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# TAPHONOMY AND DEPOSITIONAL DYNAMICS OF DEVONIAN SHELL-RICH MUDSTONES

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## Abstract

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Fossil preservation (e.g. articulation of multi-element skeletons) provides important insights into depositional dynamics. Detailed taphonomic analysis of marine mudstones and associated shell beds from the Middle Devonian of western New York indicates that these beds record primarily episodic sediment deposition of short duration. We propose a storm winnowing, mud blanketing model to explain the variety of shell and mudstone beds observed, and to explain apparent onshore–offshore gradients of shell bed characteristics. Shell beds themselves appear to have accumulated during relatively long spans of time ranging up to perhaps thousands of years. Most are internally complex and exhibit evidence for multiple events of burial and exhumation by winnowing. Shell accumulation facilitated colonization of the seafloor by hard substrate-encrusting organisms; these contributed to increasingly complex communities that were ultimately destroyed and permanently blanketed by thick mud layers.

The sparsely fossiliferous mudstones, which compose up to 85% of the Hamilton stratigraphic section, mainly record very abrupt inputs of sediment; in some instances taphonomy of enclosed fossils indicates deposition of layers up to several centimeters thick (prior to compaction) within hours to a few days.

In turn, some sequences of shell and mudstone beds were deposited within the life span of single colonial organisms, and thus also record only relatively short spans of time overall. This reinforces our conclusions that most time in mudstone sequences must be represented by discontinuities at sharp surfaces or thin condensed beds that bound more or less continuous bundles of shell and mudstone beds. Again, these often subtle discontinuities can be recognized on the basis of taphonomic criteria.

Many complex shell beds as well as simple shell beds can be traced along depositional strike for tens of kilometers. Condensed shell beds only a few centimeters thick can commonly be correlated for 100 to 200 km along and across depositional strike. The correlatable nature of shell beds apparently reflects the temporal contrast between these beds and enclosing muds; on a regional scale, shell beds represent integrated accumulations that were deposited over spans of tens to thousands of years. Conversely, the mud layers that blanketed and terminated shell bed accumulations may represent very rapid depositional events (spanning hours to days), which are locally isochronous.

Thus, the study of taphonomy of shell beds reveals a good deal of detail about their depositional history; these studies imply that the stratigraphic record is even more episodic and discontinuous than commonly recognized. Episodic deposition implies that while the stratigraphic record of epeiric seas may be adequate for examining details of community succession and paleontology, it probably can not generally be used for microevolutionary studies other than examination of patterns of stasis.

## Introduction

Comparative taphonomy, the study of the differential preservation of fossils, is a powerful tool in paleoenvironmental studies. A number of recent studies have shown that fossil preservation can be used to estimate the amount of time represented by individual beds and bed sequences, and to reveal the sedimentary processes involved in their formation. In

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addition, detailed microstratigraphy using the unique taphonomic features of some widely traceable shell beds has proven useful in establishing time lines between sections and for detecting subtle diastems and disconformities. The study of taphonomic facies also permits more accurate reconstruction of paleoenvironments. In turn, taphonomic analysis may also indicate the adequacy of the stratigraphic record for studying paleoecological and microevolutionary processes.

In this study, taphonomic data are used to work out the depositional dynamics of Devonian shellbed–mudstone sequences. Similar alternations of shell-rich and sparsely fossiliferous beds comprise a large part of the marine stratigraphic record of epeiric seas (see annotated bibliography of Potter et al., 1980). Using standard sedimentologic methods, mudstone dominated sequences are difficult to study because they are fine grained, rather uniform, and contain very few sedimentary structures. On casual inspection, most mudstone exposures appear more or less monotonous and uniform. However, more detailed examination demonstrates that, in fact, they are composed of complex sequences of shell beds, homogeneous mud layers, concretions, and minor erosion surfaces.

To understand the genesis of these sequences, several critical questions must be answered. First, how were shell-rich beds formed? Were shell beds formed by winnowing of background sediments, or by steady but slow accumulation of sediment? Second, how much of the temporal record is actually preserved in a given shellbed–mudstone sequence? Answers to these questions require some means of assessing very short intervals of geologic time, seemingly an intractable problem. However, in many cases careful assessment of comparative taphonomy permits objective inferences of depositional timing, and often yields surprising answers to the questions posed above.

The primary goal of this study is to use comparative taphonomy to determine the mode of genesis and the approximate amount of time represented by given mud or shell beds in deposits of an ancient muddy epeiric sea. An understanding of the relative amounts of time represented by shell beds and mudstone layers is vital for interpreting both depositional processes and paleoecology. Estimated average sedimentation rates for offshore marine settings, such as those calculated by Schindel (1980, 1982) and Sadler (1981), while usefull for broad comparisons between very different depositional environments, give little indication of the potential time resolution or paleoecologic utility of a particular muddy marine facies. Rather, solutions to these problems need to be based on detailed sedimentologic and taphonomic study at a bed-by-bed scale (e.g. Behrensmeyer and Schindel, 1983; Behrensmeyer and Kidwell, 1985).

There has been much recent work on storm sedimentation in the geologic record, but most of these studies have focused on nearshore environments subject to relatively frequent high-energy storm disturbance and on environments characterized by sandy to silty sediments. Relatively little attention has been devoted to storm-generated deposits in more distal and offshore mud-dominated environments. The Hamilton sequences considered in this paper were deposited almost entirely below average storm wave-base (20–50 m, see Liebau, 1980).

It is difficult, at best, to observe offshore storm sedimentation in a modern environment that is analogous to an ancient epeiric sea. Studies of the modern carbonate ramp or muddy shoreface do not address the problem of the effects of tempestites on the preservation of benthic organisms, although this type of study would be invaluable to an understanding of ancient epeiric seas. This paper provides an analysis of the affects of abrupt, probably storm-generated sedimentation of benthic communities at or below storm wave base utilizing a combination of taphonomy, faunal content, and physical properties of beds.

## *Geologic setting*

In western New York State the Middle Devonian (Givetian) Hamilton Group consists

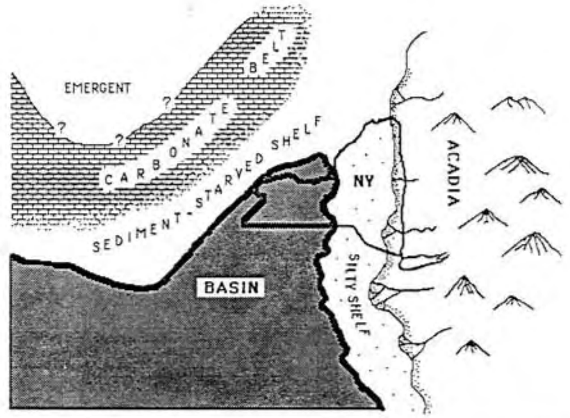


Fig.1. General configuration of northern Appalachian Basin during upper Hamilton Group deposition.

of about 100–150 m of medium to dark gray mudstones. These shales represent marine muds which accumulated in a relatively shallow (about 20–100 m; see Vogel et al., 1987), tropical (about 5–10° south of the paleoequator), epeiric sea on the northern fringes of the Appalachian foreland basin (see Faill, 1985; Kent, 1985; Woodrow, 1985) (Fig.1). The primary source of siliciclastic sediments lay about 250 km east of the study area in mountainous terraines uplifted during the Acadian Orogeny (see Ettensohn, 1985; Faill, 1985). The Middle Devonian epeiric sea was probably bordered to the north and northwest by low-lying cratonic areas, which yielded relatively little sediment.

The Windom and Wanakah Shale Members of the Hamilton Group are 5–30 m thick shale units and can be subdivided into a number of submembers, distinguished by faunal, lithologic, and taphonomic differences and bounded by condensed horizons. In turn, these submembers consist of alternating beds of nearly barren mudstone and richly fossiliferous shell beds, both on the order of 2–15 cm in thickness (see Boardman, 1960; Brett et al., 1986). The facies is intermediate between deeper water, dysaerobic, dark gray shale deposits and fossiliferous calcareous facies (for more detailed descriptions and interpretations of these facies see Brett et al., 1983, 1986; Brett and Baird, 1986b).

## *Methods*

The data base for this study includes 15 measured stratigraphic sections from the Windom Shale and 10 sections from the Wanakah Shale ranging from 3 to 10 m thick. The studied localities (see Fig.2) extend from the Lake Erie shore in the west to Owasco Lake 180 km to the east. In most sections, shell and mudstone layers, limestone beds, and concretionary horizons were measured to the nearest centimeter and briefly described. At several localities, detailed, systematic observations of shell layers were made with particular attention to shell orientation, presence–absence of species, types of trace fossils, and condition of fossils (size, degree of articulation, corrosion, pyrite coatings, etc.) Also, shell beds were classified into one of four descriptive categories (see Table I). The nature of fossil preservation is particularly important as an indicator of fast or slow burial. Articulated multi-element skeletons (e.g. crinoid stems and trilobites) and shells oriented in life position indicate very fast burial, whereas highly corroded, broken, or worn fossils suggest a long residence time on the sea floor.

The measured stratigraphic sections were divided into discrete intervals based on faunal, lithologic, and taphonomic differences. These intervals formed the basis for correlation among outcrops, and provided a framework within which the finer correlation of individual beds could be attempted. Traceability of the beds is important for assessing the constancy of bottom conditions across the basin.

Carbonate concretions and thin argillaceous limestone beds were found to be particularly useful for examining original fabrics and shell densities because they were well-indurated and provided a non-compacted view of the original sediments. Those concretions that contained shell beds were slabbed perpendicular to bedding and polished for making acetate peels. The peels were used for observing aspects of the bedding such as thin mud layers within the shell beds, mud sheltering, and sediment disturbance in the form of burrowing and escape

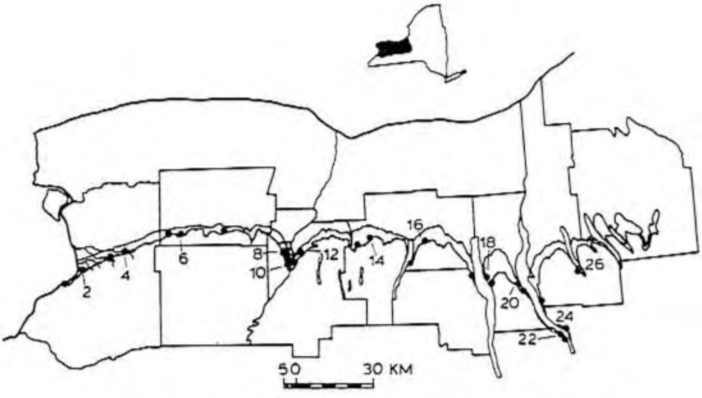


Fig.2. Map showing outcrop pattern of the Ludlowville and Moscow Formations. The study localities, denoted by dots, are numbered alternately from W to E. *1*=Lake Erie Shore. *2*=Rush Creek. *3*=Cazenovia Creek. *4*=Buffalo Creek. *5*=Eleven Mile Creek. *6*=Murder Creek. *7*=Bethany Railroad Cut. *8*=Spezzano Gully. *9*=Taunton Gully. *10*=Fall Brook. *11*=Little Beards Creek. *12*=Jaycox Creek (Locs. *8–12* are Genesee Valley localities). *13*=Frost Hollow. *14*=Keuka Outlet Creek (Locs. *13* and *14* are Bristol Valley localities). *15*=Canandaigua Lake Shore. *16*=Hopewell Gully. *17*=Kashong Glen. *18*=Kendaia Creek. *19*=Willard Creek. *20*=Barnum Shale Pit. *21*=Groves Creek. *22*=Taughannock Falls Park. *23*=Willow Point Creek. *24*=Portland Point. *25*=King Ferry. *26*=Long Hill Road cut.

traces. The relative density of shells within some shell beds as compared to the mud layers was determined by point counts. A 0.5 mm square grid etched on acetate was used as an overlay on each concretion slab. Presence or absence of shell material at each grid intersection was tallied for seven shell beds and mud layers, totaling about 700 cm$^2$.

## Description of shellbed–mudstone sequences

Within the Windom and Wanakah measured sections, shell layers comprise an average of only about 15% of the total stratigraphic thickness. The remainder of the section consists of sparsely fossiliferous, bioturbated mudstone. Consequently, these mud-dominated facies can appear quite homogeneous and their rich store of detailed stratigraphic and paleoecologic information easily could be overlooked. However, some shell layers are readily recognizable on weathered outcrop surfaces due to their carbonate-enriched matrix, or their incorporation within argillaceous limestone layers and concretionary horizons (Fig.3).

### *Shell bed types*

Hamilton shell beds can be classified descriptively on the basis of several features including geometry, internal structure, and fossil content; we have employed a modification of the scheme for classification of skeletal concentrations proposed by Kidwell et al. (1986) (Table I). At the finest scale, shell pavements and stringers are concentrations which are a single shell in thickness (generally $\leq 1$ cm) and are confined to bedding planes. Pavements are rather continuous and commonly can be traced for several meters in single exposures. These layers may pinch out locally but then reappear at the same horizon further along the same outcrop (as determined by measurements from other horizons). Pavements may become amalgamated laterally with thicker, 2–10 cm shell beds. Stringers are distinctly elongate, lenticular, and discontinuous; rarely, two or more stringers may be subparallel to one another. In some cases small shells (e.g. styliolinids or crinoid ossicles) are crudely aligned within stringers approximately parallel to the long axes of the accumulations (see Linsley, 1972, for further discussion).

TABLE I

General classification and characteristic features of Hamilton shell beds

| Bed classification | Taphonomy base of bed | Taphonomy top of bed | Traceability | Geometry |
|---|---|---|---|---|
| *Pavements and stringers* | articulated brachiopods and bivalves gradual to sharp base | articulated brachiopods and branched bryozoans | within single outcrops | thin, two-dimensional pavements or elongate stringers |
| *Simple shell beds* | sharp, scoured base shell debris of crinoids and brachiopods | In situ preservation of articulated brachiopods, crinoids, and trilobites | among local outcrops (up to 10 km) | irregular base with local gutter casts, sharp to gradational flat tops |
| *Complex shell beds* | sharp, scoured base shell debris layer at base | In situ preservation of articulated brachiopods, crinoids, and trilobites | tens of km | amalgamated simple shell beds up to 15 cm thick, with minor internal mud drapes |
| *Condensed shells beds* | sharp, scoured or stratomictic base, enriched in resistant hardparts, corroded fossils, phosphatic pebbles, or hiatus concretions | corroded fossils and resistant hardparts or well-preserved fossil material | tens of km to basinwide | variably thick and laterally uniform tabular shell beds |

Concavo-convex shells are typically convex upward within pavements and stringers, although random (50:50), even dominantly convex downward, assemblages have been observed in thin shell pavements in some dark gray pyritic mudstones (distal lower aerobic or dysaerobic settings; Dick and Brett, 1986). Articulation ratios are highly variable, but facies related. In dark gray to black, fissile shales (e.g. uppermost Windom beds) pavements of brachiopods are typically disarticulated, and some are fragmented, but corroded fossils are rare. However, some of the best fossil preservation in the Hamilton occurs on pavements and stringers. This is particularly true of those beds that occur in thick gray mudstone units as in the lower Wanakah, Kashong, and Windom members. Long sections of crinoid stems, or even completely articulated crinoids, trilobites, or moult ensembles are found which indicate that disturbance of the seafloor was minor.

Thicker skeletal concentrations, usually 1–5 cm thick, termed simple shell beds, display consistent internal fabrics and patterns of preservation (Tables I and II). The pattern typical of simple shell beds consists of a sharply erosive (sometimes irregularly scoured) base, overlain by crinoid and shell debris that makes up the bottom third of the bed (Fig.4). Shell material consists mostly of unrecognizable shell fragments on the order of 1–5 mm in size. The middle third of the bed contains mud-supported skeletal material, usually in the form of complete valves, and occasional articulated brachiopod shells, rugose corals, and larger crinoid ossicles. Robust fossils may be reworked and corroded, and may support epizoans such as encrusting bryozoans and auloporid corals. The upper third of the beds contain large sections of delicate fossils such as branching segments of ramose bifoliate cryptostome bryozoans, large frondose sections of fenestrate bryozoans, delicate branching auloporid corals, and long articulated sections of crinoid columns (Fig.4).

Simple shell beds display differential preservation of fossils from bottom to top, with the

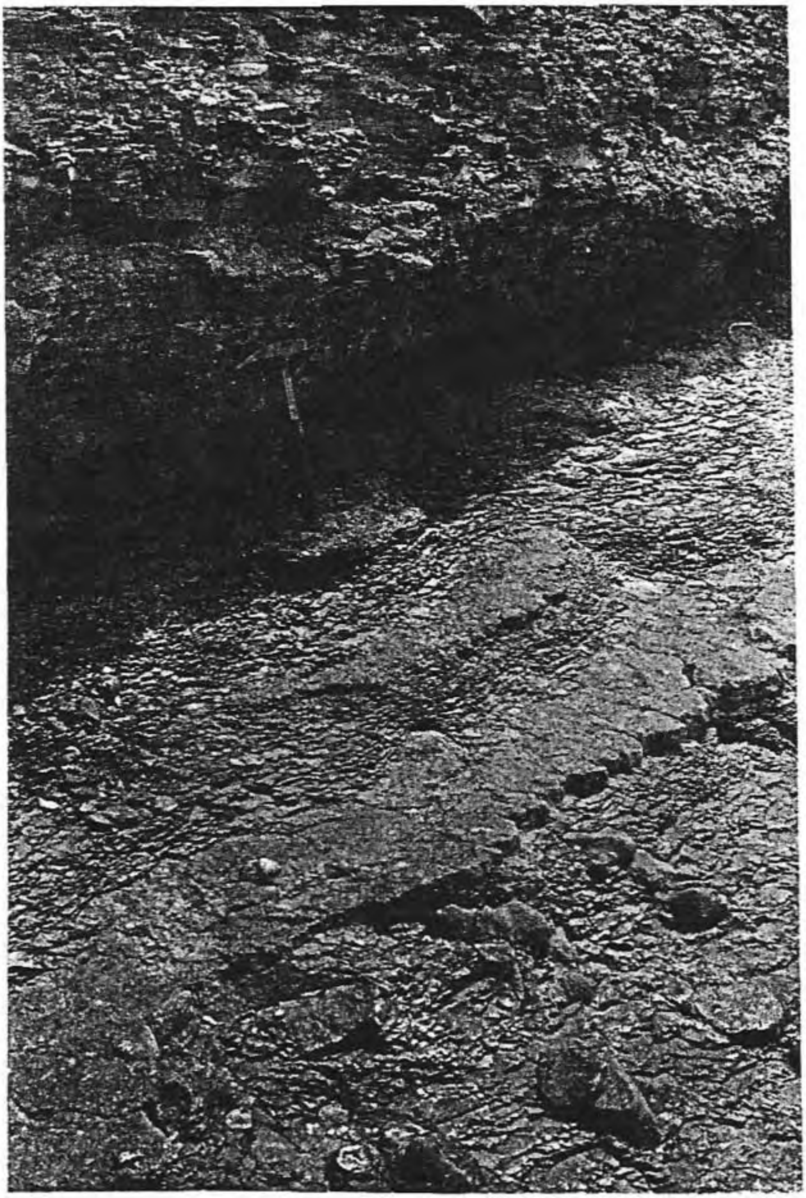


Fig.3. Outcrop appearance of shell beds and mudstones of lower Wanakah Shale Member, Lake Erie shore north of 18 Mile Creek, Erie County, N.Y. Note tubular concretions formed around pyritic burrow tubes in lower portion of the outcrop. This horizon is overlain by a thick and widespread shell-rich bed (*Nautilus* Bed) which displays articulated life-orientation brachiopods and articulated complete crinoids on a sharply defined upper contact. Note also two overlying lenticular shell beds and notch at hammer handle marking a persistent soft clay horizon.

proportion of disarticulation and fragmentation highest at the base and decreasing upward (Table II). Among 15 shell beds from the Windom Shale, the articulation ratio of brachiopods increased significantly from the bases to the tops of the beds. About 65–75% of all trilobite and crinoid material at bed bases consisted of completely disarticulated ossicles, while the percentages for bed tops were 40 and 50% disarticulation, respectively. The maximum observed length of crinoid stem segments was 3 mm at bases and 50 mm at tops. Also,

TABLE II

Taphonomic data collected from 20 simple and complex shell beds in the Upper Windom Member at Fall Brook (Loc. 11, Fig.2). Most data are in the form of percentages of specimens collected for given bed portions (i.e. bed tops show that 70% of brachiopods are articulated, while bed bottoms show only 35% articulation). Average area observed per bed is 400 $cm^2$; numbers listed are average percentages for the interval as a whole; detailed data are presented in Parsons (1987)

| Fossil condition | Tops of beds | Middles of beds | Bases of beds |
|---|---|---|---|
| *Brachiopods* | | | |
| articulated | 70% | 50 | 35 |
| convex up | 65% | 57 | 57 |
| convex down | 32% | 36 | 34 |
| vertical | 3% | 7 | 9 |
| *Trilobites* | | | |
| complete disarticulation | 40% | 50 | 66 |
| articulated segments | 46% | 43 | 33 |
| complete outstretched | 0% | 7 | 0 |
| complete enrolled | 14% | 0 | 0 |
| *Crinoids* | | | |
| single ossicles | 50% | 83 | 75 |
| articulated segments (length) | 50 mm | 5 mm | 3 mm |
| *Bryozoans (twig and fenestrate)* | | | |
| small fragments ($\leq 1$ cm) | 25% | 45 | 60 |
| long and branching segs. | 50% | 25 | 25 |
| fronds of fenestrates | 25% | 30 | 15 |
| *Robust fossils* | | | |
| completely uncorroded | 20% | 30 | 0 |
| minor corrosion | 80% | 50 | 70 |
| corroded on all sides | 0% | 20 | 30 |
| *Bioturbation* | | | |
| evidence | 100% | 90 | 100 |
| thread burrows | 100% | 100 | 100 |

about 60% of fragile ramose bryozoans occur as small fragments ($\leq 1$ cm in length) at the bed bases while 45 and 25% are so fragmented in the bed middles and tops, respectively.

Among 48 shell beds studied in the Windom Shale of the Genesee Valley, 38 contained some evidence of very rapid burial on their upper surface, even though only about a 10 × 40 cm surface was examined on each bed. In this study complete trilobites and well-articulated crinoid remains were found at or near the bed tops, although rarely we have observed crinoid calyces buried at the bases of shell beds. The tops of certain beds also display articulated, closed brachiopods, large branching trepostome bryozoans and corals, massive colonies of fistuliporoid bryozoans, and in situ favositid and rugosan corals. Bed tops have a somewhat variable geometry. The contact of the shell beds with the overlying muds is usually sharp, although the uncompacted sediments within some concretions show minor gradations of diminishing shell debris through about 2–3 cm of sediment. In rare cases, ripples, aligned elongate fossils, and imbricated shells occur on or near the tops of simple shell beds.

Simple shell beds are usually burrowed internally; traces include horizontal and ver-

Fig.4. Cross-section of a concretion with centrally-located shell bed. Note sharp basal contact of bed with minor erosional relief; overlain by closely packed crinoidal and bryozoan fragments; upper portion of accumulation shows intercalation of vaguely defined shell and mud layers; top surface (marked by arrow) overlain by nearly barren mudstone. Note cross-section of probable coiled intact crinoid column (arrow) buried in capping mud layer. Bar equals 4 cm. Windom Shale, lower Taunton beds; Honeoye Valley, Frost Hollow, Ontario Co., N.Y.

tical pyritized burrows, vague *Zoophycos* and subtle burrow mottling that is recognizable in peels by slight differences in color. The pyritized burrows are found at all angles, in both the shell beds and in the mud layers.

The third category, complex shell beds, consists of thicker, amalgamated, multi-event beds that commonly have relatively diverse faunas and complex internal structures including thin laminae or lenses of barren mudstone. These beds range from 5 to over 10 cm in thickness. They are recognizable from outcrop to outcrop because they have unique faunal assemblages or mixtures of assemblages that are different from shell beds above and below them. Detailed micro-correlation demonstrates that many of these beds are persistent over great distances and thus are good stratigraphic markers.

Condensed beds form a subset of the complex beds, comprising those layers which are very laterally continuous and usually consistent in thickness (Tables I and III). These beds tend to occur at lithologic or biofacies boundaries and contain mixed faunas. Distinctive taphonomic features of condensed beds include phosphate pebbles, pyrite nodules, and corroded fossils.

### *Mudstone layers*

Individual mudstone layers range in thickness from 1 to 25 cm and contain sparse shell material (skeletal grains constitute 0.06% of the cross-sectional area in slabbed concretionary mudstones as compared to 76% in the shell beds). The fauna consists of scattered small brachiopods and bivalves that are commonly articulated (closed or splayed), small sections

TABLE III

Taphonomic and stratigraphic characteristics of several Middle Devonian condensed shell beds in western New York

| Unit | Stratigraphic characters | | | | | Taphonomic characters | | |
|---|---|---|---|---|---|---|---|---|
| Name of bed references | Stratigraphic position | Thickness (cm) | Regional extent along E–W belt | Sharp grooved base | Mixed biofacies | Corroded-reworked fossils | Resistate | Hiatus concretions |
| *Peppermill Gulf*<br>Gray (1984) | boundary between Levanna black shale and Centerfield gray mudstone (erosional discontinuity) | 5–20 | Cayuga Lake to Tully Valley (55 km) | X | X | X (corals) | minor phosphate nodules | X (rare) |
| *Moonshine Falls*<br>Gray (1984)<br>Brett et al. (1986) | boundary between Centerfield calcareous mudstone, Ledyard black shales (erosional discontinuity) | 5–10 | Seneca Lake to Chenango Valley (130 km) | X | X | X (corals-brachiopods) | conodont concentration, phosphate, reworked pyrite | X (rare) |
| *Staghorn Phosphate Bed*<br>Brett et al. (1986) | Otisco Member, top of Staghorn Submember; boundary between silty fossiliferous gray mudstone and dark gray shale (erosional discontinuity) | 5–10 | Owasco to Otisco Valley (23 km) | X (locally) | X (minor) | X (corals) | phosphate nodules quartz sand | — |
| *Barnum Bed*<br>Baird (1981) | lower King Ferry Shale overlain by dark gray shale (erosional discontinuity) | 10–20 | Seneca Valley to Owasco Valley (40 km) | —<br>stratomictic | X | X | — | X (abund.) |
| *Bloomer Creek Bed*<br>Baird (1981) | erosional-discontinuity overlain by dark gray to black shale | 10–50 | Seneca Lake to Owasco Valley (40 km) | —<br>stratomictic | X | X | — | X (abund.) |
| *"R-C" Bed*<br>Baird (1981)<br>Lukasik (1984) | between lower and upper submembers of Kashong Shale Member | 50–90 | Canandaigua to Chenango Valley (175 km) | X (locally) | X | X (brachiopods) | —<br>very rare phosphate | — |
| *Unnamed top-Kashong Phosphate Bed*<br>Baird (1978)<br>Lukasik (1984) | at or near boundary between gray Kashong mudstones and dark silty Windom Shales | 5–10 | Lake Erie Shore to Owasco lake (230 km) | — | X | X | abundant phosphatic nodules, reworked pyrite conodont concentration | X |
| *Ambocoelia-Praeumbona Bed*<br>Parsons (1987)<br>present paper | Windom Shale at boundary of calcareous Spezzano gray mudstone submember and overlying dark gray Gage Gully Submember | 5–10 | Genesee Valley to Cayuga Lake (100 km) | X | X | X | rare phosphate nodules reworked pyrite | none observed |

of fenestrate and ramose bifoliate (*Sulcoretepora*) bryozoans, and rare crinoid ossicles. The preservation of the shells is as good as, or better than, that seen in the shell beds. The mudstone units usually contain *Zoophycos* burrows and pyritized, thread-like burrows that are oriented both horizontally and vertically. Probable escape trails have also been observed extending from the tops of the shell beds into the overlying mudstone layers in concretions from the Wanakah Shale.

### *Concretions*

Small (5–10 cm diameter) and larger (10–30 cm thick) calcareous concretions occur at particular levels in single horizons or in multi-level sets. Concretions tend to be centered on shell beds (Fig.5), but also may immediately overlie or underlie them. The surrounding beds tend to be bowed around the concretions due to differential compaction, in some instances greater than two-fold. Certain concretion layers are laterally continuous (Fig.6), as can be demonstrated in single long outcrop sections (e.g. Lake Erie cliffs, where concretion beds can be traced continuously for over 2 km) and by bed-by-bed correlation of closely spaced outcrops. Different horizons are consistently distinguishable by size, shape, and faunal content of concretions, and as a result are useful for correlation among outcrops. Concretion horizons are also commonly associated with heavy concentrations of pyrite, either in the associated shell beds or in the form of tubular burrow-fills. In some cases

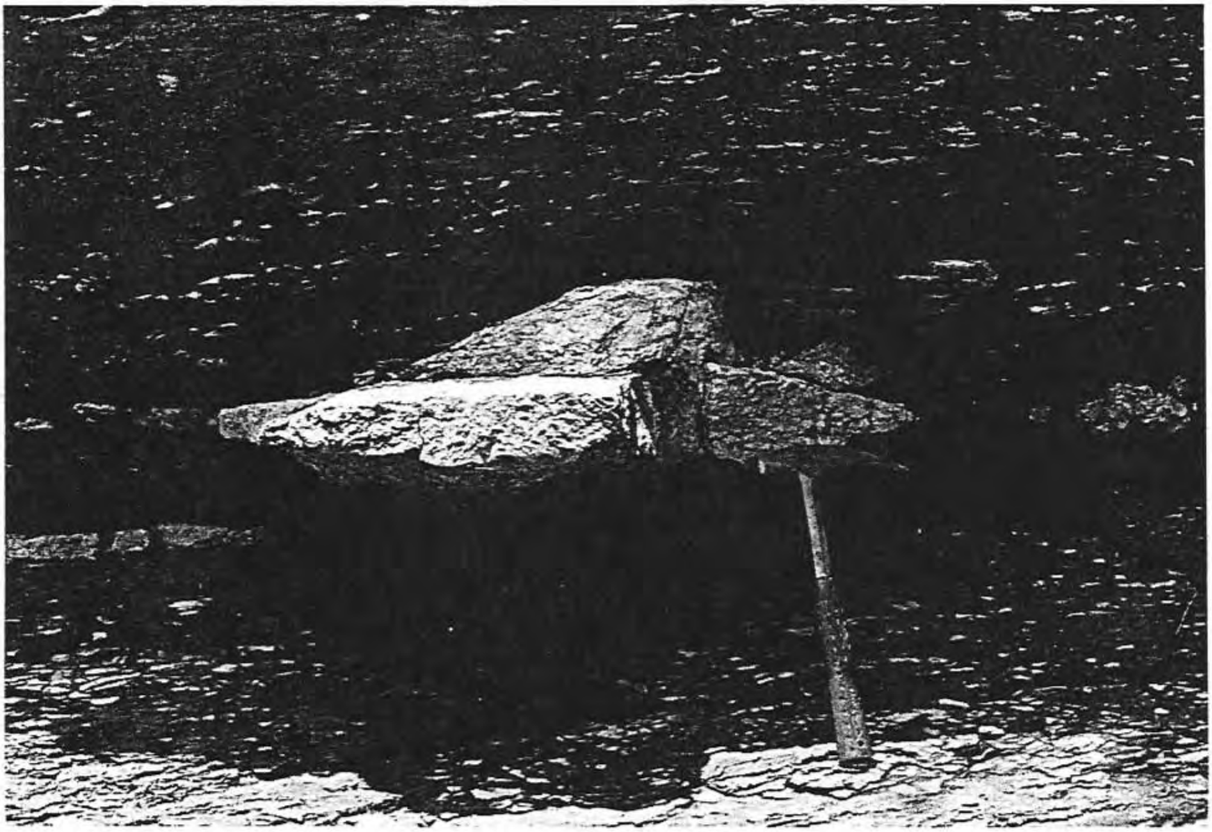


Fig.5. Shell bed accentuated by concretionary overgrowth. Mass of concretion extends both above and below the plane of the shell bed which extends laterally on either side of the concretion. Lower Wanakah Shale Member, "*Nautilus* Bed", Buffalo Creek, Erie Co., N.Y.

Fig.6. Concretionary horizon showing lateral persistence of concretions in a single outcrop of Lower Wanakah Shale member, Buffalo Creek, Erie Co., N.Y.

these burrows control the size of the concretions. Fossils within concretions display little or no compactional deformation and are more sparse and scattered than in immediately adjacent shales. Finally, certain condensed horizons yield fossil-encrusted and bored hiatus concretions, reworked from underlying sediments (see Baird, 1981; Baird and Brett, 1981; and Gray, 1984; for detailed discussion). These observations indicate that concretions were formed during early diagenesis prior to compaction, and probably in the upper few decimeters of sediment.

## Depositional dynamics of Hamilton shell-mud sequences

The comparative taphonomy of these shell-bed–mudstone sequences has proven to be a key to understanding the depositional dynamics of these beds. Also, it has been invaluable in reconstructing the depositional environments of the deeper part of the basin. In the following sections we consider the modes of genesis of shell beds, sparsely fossiliferous mudstones, and associated concretionary horizons.

### *Shell-bed formation*

The fundamental pattern of alternating sparsely fossiliferous sediments and thin, but locally persistent (at least in single outcrops) shell-rich beds is pervasive in the Hamilton Group and it resembles situations observed in other shallow shelf and epeiric sea settings (e.g. Bloos, 1982; Fürsich, 1982; Kidwell, 1982; Kidwell and Jablonski, 1983; Norris, 1986).

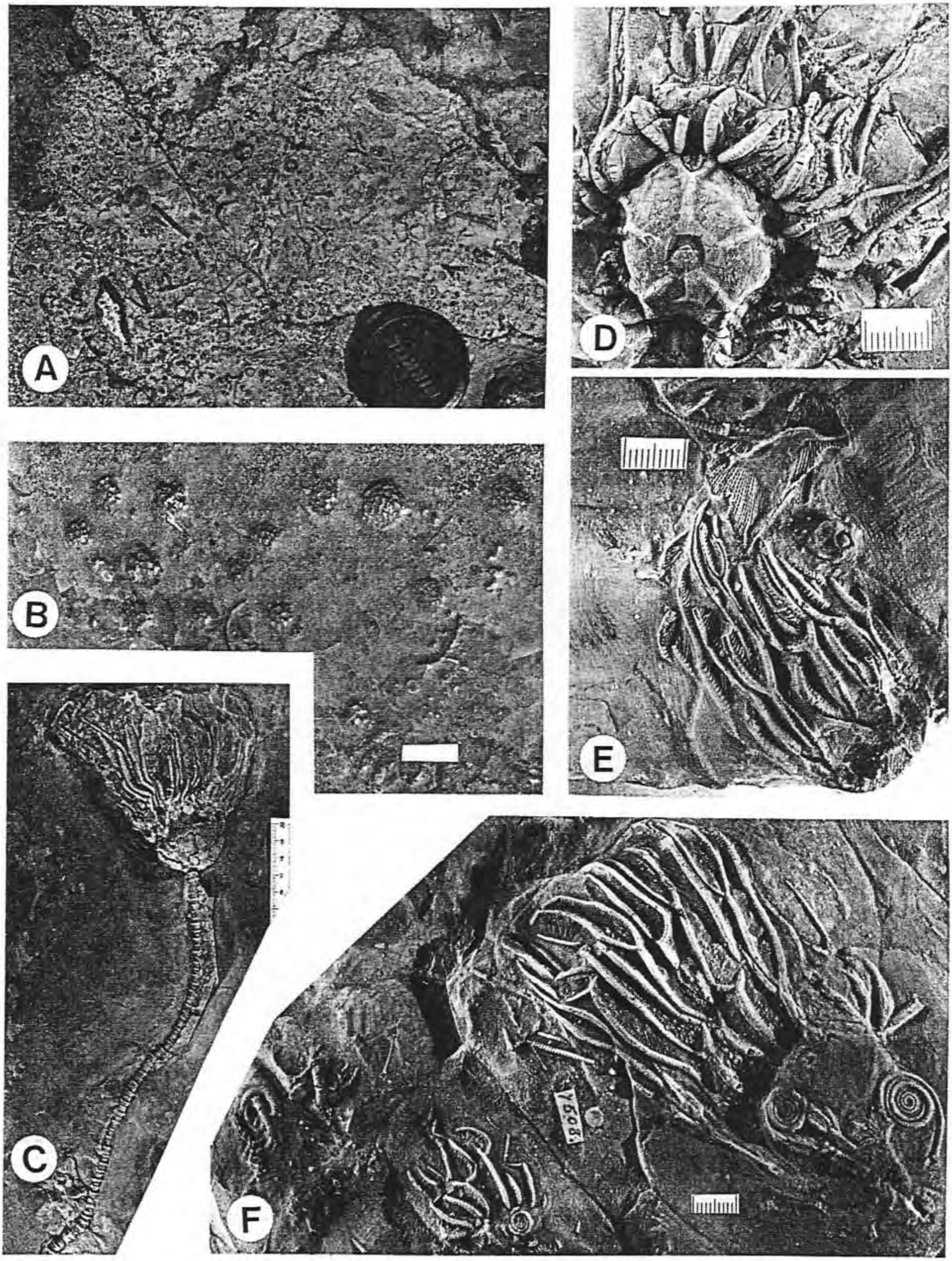
A variety of explanations have been proposed to explain such shell-rich/shell-poor alternations, including diagenetic effects, allochthonous transport of skeletons into shell-poor environments, storm winnowing of shell-bearing sediments to produce shelly lag deposits, and alternating intervals of sediment deposition and sediment starvation (Fürsich, 1982; Kidwell and Jablonski, 1983; Kidwell, 1986; Table II, for review). Such fossil concentrations also have been characterized as being either autochthonous (in place assemblages), parautochthonous (disturbed neighborhood of Scott, 1970), or allochthonous (transported; see Johnson, 1960; Fagerstrom, 1964; Scott, 1970; Aigner et al., 1978). Kidwell et al. (1986) have proposed a genetic classification of skeletal concentrations based on the three end members of biogenic, sedimentologic, and diagenetic concentration mechanisms and various combinations of these processes.

Any explanation of Hamilton shellbed–mudstone sequences must account for several consistently observed features: (1) shell beds vary in thickness and complexity; (2) simple beds display a consistent internal fabric with: (a) generally sharp bases, overlain by comminuted to corroded skeletal debris; (b) upper portions with extremely well-preserved fossil material variably mixed with disarticulated and fragmented material; (3) shell beds are laterally extensive; (4) mud layers abruptly overlie shell beds and may show exceptionally well-preserved fossils.

Selective loss of skeletal material by dissolution from the sparsely fossiliferous layers (e.g. the "diagenetic extinction model" of Fürsich, 1982), can be excluded for Hamilton shellbed–mudstone alternations. Fossils that do occur in the mudstone layers are of similar type, and equally well preserved as those in the shell beds. Molds of aragonitic mollusk shells are actually more common in the mudstones than in the shell beds, whereas this type of skeletal material should have been lost first had selective dissolution affected the sparsely fossiliferous mudstones. Moreover, for samples from concretions in which the mudstones as well as the shell layers have undergone early cementation, the mudstones are as barren as surrounding mudstones that have been compacted. (Due to preservation of original loose sediment fabrics in concretions, the density of shells in mudstones may actually be lower than that of the compacted shales). Thus concretions do not preferentially preserve shell material and therefore shellbed–mudstone sequences must be the result of primary differences in shell distribution.

Nearly all of the shell beds examined in this study fit the criteria listed by Aigner et al. (1978) for autochthonous or parautochthonous coquinites. Many, though not all, of the fossil taxa found in shell beds also occur in the intervening sparsely fossiliferous mudstones such that shell bed faunas do not appear to be allochthonous. The upper surfaces of many beds preserve complete bryozoans, brachiopods, or crinoid holdfasts in apparent life

Fig.7. Taphonomic aspects of shell bed tops. A. Distinct upper pavement of *Nautilus* Bed with trilobite debris, brachiopod valves (and articulated and in situ individuals), and bryozoan and crinoid fragments. Note weakly defined alignment of elongate fossils and overlying barren mudstone. Lower Wanakah Shale, Lake Erie Shore, Erie Co., N.Y. B. Surface of bed showing a large number of in situ specimens of the tabulate coral *Pleurodictyum* covered by barren overlying mud. Lower Wanakah Shale, Lake Erie Shore, Erie Co., N.Y.; bar scale 5 cm. C. Complete specimen of crinoid (*Gennaeocrinus*) from upper Windom Shale (Taunton beds); Vincent, Ontario Co., N.Y. Specimen in N.Y. State Museum Collection. 4220/5 (also figured by Goldring, 1923, pl. 23). D–F. Views of upper surface of a large slab of concretionary calcareous mudstone containing numerous camerate crinoids (*Clarkeocrinus troosti*) and other fossils from the upper Windom Shale (Taunton beds) Vincent, Ontario Co., N.Y., scales in millimeters. Slab in N.Y. State Museum, includes specimens numbered 7507, 7508, and 7452, figured by Goldring (1923, pl. 25). D. Crown of *Clarkeocrinus* showing typical mode of preservation for disarticulated crowns, with dorsal cup oriented upward and arms splayed out radially, column disarticulated (NYSM 7508). E. Laterally compressed crown with well-preserved pinnulate arms; also note upright (in situ) colony of fenestrate bryozoan in adjacent shale. F. Large crown of *Clarkeocrinus* with intact column bearing whorls of coiled cirri (NYSM 7507); also note distal coiled stem of *Acanthocrinus*; slightly displaced but in situ cirriferous holdfast of *Clarkeocrinus* and upright colony of fenestrate bryozoan in the left of view.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positions (Fig.7A). Moreover, the occurrence of well articulated multielement skeletons of trilobites and crinoids within at least 80% of shell beds (Fig.7) requires rapid burial and mitigates against long-term transport of remains. On the other hand, the presence of sharp, erosional bases on many thicker shell beds indicates some minor scouring and probably local shifting and transport of skeletal material. Similarly, rippling of some bed tops, predominance of convex upward shells, and minor orientation of grains suggests that minor current action affected skeletal accumulations prior to burial.

As noted, simple shell beds display a crude gradient of preservation, often manifest as an inverse size gradation, from finely comminuted skeletal debris at the base to well-preserved, commonly articulated shells, crinoid skeletons, etc. at the top. Hence, these beds probably do not record single events of reworking and winnowing as in the case of simple storm-generated coquinites or tempestites (for example Kreisa, 1981; Aigner, 1982, 1985). Rather, the bases of beds represent relatively long term reworking and winnowing of skeletal material, while the tops record less reworked material. A complex history of physical and biogenic reworking may have destroyed most skeletal particles, leaving a residue of resistant, small debris at the bases. The main upper portions of beds display taphonomic evidence that most skeletons have been buried rapidly with minimal reworking. In the case of complex shell beds there is even more direct evidence of multiple reworking and burial events within a single bed. In most cases, Hamilton shell layers have experienced some storm concentration, but have not formed by ablation of background mud, as has been inferred in many shelly tempestites (Bowen et al., 1974; Aigner et al., 1978; Craft and Bridge, 1985).

Thus the studied skeletal concentrations apparently reflect a combination of intrinsic biogenic, and to a lesser extent, sedimentologic concentration (see Kidwell et al., 1986 for definitions). More resistant skeletal elements (e.g. thicker calcitic shells and crinoid ossicles, see Seilacher, 1982) accumulated at or near the living sites of the organisms as the residue of destructive processes active at the sediment surface. Intermittent minor resuspension and winnowing of muds during storms probably further concentrated shells into pavements, stringers, or thicker lenses. Finally, remains of the last few generations, including those living at the time of shell bed termination, were rapidly buried and not later reworked. In the case of thicker, complex shell layers, this process was repeated several times leading to an amalgamated deposit with internal mud layers.

### *Mud layer deposition*

The exact processes that occurred during final burial of shell beds by mud layers are not completely understood and can only be inferred indirectly from circumstantial evidence. However, taphonomic data can place some rather strong constraints on the interpretation of sedimentologic processes. Mudstones separating shell-rich beds might be interpreted as "background sediment" (sensu Brett and Baird, 1986a). However, the fact that many (or most) mudstone layers abruptly overlying shell beds contain exceptionally well-preserved fossils strongly argues that these mudstones represent episodically deposited mud layers (or unifites, sensu Stanley and Kelling, 1968).

Convincing evidence for the single-event deposition of some thick mudstone layers was found at the tops of several shell beds which had articulated crinoid columns that appeared to be anchored in the beds, and extended up through as much as 2–7 cm of the overlying mud layer (perhaps as much as 10–35 cm of uncompacted water-rich mud; see Ferguson, 1963 for estimates of compaction; Fig.7). These crinoids must have been living at the time of the onset of rapid mud deposition. The incoming mud probably killed them by clogging their ambulacral systems. However, between the time of initial onset of mud accumulation and the time of death of the crinoids, the mud was able to partially bury the crinoid. Because it is impossible for crinoid columns to have remained articulated after death while mud gradually accumulated around them, we conclude that the full thickness of enclosing sediment must have been deposited during a single event.

More commonly, mudstone layers record several episodes of rapid sedimentation. Scattered, small in situ clusters of sessile epifauna may be the only indication of a depositional break. In some cases, subtle horizons of articulated bivalve shells are present and suggest the rapid burial of an infaunal or semi-infaunal community (see Peterson, 1985). The frequent influx of thin (~1 cm thick) mud layers is well documented by the internal mudstone laminations found within nearly all fistuliporoid bryozoan mounds (Fig.8). Unless resuspension and winnowing occurred, individual thin mud layers would accumulate without intervening shelly horizons. Subsequent bioturbation would tend to obliterate any textural evidence of the episodic, pulsational nature of mud deposition.

In some instances we can be certain that the organisms were not buried alive, as they had undergone some decay prior to mud emplacement. However, the fact that some crinoid and trilobite skeletons display very minor disarticulation and displacement of ossicles despite being generally associated, indicates not only that the organisms had died before final burial but that very minor disturbance (probably very weak currents) moved the partially decayed carcasses just prior to, or contemporaneous with, emplacement of the mud layers. The existence of minor agitation of the bottom at or close to the time of mud deposition is further indicated by some imbrication of fossils within the mudstone, and mudstone-supported fossils that extend upward from the buried shell layer. Moreover, we have observed cases in which concavo-convex shells were apparently overturned to a convex-downward orientation just prior to burial. Strophomenid and *Tropidoleptus* shells with epibionts encrusted onto their convex (pedical) valves are now preserved with

Fig.8. Polished cross-sectional view of a fistuliporoid bryozoan colony (scale in centimeters). Note intercalation of bryozoan zoarium with mudstone layers indicating episodic burial and regrowth of the colony; lower Wanakah Shale, Buffalo Creek, Erie County, N.Y. (figured by Miller, 1986).

that valve downward in the sediment (as in life but obviously recording a secondary episode of inversion). These convex-downward inversions could have been produced by minor stirring of the shells off the seafloor followed by resettling, suggesting that minor agitation occurred prior to or contemporaneous with mud deposition.

These observations raise important questions regarding the mode of emplacement of mud layers. How is it possible for significant accumulations of fine grained (dominantly clay-sized) sediment to be deposited in relatively short periods of time? How could there be tractional movement of skeletons contemporaneous with mud deposition? And finally, what was the source of the muds? Were they in fact introduced de-novo into the depositional basin from allogenic sources, or simply resuspended from earlier accumulations within the basin? We can only offer tentative answers to these questions in the absence of detailed studies of modern analogous situations.

First, it is obvious that the rapidly deposited mud could not have originally been in the form of discrete clay grains. Studies of recent marine mud deposition demonstrate that most clays are deposited as pelleted aggregates (Drake, 1976). Wygant (1986) has shown that Hamilton Group (Ludlowville Formation) shales consist of 85% micropeloids and 15% silt. However, we have not observed graded silt to clay layers associated with burial beds, rather silts and pellets appear admixed. This suggests that simple segregation by particle size or density did *not* occur. Possibly the micropeloids and silt were aggregated into larger flocculated grains at the time of deposition. If so, settling rates of the muds might have been as great, or greater than that for the silts alone.

This hypothesis provides a plausible answer to the remaining questions posed above. First, if the sediment was deposited as larger flocculated grains, it is possible that tractional processes, such as slight uplift of lightweight skeletons could have occurred as the sediment was accumulating. Perhaps the muds came in as thick slurries which flowed close to the substrate, rather than as dilute turbid suspensions. The fact that some organisms had undergone decay prior to burial only indicates that the fatal disturbance event occurred prior to sedimentation. Such a pattern seems a reasonable response to major hurricanes which may last for days and in which sediment suspensions and basinward transport might be produced in late phases of the storm.

Finally, the fact that Hamilton muds are pelletized (Wygant, 1986) suggests that the burial muds were not input directly from the source area, but instead represent reworking of marine muds that had already been processed by organisms.

### *Diagenetic effects*

Several of the more widespread shell-rich beds both in the Wanakah and Windom shales are associated with pyritic crusts and/or calcareous concretions. The pyrite occurs in facies-related patterns in gray bioturbated mudstones with limited low to moderate diversity assemblages inferred to represent dysaerobic to lower aerobic conditions (Dick and Brett, 1986; Kammer et al., 1986; Wygant, 1986). Pyrite is commonly associated with rapidly buried fossil layers, where it occurs as framboidal to stalactitic steinkerns in enclosed shells or voids, as in enrolled trilobites, as well as drusy macrocrystalline crusts ("overpyrite") or nodules overgrowing shells and shell accumulations.

Dick and Brett (1986) inferred that the pyrite steinkerns developed very early, prior to compaction, in organic-rich microenvironments of shell interiors that were buried rapidly within otherwise organic-poor, anoxic, non-sulfidic sediments (see Berner, 1980; also Hudson, 1982). Hence, pyritic fossil beds are an indirect reflection of rapid entombment of organisms in organic-poor mud.

The macrocrystalline overpyrite probably records a latter generation of sulfide commonly nucleated on pyritic molds or directly on shell material. Pyritic crusts of this sort also occur in more aerobic facies where framboidal pyrite molds are rare. They highlight certain fossil layers, some of which can be traced across several closely spaced outcrops. Pyritic crusts may be concentrated along thicker shell beds either because they were more porous (better fluid flow) or because they were richer in organic matter than surrounding sediments.

Processes of carbonate concretion formation also may be associated with burial of organic matter or carbonate shell layers (see Brett et al., 1986, for further discussion of Hamilton concretionary fossil beds). As noted above, many shell layers are partially encased within carbonate concretions at persistent horizons. Selective early diagenetic precipitation of carbonate cements in sediments enclosing rapidly buried organic remains allowed exceptional preservation of well-articulated skeletons. Generation of ammonia due to anaerobic decay and consequent elevation of pH (Berner, 1968, 1971) may have been critical in triggering carbonate precipitation. Carbonate nucleation sites (shells) and bicarbonate production via bacterial sulfate reduction also may have aided the process (Raiswell, 1976, 1982).

## Onshore–offshore trends

Taphonomic studies of various facies of the Hamilton Group demonstrate distinct, apparently depth related, changes in shellbed–mudstone alternations (Brett et al., 1986; Miller et al., 1988). For example, black shale facies representing offshore, basin-center deposits, contain extremely thin (0.1–2.0 mm), micrograded silty laminae that overlie laterally extensive, sharply defined bedding surfaces. These bedding planes display concentrations of styliolinids and disarticulated to fragmented small brachiopods and mollusks. These distinctive laminae are thought to represent relatively long spans of time between episodic thin, but widespread, burial layers. Anoxic conditions within the sediment, and at least dysaerobic conditions at the sediment/water interface precluded large-scale burrowing and preserved the fine-structure of event sedimentation. Burial layers are uniformly thin and the intervening shelly laminae display current alignment of styliolinids and, locally, windrows of shell fragments indicating some current action prior to burial. Rarely, well-articulated fossils, including intact fish skeletons, occur on bedding planes within similar black shales (Brett and Baird, 1986a), attesting to the rapidity of accumulation of overlying muds. These features are indicative of the most distal effects of storms, i.e., episodic thin mud blankets.

A variety of stratigraphic, paleontologic and micropaleontologic evidence (see Brett et al., 1983, 1986; Vogel et al., 1987) indicates that bioturbated, commonly pyritic, gray mudstones represent slightly shallower water deposits in the Hamilton Group. Detailed study of the taphonomy of these facies (Brett et al., 1986; Dick and Brett, 1986) suggests that they contain mud tempestites. These beds comprise widespread layers of fossils separated by thicker 1–10 cm intervals of barren or sparsely fossiliferous, bioturbated mudstone. Biostratinomic evidence (e.g. complete trilobites and moult ensembles; Speyer and Brett, 1985, 1986) reveals the presence of a succession of single-event mud burial deposits. On average about 10–15 such layers could be recognized in half-meter intervals which were excavated in detail. The intervening barren mudstone layers appear to be thicker on average than the black shale laminae, although the sample is probably strongly biased toward thicker mud blankets because of pervasive shallow burrowing in these more aerobic facies, which would have obliterated thinner alternations. Although effects of winnowing are rather subtle in these beds, elongate stringers of vaguely oriented shell debris occur in several beds (Linsley, 1972).

Taphonomy of inferred intermediate-depth (between normal and maximum storm wave base, about 15–50 m, see Liebau, 1980) deposits in the Hamilton Group has been investigated in the present study and in a detailed petrographic study of the Kashong Shale by Lukasik (1984). These studies indicate the combined effects of winnowing and aggregation of shelly layers, including gutter casts on the bases of shell beds and minor rippling of shell beds. Shell orientation is generally less well developed in the shallower-water deposits than in distal black and dark-gray shale facies. This probably reflects a predominance of oscillatory wave currents over unidirectional currents, as well as later disorienting effects of deep burrowers in the proximal facies. Within medial deposits, barren, single-event mud layers are commonly quite thick (1 to over 10 cm).

Relatively few studies have addressed the onshore end of the spectrum among Hamilton facies. However, transitions from offshore mudstones to condensed shelf carbonates have been examined in the Moscow Formation (Baird, 1979; Baird and Brett, 1981; Lukasik, 1984; and Brett et al., 1986). In these cases, the proportional thickness of winnowed shell-debris layers increases in an apparent upslope direction. There is a concomitant loss of mudstone layers, although a few rather thick mudstone layers abruptly separate shell beds even in condensed sections. The most onshore end point is probably represented by winnowed and amalgamated encrinite-shell lag deposits, such as those in the Tichenor and Portland Point Members (see Brett et al., 1986 for further discussion and illustrations).

Based on these observations we propose a simplified model to explain proximal to distal changes in shell beds in terms of winnowing, current, or wave scouring of the seafloor and removal of fine grained sediment, followed by blanketing deposition of sediment layers over bottom communities. We consider winnowing and mud blanketing to be the storm effects having the greatest sedimentologic and paleoecologic impact on the benthic environment. The relative proportion of winnowing vs. blanketing is a function of water depth (Fig.9) and severity of each storm as well as orientation of the storm with respect to the coast and other factors. During storms, stronger waves affected the shallow seafloor to varying depths depending on the strength and duration of the storm. In such areas storm-generated waves or currents would have caused variable degrees of scouring, winnowing, and concentration of shells, leaving surficial lags of shell material. Winnowed muds would have been carried basinward (downslope) by gradient or geostrophic currents, where they ultimately blanketed more distal beds and living communities. As the velocity of these turbid suspensions diminished toward the basin center, a thinning layer of barren mud was deposited by gentle currents. Most mud layers thus would represent pelleted marine sediments that were resuspended by storms in nearshore areas. However, some of the mudstones, especially in more proximal beds, may represent sediment plumes transported into the basin as a result of flooding in source areas following major rain storms (Field et al., 1986).

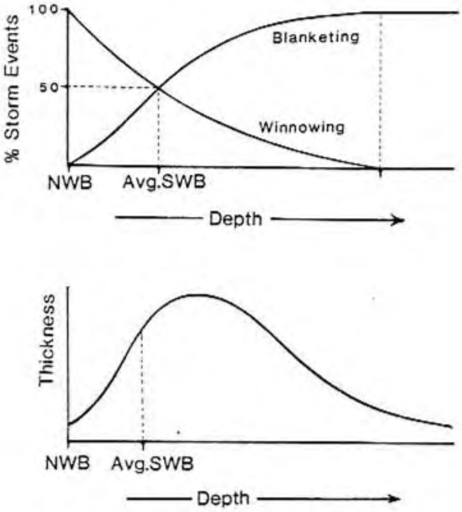

Fig.9. Upper graph shows the predicted percentage of storm events that affect the bottom from nearshore at the left to offshore at the right. At normal wave base (*NWB*) winnowing will occur 100% of the time; at average storm wave base (*SWB*) winnowing and blanketing will contribute equally to the storm deposit and will produce winnowed shell beds blanketed by nearly barren muds. The lower graph shows the predicted thicknesses of mud blankets that cover shell beds. Notice that blanketing is almost non-existent at *NWB*, and is greatest probably at maximum *SWB*.

This model leads to a predicted onshore–offshore gradient in the frequency and character of storm deposits (Fig.9). Over time, shallow water areas would experience more winnowing than blanketing. At normal wave base, where wave energies are consistently high, nearly all storm deposits would be represented by reworked shell material; and mud layers, if deposited, would rarely be preserved. In areas close to average storm wave base, winnowing and blanketing would be nearly equal, whereas in more distal areas, blanketing following storms would be the norm. This model predicts regular proximal to distal trends in shellbed–mudstone proportions. Shell beds would be amalgamated in nearshore areas, but would become thinner, simpler, and more numerous farther offshore. Mudstone layers would thicken proximally, and thin distally. Very distal areas would display more numerous but thinner mud layers, subject to disruption and destruction by burrowing, except under anaerobic basinal conditions (Allen, 1982). This gradient is directly comparable to onshore–offshore trends in storm-generated shell beds described by Aigner (1985) for mixed carbonate–clastic sequences in the Triassic Muschelkalk.

A special test case of this proximality model has been observed at Skaneateles Lake (Brett et al., 1986), in which a suite of storm beds associated with a buried erosional submarine escarpment can be traced for 2.5 km. In this case the most proximal beds are amalgamated coral-shell rubble beds; these are split distally by mudstone layers. In turn, the mudstones are lenticular, thickening for some distance down the buried submarine slope and then thinning into a series of shale laminae. This pattern again bears out the general predictions of our winnowing-blanketing model. Although much more study is needed, our preliminary studies of comparative taphonomy in the Hamilton Group tend to corroborate this model.

## Temporal scale of shell and mudstone beds

From the above discussion we conclude that barren mud shales were not deposited by a steady slow rain of clay particles to the sea floor. Rather, the preservation of articulated and in situ fossils on the upper surfaces of shell beds (Fig.7) demonstrates that many Hamilton mud layers were deposited very rapidly, perhaps in a matter of hours or days. In 3–5 m sections of the Windom Shale, at least 80% of mudstone layers display some taphonomic evidence of being very rapidly deposited mud blankets. Moreover, this is probably a conservative estimate as bioturbation has probably eradicated key evidence in some buried beds.

Taphonomic studies of recent organisms allow us to estimate the duration of these burial events. In modern marine situations, the ligaments which hold a crinoid or arthropod skeleton together decay and cause disarticulation in a matter of hours after death (Meyer, 1971; Liddell, 1975; Meyer and Meyer, 1986; Plotnick, 1986). Partial disarticulation will occur no more than twenty-four hours after death for a crinoid lying exposed at the sediment/water interface. For a bed surface containing articulated crinoids, at least several centimeters of mud had to have accumulated in several hours or a very few days. In the intervals examined in this study, complete articulated crinoids are extremely rare but articulated portions of crinoid skeletons (including crinoid columns up to 15 cm long, isolated calyces, and cirrus-type holdfasts) are quite common at the tops of beds (Fig.7F). Preservation of partial articulation probably requires somewhat less rapid burial, spanning days to weeks (Brett and Baird, 1986a), but nonetheless it is very rapid with respect to previously estimated average sedimentation rates (e.g. Schindel, 1980) in this type of sequence.

The shell beds themselves appear to represent much longer periods of time than do the intervening mudstones. Some shell stringers and pavements may represent only enough time for a single community to develop, probably a few tens of years, before being covered by a mud burial event. Most of this time is probably represented within simple and complex shell beds by the basal layers of highly comminuted shell debris and resistant skeletal particles such as crinoid ossicles (Fig.10). Also,

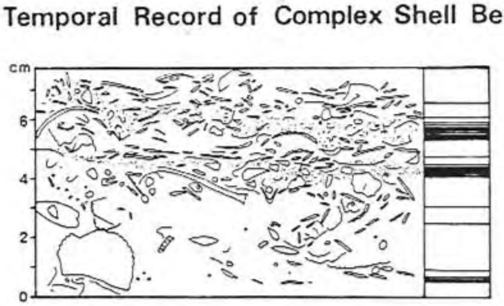
Temporal Record of Complex Shell Bed

Fig.10. Sketch of a polished and acid-etched cross-section of a complex bed from the lower Wanakah at Lake Erie Shore. Fine comminuted shell debris at base of shell layers is overlain by articulated brachiopods and abundant bryozoan fragments. The column of horizontal lines on the right represents the inferred amount of time recorded by various levels within the shell bed. Closer spacing of lines indicates more time.

as noted above, complex shell beds evidently record multiple burial and winnowing events. These events were separated by ecologically significant periods of nondeposition during which winnowed shelly pavements were colonized. Ecological succession probably occurred during these periods of low physical stress, but due to faunal condensation it is recorded only by preserved attachment and encrustation relationships (Fig.11).

Evidence for repeated winnowing events during the formation of complex beds include corals that have been toppled and reoriented several times (Fig.12), and large or robust fossils with several generations of epibionts. In many cases thicker shell beds display differentially preserved fossils; some highly corroded and broken, others perfectly preserved. Similarly, the previously cited bryozoan mounds record multiple burial events prior to the final burial of the shell bed. The upper parts of these complex beds show mud and shell mixtures of the younger communities, and are capped by the community that was killed in the final burial event. These beds probably represent time periods on the order of tens to hundreds of years, during which little net sediment accumulation took place.

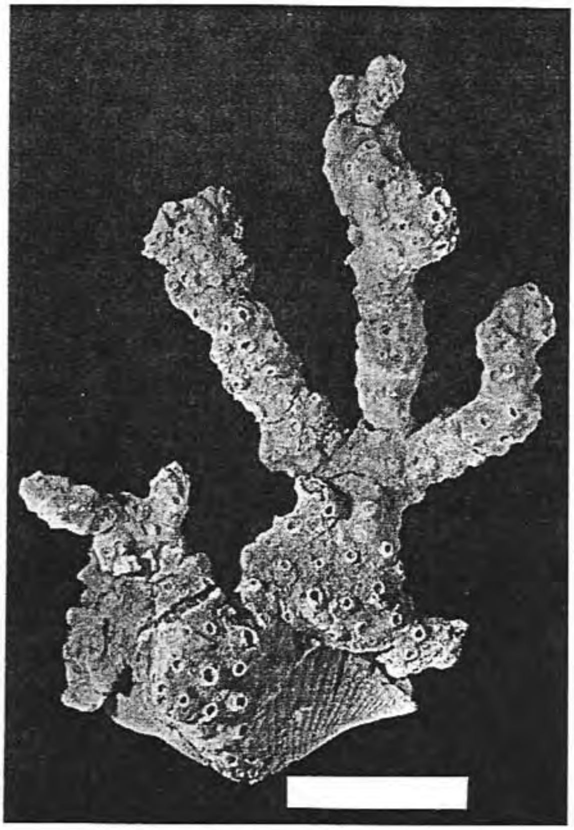
Fig.11. Specimen of the brachiopod *Spinocyrtia granulifera* overgrown by a consortium of the coral *Aulocystis jacksoni* and a bryozoan *Leptotrypella* sp. (× 0.9). This host-specific interaction (the coral–bryozoan complex invariably began growth on the brachial valve of *Spinocyrtia*) illustrates an example of true autogenic succession. The excellent preservation of the delicately branched colonies illustrates rapid burial with only toppling in place. Specimens of this sort occur commonly in a single horizon in the lower Wanakah Shale that can be traced some 30 km in outcrop. Lake Erie Shore, Erie Co., N.Y. 4 cm scale bar. Specimen courtesy of G. J. Kloc.

Therefore, the preserved sediments within a meters-thick stratigraphic section of alternating shell beds and mud layers record only a tiny fraction of the total elapsed time (Fig.13). The greatest amount of time is represented by scoured surfaces and the thin layers of shell debris overlying them, and by nondepositional surfaces. The better-preserved shell material, often comprising the bulk of the individual shell beds may record only the last few generations of the epifaunal community. Rapidly and episodically deposited mud layers, while comprising the bulk of the total strati-

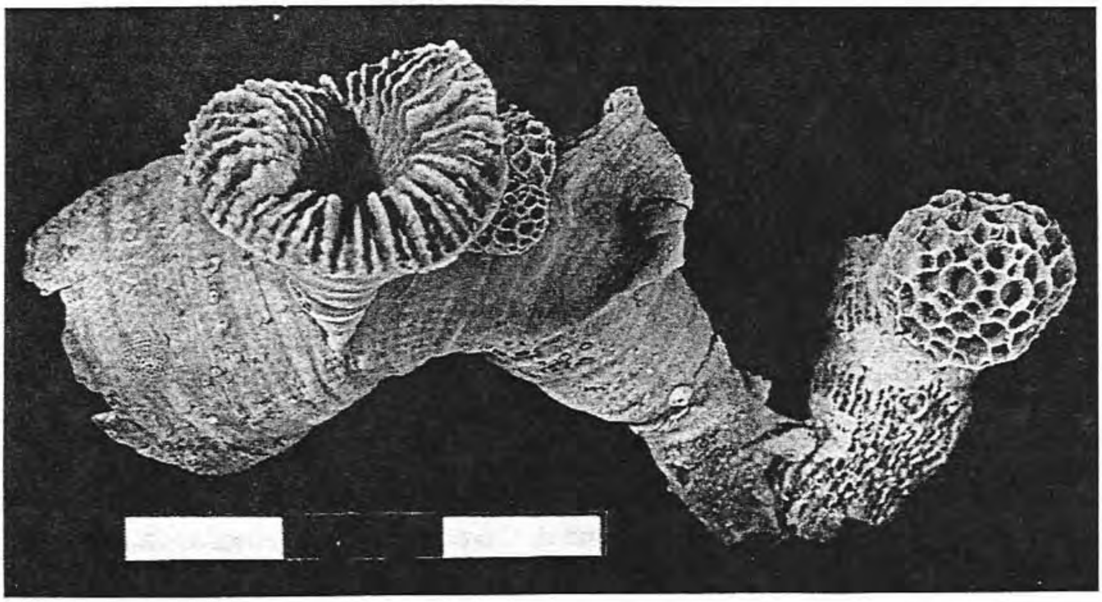

Fig.12. Specimen illustrating repeated reworking and encrustation of coral skeletons. Small corroded fragment of coral was colonized by a solitary *Heterophrentis* coral which toppled at least once and reoriented its growth (note geniculation). This coral was ultimately overturned and killed but the skeleton served as a substrate for favositids and another solitary coral (*Heliophyllum*). Scale in cm. Lower Wanakah Shale; 11 mile Creek, Darien, Genesee Co., N.Y. Specimen courtesy of G. J. Kloc.

graphic thickness, appear to represent an almost insignificant amount of geologic time.

Evidence for this inferred timing is found in some bryozoan colonies which extend upward from the tops of shell beds, through the overlying mud layer, and into the next shell bed. One spectacular example of this was found in a roadcut along Long Hill Road just north of Moravia, New York (Loc. 25, Fig.2). The specimen (Fig.14) is a fistuliporoid bryozoan which was initiated and laterally expanded during the development of a complex shell bed. Mudstone layers within the lower portions of the mound probably record the occurrence of minor partial burial events during shell bed formation. The mound survived the final burial of the lower shell bed, and continued to grow, though becoming partially buried and severely constricted during this event, or a subsequent episode of mud deposition. With the return of a shelly substrate (probably initiated by a winnowing event followed by non-deposition) the bryozoan became reestablished and expanded laterally. Although the colony was nearly extinguished by the burial event which smothered this upper shell bed, a few thin bryozoan lamellae immediately overlying the mound attest to a final attempt at recolonization on yet another thin shelly horizon. Therefore, the colony expanded and thrived during times of shell bed accumulation for relatively long periods of time (20–100 years). The individual mud layers were introduced quickly (hours to days) and caused restriction of the bryozoan colony. Thus two complex shell beds, one pavement shell bed, and their intervening mud layers are bracketed within the lifetime of this single bryozoan colony, which was probably at most only a few hundred years (R. J. Cuffey, pers. comm., 1987). This is a remarkably small amount of time for the accumulation of a package of about 30 cm of shale and shell beds.

If the mudstones represent days, and most shell beds represent only a maximum of a few hundred years each, then a 3 m section composed of about 25 alternating shell beds and mud layers would not represent more than a

Temporal Record of Event Deposition

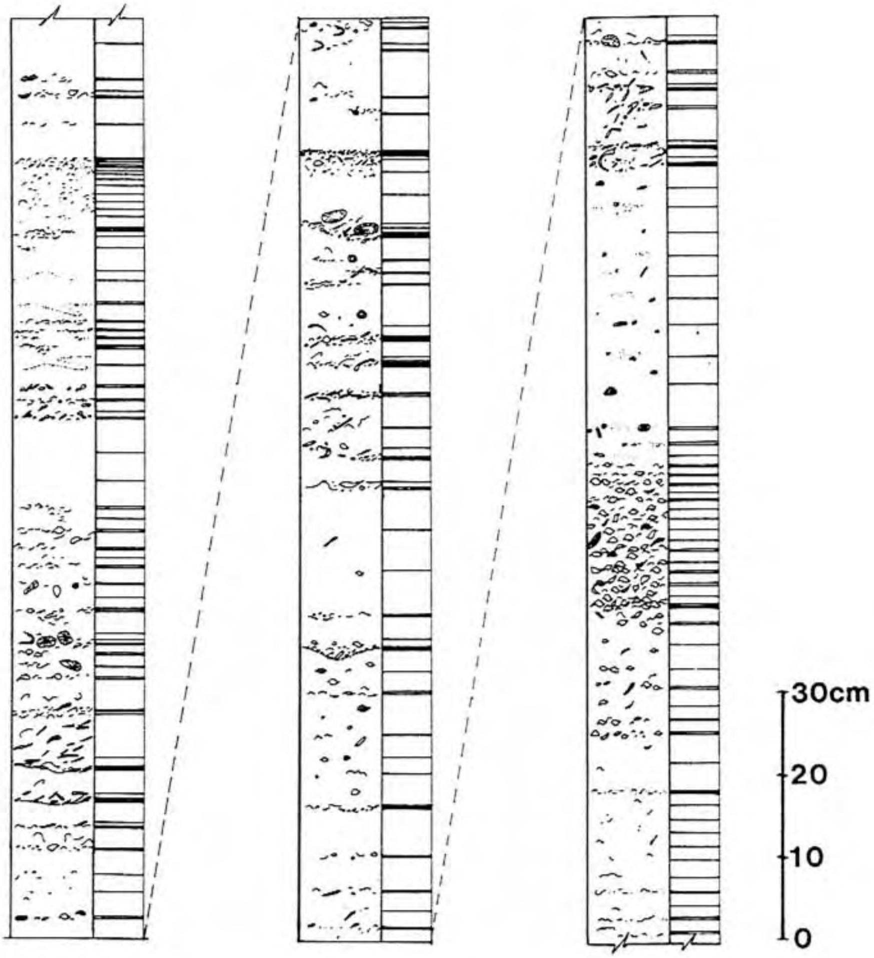

Fig.13. Sketch of an acid-etched drill core of basal 3 m interval of Wanakah Shale from the Retsof Salt Mine showing sequence of shell stringers, pavements, simple beds, and complex beds. Attached column of horizontal lines represents inferred amount of time recorded by shell and mud layers. Closer spacing of lines indicates more time.

few thousand years. Yet, crude estimates based on absolute dates for the duration of the Givetian (Middle Devonian) stage (about 6 Ma; Harland et al., 1982) and overall formation thicknesses in the Hamilton Group suggest that the upper Windom cycle should actually represent 1 or 2 orders of magnitude more time than that. Where is all the time recorded? Much of this time must be represented by particular shell beds that bound packages of alternating mud and shelly layers.

It is evident from the above discussion that the shell beds represent considerably longer periods of time than the mudstones. However, there are particular shell beds, herein referred to as condensed beds, that seem to represent considerably longer periods of time than the common simple or complex shell beds. In the strict sense, condensed beds have been defined as units in which several zonal index fossils were mixed, indicating an obvious condensation of the temporal record (see Fürsich, 1978). However, extended gaps in sedimentation of sub-biostratigraphic duration can be located

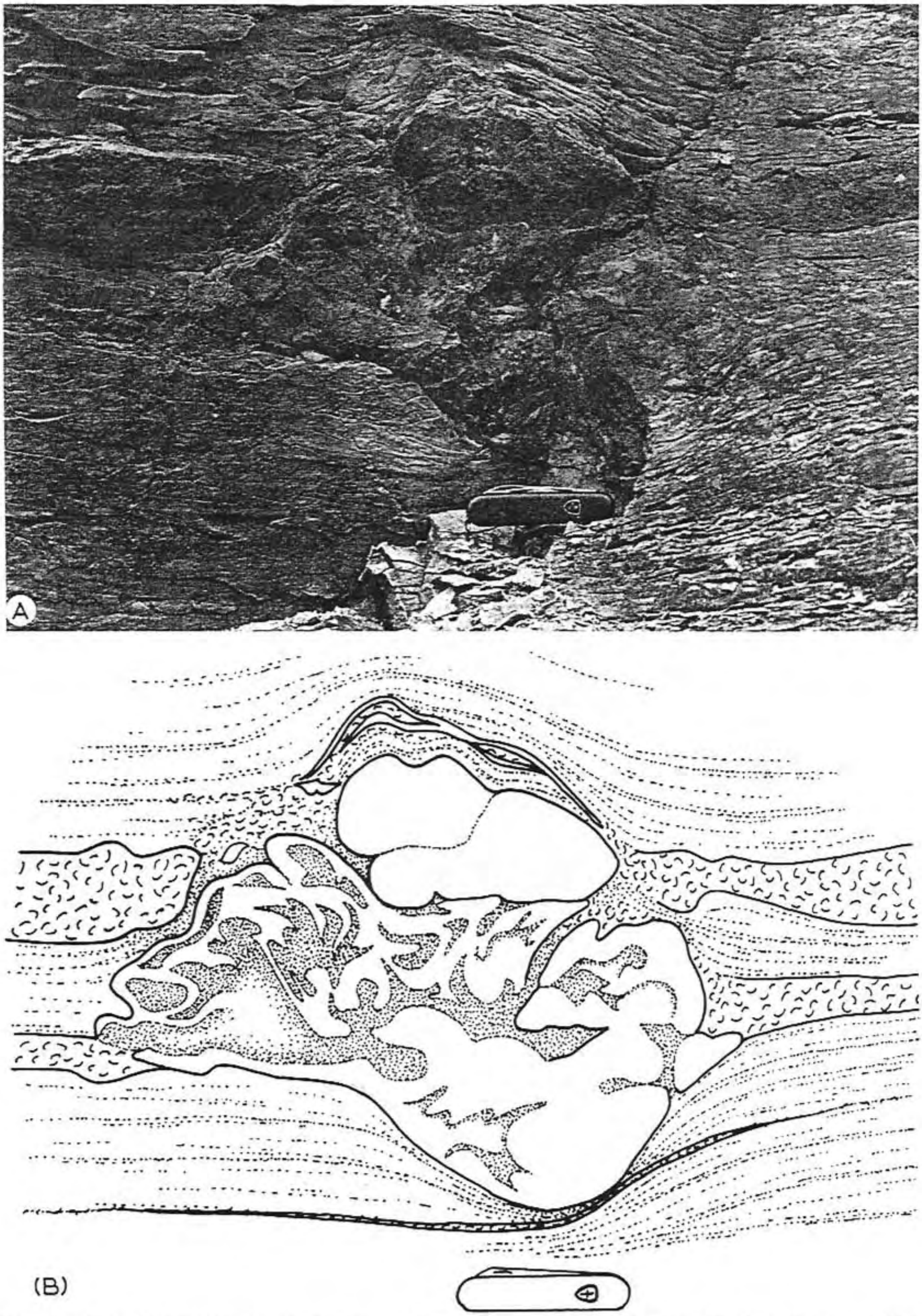

Fig.14. Large fistuliporoid bryozoan showing regrowth through several shell layers; upper Windom Shale, Long Hill Road section, Moravia, N.Y. Photograph (A) and sketch (B) of the bryozoan. See text for description.

using more subtle indicators such as encrustation, corrosion, phosphate pebble formation, and skeletal concentrations (e.g., many papers in Einsele and Seilacher, 1982; Kidwell, 1982; hardground literature).

In the Hamilton Group, condensed beds range in thickness from a few millimeters to several centimeters, but are never very thick (Table III). Each condensed bed has a characteristic signature that separates it from adjacent shell beds and allows recognition and correlation among outcrops. The signature of each bed may be a distinct fauna, or a unique type of preservation or mineralization. Most often, however, condensed beds are recognizable on the basis of a unique combination of taphonomic characteristics and faunal content.

Condensed beds record long spans of nondeposition, reworking, and erosion, and they are persistent over wide geographical extents. We have noted that they tend to occur at sharp lithologic and biofacies boundaries, sometimes with evidence of erosional truncation. However, they are only recognizable upon very close examination. Evidence suggesting that particular beds represent a considerable length of time is found in the large percentages of broken shell debris in these beds. Secondly, the bases of the beds are sometimes scoured, leaving sharply defined burrows and groove marks filled with shell debris. This indicates removal of upper soft sediment layers down to the level of compacted muds which preserved distinct burrows and scour marks. Thus the beds may have undergone multiple episodes of scouring and winnowing. Third, the condensed beds show features that indicate long residence time, such as rounded phosphatic pebbles, corroded fossils, and fossils overgrown with auloporid corals and other epibionts. Each of these beds is finally capped by a barren mud layer which had to have been deposited quickly (due to well-preserved, delicate fossils at the tops of condensed beds, as observed in simple and complex beds), which suggests that each of these beds might be used as an isochron for basinwide correlation.

We should note that the last communities to occupy the seafloor during non-depositional intervals are probably greatly overrepresented in the final fossil assemblage. Remnants of countless earlier generations of shelly organisms are represented only by resistant particles (e.g. conodonts and prefossilized phosphatic steinkerns) or unrecognizable shell fragments. This conclusion is strengthened by studies of shell residence time on modern muddy seafloors (Cummins et al.,, 1986; Davies et al., 1986). Such studies show that the "half-life" (i.e. the time at which only half of a given cohort of shells is still present as recognizable skeletons) for unburied mollusk shells is normally less than one year in coastal lagoons. This study included primarily small, thin-shelled aragonitic mollusks; we would expect that thicker calcitic skeletons would remain stable for substantially longer periods, perhaps up to tens of years. However, these actualistic studies do underscore the ephemeral nature of shell material on the seafloor.

## Stratigraphic correlation and interpretation

As interpreted herein, shell beds represent relatively long periods of time during which little sediment accumulated over broad areas of sea floor. If so, these beds might then be expected to be regionally traceable. As a test of this expectation we attempted very fine-scale correlations of certain 3–5 m sections of the Windom Shale. We found that some complex beds could be traced over the entire study area (greater than 150 km in some cases; Fig.15) before they pinch out or are erosionally truncated. These beds retain their distinctive geometry and taphonomy over broad areas. Moreover, many of the beds display lateral gradients in biofacies from basinal to shelf environments. This suggests that sediment starvation occurred over broad regions including varied benthic environments. Condensed beds represent widespread, even basinwide, changes in the chemical or physical conditions at the sediment/water interface. These changes

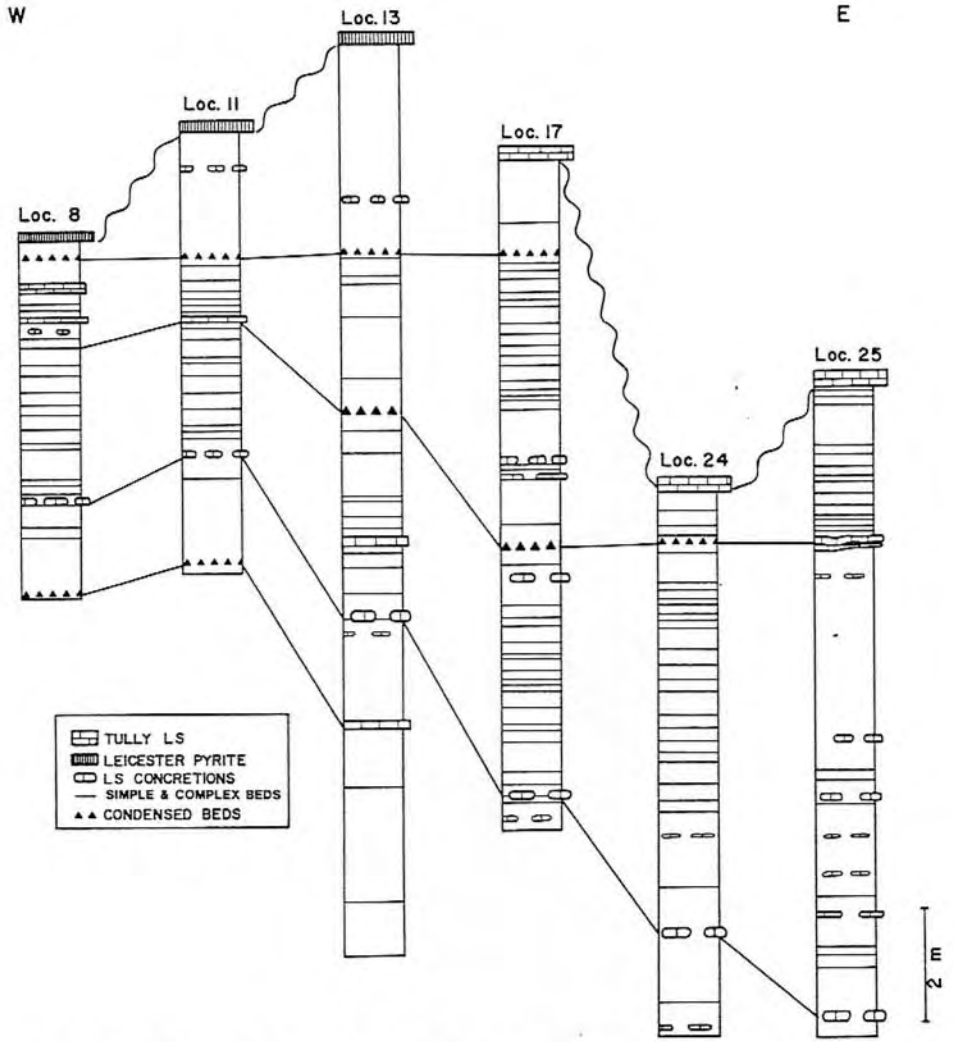

Fig.15. Correlation of selected sections of upper Windom Shale from the Genesee Valley in the west to Owasco Lake in the east, a distance of 150 km. Notice that concretion horizons and condensed beds are correlated great distances. Simple and complex beds between condensed beds are correlatable for shorter distances. An erosional disconformity (wavy line) below the Leicester Pyrite and the Tully Limestone truncates the uppermost condensed bed between localities *17* and *24* (it is last found 30 km east of locality *17* at locality *21*). See Fig.2 for locality information.

are evident in both fauna and lithology, since both change considerably above these marker beds.

Once it was determined that some beds were laterally traceable, we attempted to trace other complex and even simple shell beds between them in the more continuously deposited intervals. We found that these shell beds are highly traceable, but over a somewhat more limited area than the condensed beds (Fig.16). The intervals bounded above and below by condensed beds contain a relatively consistent number of shell beds over the entire outcrop belt. For example, the upper Windom (Taunton) interval undergoes a two-fold thickening without significant change in the number of 5–10 cm thick shell beds. In the westernmost section (Loc. 10, Fig.2), it contains 15 shell beds within a stratigraphic thickness of 2.1 m. To the east (Loc. 26, Fig.2) there are 13 shell beds through a thickness of 4 m. This suggests that individual shell beds may have been very persistent and widespread phenomena, but that the volume of mud deposited on top of the beds increased considerably to the east, toward the sediment source.

To test this assumption we attempted to locate certain beds that contained distinctive features permitting recognition among outcrops. These included peculiarities of faunal content and biostratinomy. For example, one bed that contains abundant complete *Clarkeocrinus* specimens (Fig.7C–F; see Gold-ring, 1923) can be traced from Bristol Valley to eastern Seneca Lake (about 37 km). Also, beds with characteristic diagenetic features, such as crinoid columns associated with pyritic crusts and large ellipsoidal carbonate concretions, can be traced with confidence over about 32 km in the Genesee Valley area. The existence of such beds illustrates two very critical points. First, unique conditions associated with particular burial events (that terminated given complex and condensed shell beds) were nearly uniform over very broad areas, at least parallel to depositional strike. Second, because fossil preservation demands very rapid burial and because the preservational conditions were unique for given beds, these layers must represent single widespread events, perhaps comparable to ash layers. While the individual shell beds themselves may record slightly different spans of time from place to place, the terminal mud burial layers appear to be isochronous beds.

To bury a shell bed rapidly across a very large areal extent requires an extremely widespread burial event. The process invoked for Hamilton sequences is rapid deposition of a cloud of mud generated in the nearshore either by a storm, or

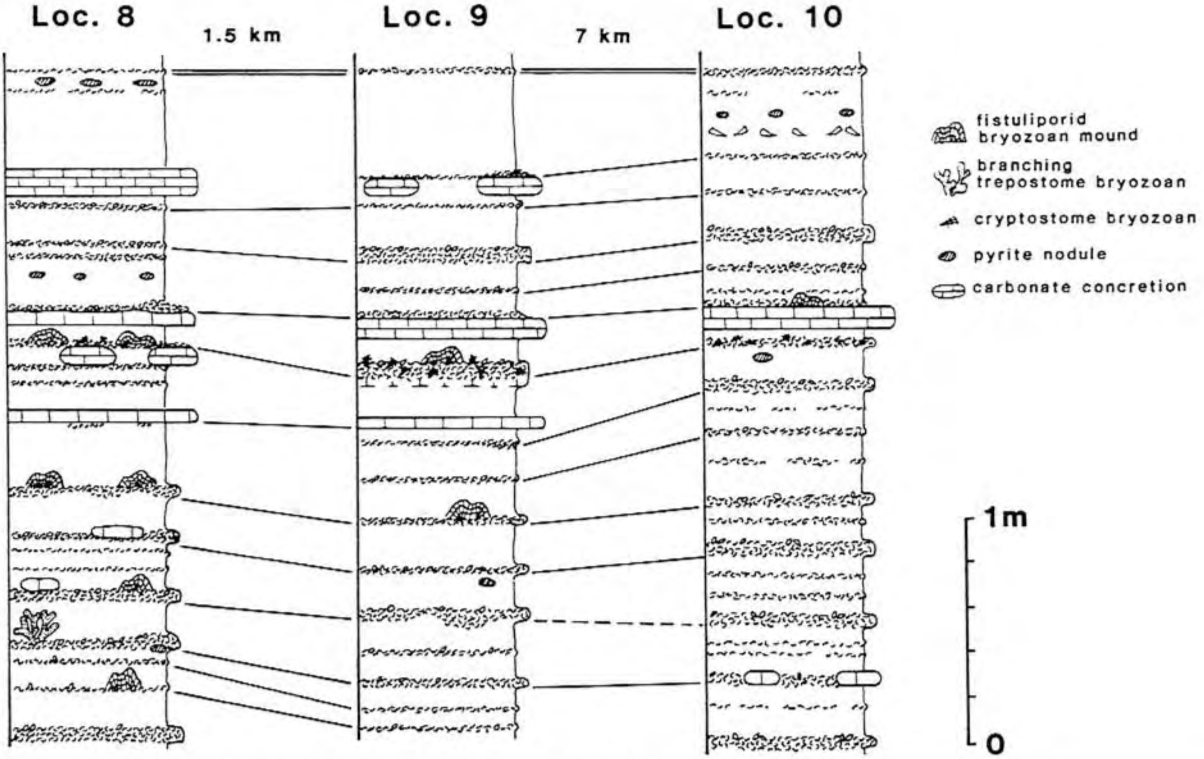

Fig.16. Detailed correlation of the upper Windom Shale shell-rich and concretionary horizons among three closely spaced Genesee Valley localities. Nearly every simple and complex shell bed can be traced on the basis of faunal content, taphonomy, and spacing. Limestone concretion layers are also highly traceable.

by flooding in the most proximal land areas. The sediment, in the form of pelletized mud, is carried out beyond the limit of storm wave base by a storm generated current. All of the sediment with higher specific gravity was deposited in proximal areas and only pelletized mud and minor amounts of silt were transported great distances offshore.

## Discussion

In summary, marine shellbed–mudstone intervals, such as those examined in this study, do not represent random sequences of localized and lenticular winnowed shell-hash layers and slowly accumulated background muds.

Rather, our analysis of the Hamilton sequences and preliminary examination of similar sequences (e.g. in the Ordovician Richmond Group of Ohio; Velbel, 1985; and the Silurian Rochester Shale of New York; Brett, 1983) indicates that shell beds, and not muds, represent the majority of time in these sequences. Thicker shell beds are very definitely continuous on the scale of outcrops up to 2 km long, and in many cases, over larger regions of several hundred square kilometers. Many, but not all, shell layers have been processed by episodes of storm-generated oscillatory or unidirectional currents resulting in reworking and winnowing. However, transport of shells, if present, was minimal.

More importantly, shell layers are not formed in most cases by ablation of major amounts of "background" shelly muds. indeed we are not convinced that much, if any, of the main thickness of the mudstone sequence represents "background" conditions (cf. Dott, 1983). In fact, many, and probably most shale layers, ranging from millimeters up to 5–7 cm in thickness (after compaction), are demonstrably single event deposits. These probably formed as a result of deposition from suspension clouds or turbid flows formed by winnowing in upslope areas, or less commonly by sediments derived directly from source areas following storm flooding. In any case, mud layers, sometimes of considerable thickness, were deposited within hours to a few days of the extermination of the last members of any given shelly accumulation, as evidenced by the well-preserved multielement skeletons of trilobites and echinoderms.

Perhaps the most surprising result of our studies in the Hamilton Group, and also in several other shaley sequences, is that individual burial layers with unique taphonomic signatures can sometimes be traced for tens of kilometers along depositional strike. This implies that the mud blankets, whatever their mode of emplacement, are of considerable lateral extent. When they can be recognized as such, they provide excellent, nearly isochronous key beds in local sections (see Waage, 1964). Most such beds have remained undiscovered in outcrops and their recognition and mapping should permit an order of magnitude improvement in time-correlation of local sections. The winnowing-blanketing model for shell-bed genesis may also prove useful in assessing relative depth of mudstone sequences.

In some instances we can also be certain that bundles of mudstone and shell layers represent relatively brief amounts of time (hundreds to at most a thousand years). It was shown that an entire sequence up to 30 cm thick accumulated within the life span of a single clonal organism (i.e. bryozoan). Bundles of beds such as these must be bounded by surfaces that incorporate much more time. Taphonomic and paleontologic (including biostratigraphic) evidence for long spans of non-deposition and reworking are important keys to recognition of condensed beds. These beds, recording very long spans of time, are typically very thin, apparently because unburied skeletal materials on the seafloor are very rapidly comminuted and/or dissolved, as observed in modern environments (Cummins et al., 1986; Davies et al., 1986). Once discovered these thin beds or surfaces can commonly be traced very widely (up to hundreds of kilometers) parallel to depositional strike. At a cruder scale of resolution than for event beds, these boundary surfaces also permit refinement of intrabasinal correlations.

The record of offshore marine beds in the Hamilton Group is much more orderly and less noisy and random than we might have expected. At least along depositional strike, regular stacking of widespread stratigraphic units is the norm rather than the exception. Older views of "layer cake" stratigraphy were, of course, overly simplistic; such patterns can not extend far in three dimensions. However, the fact that individual layers and bundles of layers can be traced along strike probably is partly a result of the great contrast in temporal scale between surfaces or thin layers and the sediment packages they bound. Whether at the scale of beds or bundles of beds, the amount of time represented on bounding surfaces is commonly an order of magnitude greater than that represented by the sediment between the surfaces. Given this view, the traceability of bundles of beds becomes predictable rather than enigmatic.

Major unresolved problems include: (a) how to determine the relative amounts of time represented on various condensed beds or boundary surfaces, and (b) elucidation of processes which led to rapid deposition of bundles of sediment between extended periods of non-deposition. Ironically, while the precise timing of short-term depositional events is resolvable with taphonomy, the determination of longer time spans is not. At present we know of no good means for determining relative spans of condensation that are sub-biostratigraphic in duration. Concentration of rare resistant sedimentary particles (e.g. fish teeth, quartz granules, conodonts) may eventually provide at least a qualitative index for comparing condensed beds.

We emphasize that many of the observations regarding depositional dynamics summarized in this paper could not have been recognized without detailed study of fossil preservation. For example, in the absence of fossils it would be virtually impossible to determine whether a given layer of mud accumulated over a short time or gradually over a period of thousands of years. Simple field observations of pertinent details provide immediate and essentially unequivocal answers in many cases. Moreover, attention to taphonomic detail has greatly facilitated detailed correlation of event beds. It may be possible, using a purely physical-stratigraphic approach, to identify the same number of shell beds at a given section and perhaps even to trace these layers laterally. However, in the absence of taphonomic evidence it would be impossible to recognize certain layers as being nearly time-equivalent deposits.

Finally, there has recently been much discussion of the adequacy of the stratigraphic record for the study of paleobiological problems. Many previous attempts to estimate stratigraphic resolution have been based on *net* accumulation rates in modern environments (e.g. Schindel, 1980, 1982). On this basis it has been argued that short-term processes, such as succession and microevolution, should not be resolvable in most cases, whereas longer term community change or evolutionary processes might be. However, the fundamentally episodic nature of sedimentary accumulation undermines these conclusions. Because "snapshots" produced by rapid burial are frequent and random with respect to time of colonization of the seafloor, the stratigraphic record *may be* adequate to elucidate succession (at least a "time lapsed" view of succession) and other short-term ecological responses (see Miller et al., 1988); in rare cases the record may provide detailed views of paleobiology or behavior of ancient organisms (e.g. clustered trilobites documented by Speyer and Brett, 1985). On the other hand, the existence of sizeable gaps between depositional bundles argues against direct use of the stratigraphic record of muddy epeiric seas to study potentially rapid episodic evolutionary processes such as speciation. However, taphonomically-refined event stratigraphy should provide an excellent framework for testing evolutionary morphologic stasis.

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