, perhaps) is missing from any paleocommunity analysis. And the characteristics of the living environment - such as vegetated patches vs. open mud bottom cannot be determined. The loss of entire phyla from the fossil record skews any analysis of morphological disparity through time, studies of evolutionary (taxonomic and ecologic) rates, species diversities (which then affects extinction studies), inter-taxa associations and interactions, etc.

Konservat-Lagerstätten give us a rare, though still never perfect, window into the missing component of paleocommunities. There are few examples through the Lower Paleozoic, and include the Cambrian Burgess Shale, the Lower Devonian *Hunsrückshiefer*, and the Pennsylvanian Mazon Creek biota.

The Eramosa Lagerstätte is exceptional in a variety of ways. The very near shore, shallow-water community, so close to the plane of erosion/deposition (sedimentational base level), is an environment that is rarely preserved, even if it didn't represent a *Lagerstätte*. This community may have been common, perhaps dominant, around the shorelines of most Silurian carbonate basins. Among the other Silurian *Lagerstätte*, the Eramosa is more diverse than either the Brandon Bridge and Gasport biotas, possibly representing either a more complete taphonomic view, or an originally more diverse community. While *Lagerstätte* deposits have often been viewed in the past as possibly unique communities, and therefore perhaps less important, the strong similarities to other Silurian *Lagerstätte* of different ages would seem to indicate that the community was not unique to particular location or time. Organisms such as the clawed arthropod (the "remipede"), possibly common in this type of environment during the Silurian as shown by its presence in several Silurian

Lagerstätten, show how an entire ecological tier (possible top-tier predator in this case) can be missing from the fossil record.

Further work on the Eramosa *Lagerstätte* would include a more detailed taxonomic analysis of this highly diverse fauna, including the comparison of Eramosa taxa to similar taxa found in other Silurian *Lagerstätten*, and how the Eramosa taxa fit into the evolutionary and ecologic history of a number of poorly understood groups. Continuing fieldwork will also likely reveal more new material, since past fieldwork suggests that the top of the sample rarefaction curve has not been reached. Chemical analysis of the fossils within the Lagerstätte, beyond the very basic tests performed during this study, may reveal further insights into the preservation of exceptional biotas. Further geophysical work could reveal a detailed 3-dimensional picture of the lagoonal topography, and drill coring proposed by Owen Sound Ledgerock Inc. could tie precise lithologies to the GPR sections. Lastly, a more detailed examination of the vast number of micro- and macro-lithologic and sedimentologic features of the Eramosa Formation could reveal further insights into the nature of the very-near-shore, carbonate environment.

The study of such exceptionally preserved biotas, when using an interdisciplinary approach, can shed light not only on their individual paleoenvironment and ecology, but contribute to our understanding of ancient communities and processes through time.

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