SUBMARINE EROSION AND CONDENSATION IN A FORELAND BASIN: EXAMPLES FROM THE DEVONIAN OF ERIE COUNTY, NEW YORK.

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INTRODUCTION

Geologists have long recognized the importance of unconformities in the stratigraphic record. Sloss (1963), for example, used six widespread unconformities to subdivide the North American stratigraphic succession into five major sequences or megasequences. This seminal work was, in some ways, the forerunner of sequence stratigraphic analysis which has recently resulted in a revitalization of stratigraphy (see articles by Vail and Mitchum, 1977; Vail et al., 1977; Posamentier et al., 1988; Van Wagoner et al., 1988; Baum and Vail, 1988; see Fig. 1). It is generally accepted that the stratigraphic record is highly incomplete and that much time is represented at some bed contacts. However, it is not always clear where these surfaces exist within stratigraphic sections. Many erosion surfaces, particularly in marine mudstone successions, are very subtle and can only be recognized with detailed observations. Nonetheless, many such surfaces are traceable over vast areas, forming the basis for a new dynamic view of stratigraphic processes within epicontinental sea and foreland basin settings.

Traditionally, geologists have associated erosion surfaces with major shallowing events that produced subaerial exposure. By definition, the sequence boundaries recognized by seismic stratigraphers (see Van Wagoner et al., 1988) represent, at least in part, subaerial erosion surfaces (Fig. 1). Obviously, subaerial processes of stream entrenchment and freshwater solution of carbonates are key agents in producing the major unconformities. A number of agents may also produce extensive truncation of older sediments in submarine environments; major storm waves, deep bottom currents, and internal waves may act to erode or winnow sediments on the shallow seafloor.

Condensed sections are relatively thin, time-rich intervals that are often widespread and may correlate laterally with much thicker sedimentary successions. These intervals, which range from millimeters to a few meters in thickness, are characterized by multiply reworked fossils and clasts, commonly showing a mixture of biofacies; fossils heavily corroded and may be fragmented. They may show evidence of prefossilization i.e., a phase of early diagenesis within sediment followed by exhumation. Diaclasts, such as hiatus concretions, reworked pyrite, and reworked fossils may be common within condensed beds. Biostratigraphically condensed intervals may show a mixing of zonal fossils; they are often enriched with respect to zonally important index fossils, such as conodonts. Chemically resistant skeletal elements such as phosphatized fish bone and teeth, are common in condensed beds, at least in post-Silurian time. The presence of certain early diagenetic minerals, such as phosphate, hematite, and glauconite is also indicative of sedimentary condensation.

Sedimentary condensation in siliciclastic dominated sedimentary environments results from two major processes: (1) winnowing and bypass of fine-grained sediments due to persistent or episodic current action; and (2) sediment starvation in marine basins as a result of nearshore sediment entrapment. In carbonate depositional systems, condensation may result from a restriction or near elimination of carbonate production in the absence of input of extrabasinal sediment.

Surfaces of erosional truncation and condensed sections occur predictably within sedimentary cycles (Fig. 1). Erosion surfaces should be associated with rapid relative sealevel drop. Conversely, condensed horizons are associated with rapid relative sealevel rise and transgression, which commonly produces offshore sediment starvation. The rate of fall may exceed local subsidence leading to exposure of formerly inundated areas and subaerial erosion. Furthermore, the lowering of wave base and of storm wave base may produce erosional truncation of sediments, particularly muds, which accumulated initially below the reach of wave erosion. This may result in erosion and redeposition of muds and silts by storm-generated gradient currents into deeper portions of the basin. The gradient currents themselves may produce erosive effects in some areas, particularly in regions of slopes, where minor bypass channels may develop that permit more rapid basinward sediment transfer of fine-grained sediments across or down gently sloping ramps and into basinal regions. Consequently, relatively thick and "time-poor" successions in mid-basin depocenters should be expected to coincide with erosion on the basin margin. Condensed sections would not be predicted to occur near the bases of sedimentary sequences associated with sealevel fall.

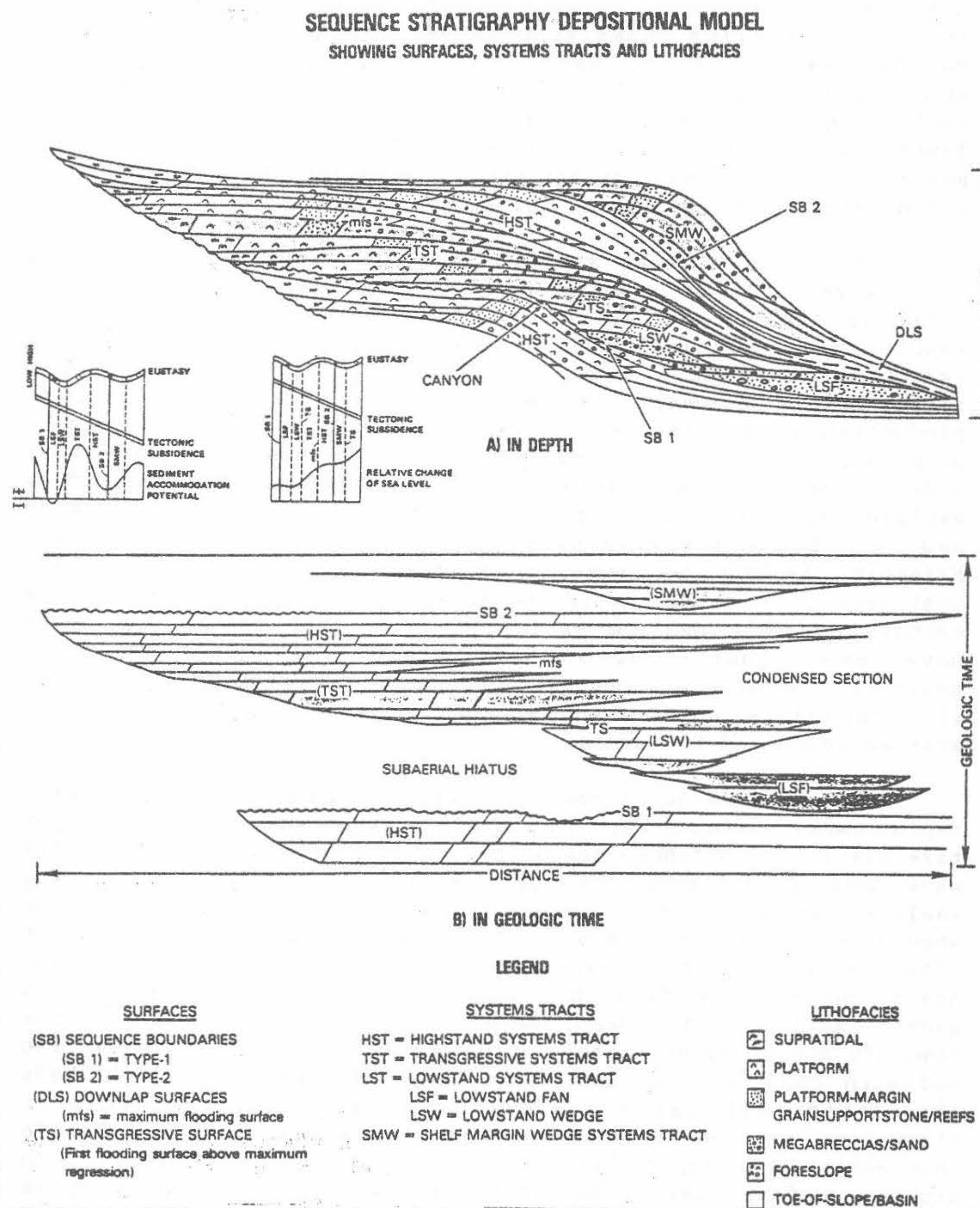


Figure 1. Idealized sequence stratigraphy model showing key surfaces and systems tracts. Sequence boundary 1 (SB-1) is a type 1 (incised) boundary, SB-2 is a type 2 sequence boundary. Note that the sequences are separated by an unconformity representing exposure during times of maximum rate of sea level fall - this unconformity can be traced to continuity offshore. This correlative conformity is a time boundary. From Baum and Vail (1988).

Nonetheless, as we illustrate in this paper, condensed beds, closely resembling those associated with sediment-starvation during sealevel rise, were formed during early phases of shallowing cycles. Such condensed beds at the bases of coarsening-up cycles often appear as "precursors," in terms of fauna, to the fossil assemblages which characterize the regressive maximum of a given sedimentary cycle. Precursor beds of this sort are difficult to explain in traditional models.

The sequence model also predicts that rapid relative rises in sealevel will be associated with sedimentary condensation in offshore areas. Relative sediment starvation will commonly result from rapid transgression, which drowns rivers, producing estuaries and bays that serve as collecting traps for siliciclastic sediment. In areas of shallow water where carbonate production may be high, siliciclastic sediment starvation could be associated with the development of limestone beds. Indeed, this model of nearshore siliciclastic alluviation has been proposed to explain thin, continuous carbonate units in the Devonian rocks of New York State and elsewhere (see McCave, 1973; Johnson and Friedman, 1969). We have argued (Brett and Baird, 1985, 1986) that most thin carbonates in the Middle Devonian of New York State cannot represent maximum marine flooding, but rather appear to have been deposited at or immediately after major drops of sealevel. Nonetheless, certain phosphatic bone-rich or conodont-rich carbonate beds do appear to represent genuine sediment-starved condensed intervals.

The sequence-model does not predict erosion associated with rapid transgression except in shoreface areas where ravinement may take place. In offshore areas, the raising of wave base and storm wave base should have the opposite effect of that seen during sealevel lowering (i.e., areas formerly affected by winnowing should be deepened to the point that they are no longer eroded and offshore areas should experience little or no wave erosion. Again, however, we find that there are many exceptions to this generalization, and indeed, major erosional truncation surfaces commonly appear to be associated with rapid relative sealevel rise and with condensed sections. In many instances, condensed beds associated with rapid sealevel rise and relative sediment starvation, may be truncated by erosion surfaces that underlie apparently deep water facies, particularly black shale. Such erosion surfaces may be marked by unusual lag deposits, such as lenticular bodies of reworked sedimentary pyrite, fish bones, and conodonts (Baird and Brett, 1986; Baird et al., 1988).

In the present paper, we illustrate a variety of condensed and erosional intervals within Middle to lower Upper Devonian rocks of Erie County, New York. We find that most erosion surfaces and condensed horizons are associated with rapid changes in sealevel; these include both rapid drops associated with the falling inflection point (on a sinusoidal sealevel fluctuation curve) and rapid sealevel rises associated with the rising inflection point (see Posamentier et al., 1988; Van Wagoner et al., 1988). However, not all such surfaces are associated with major fluctuations in sealevel. For example, it is possible for a condensed interval to occur within a carbonate simply by poisoning of the "carbonate factory" by sedimentary events such as the influx of volcanic ash.

GEOLOGIC SETTING

Tectonics and Paleogeography

The Middle and lower Upper Devonian strata of western New York State consist of carbonates and fine-grained siliciclastics belonging to the Onondaga Group, Hamilton Group and Genesee Formation (for summary discussions see, Rickard, 1981; Woodrow et al., 1988; Fig. 2). These sediments accumulated in shallow shelf to deeper basinal environments along the northwestern margin of the Appalachian foreland basin.

Precise paleogeographic positioning of North America during the Middle Devonian has been rendered uncertain by the pervasive Permo-Carboniferous overprinting of paleomagnetic signatures. Kent (1985) suggested that the Appalachian Basin was positioned at or near the paleoequator. However, more recent reconstructions place the area between 10 and 15^{o} S latitude (Van der Voo, 1988). A humid, possibly, monsoonal, climate would have prevailed. Devonian seas in the Appalachian Basin were of normal salinity. Through much of Middle and Late Devonian time these seas were density-stratified with anoxic waters in deepest portions of the Appalachian basin. Thermohaline density-stratification may have resulted from restriction of circulation and/or influx of fresh water from the Catskill deltaic complex (Ettensohn, 1985; Woodrow, 1985).

Acadian orogenic activity during the Middle and Late Devonian probably resulted from oblique convergence between Laurentian and the Avalon terranes (Ettensohn et al., 1988). Thrust loading was associated with the Acadian crustal shortening and northwestward migration of the Appalachian foreland basin. Erosional denudation of the Acadian source terranes resulted in gradual and progressive infilling (to overfilling) of the Appalachian Basin, thus producing the Catskill deltaic complex (Ettensohn, 1987).

General Stratigraphy

The early Middle Devonian (Eifelian) Onondaga limestone rests with a major erosional unconformity - the so-called Wallbridge unconformity (Dennison and Head, 1975)- on upper Silurian dolostones. This is a second order unconformity recognized by Sloss (1963) as the boundary between the Tippecanoe and Kaskaskia sequences. The surface is irregular with a relief of up to a meter, and reflects a karstified surface developed on the Silurian carbonate during a major, second order eustatic drop in relative sea level (Johnson et al., 1985). Minor amounts of late Early Devonian Oriskany Sandstone occur locally in pockets along the unconformity.

The Onondaga Limestone comprises about 30-50 meters of shallow shelf carbonates. The Edgecliff Member is characterized by crinoidal grainstones and bioherms, while wackestone and packstone with abundant nodules and beds of chert, typify the Clarence and Moorehouse Members.

The Onondaga carbonates accumulated in near-wavebase to deeper subtidal environments prior to the onset of the major phase of the Acadian Orogeny. Widespread metabentonitic ash layers within the upper beds of the Onondaga herald the onset of renewed tectonism in southeastern source areas. The upper Onondaga displays a relative deepening-upward succession. Upper beds of argillaceous, dark, micritic limestone are abruptly overlain by black, fissile and organic-rich shales of the lower Hamiton Group (Marcellus, Skaneateles formations). Hamilton siliciclastics represent the first major pulse of terrigenous sediments from the Catskill deltaic complex.

Upper Hamilton beds (Ludlowville, Moscow Formations) in western New York are fossiliferous grey, commonly calcareous mudstones that record general, but not progressive, shallowing. A series of major and minor cycles are recognized in western New York (Brett and Baird, 1985, 1986); where best developed each cycle displays a gradation from dark gray calcareous mudstones to fossiliferous pelletal wackestone-grainstone deposits. These limestones, deposited at or immediately following major shallowing events, form widespread marker units in the Hamilton Group that have been used to map component formations; in ascending order, these are the Stafford Limestone at the base of the Skaneateles Formation; the Centerfield Limestone at the base of Ludlowville Formation, and the Tichenor Limestone at the base of Moscow Formation (Figs. 2, 3).

Subsymmetrical shale-limestone-shale cycles in the Hamilton of western New York have been interpreted as 4th and 5th-order shallowing-deepening cycles (Brett and Baird, 1985, 1986). Carbonate beds appear to correlate approximately with the siltstone and sandstone caps of coarsening-upward cycles in central New York. The relatively sharp basal contacts of major limestone or sandstone units also can be considered to represent sequence or at least subsequence boundaries. Toward the basin margin the largest-scale cycles appear to become asymmetrical deepening-upward sequences.

The top of the Hamilton Group is marked by a major unconformity in western New York. The angular unconformity documented at this level (Brett and Baird, 1982) reflects major tectonic arching of the northwestern margin of the Appalachian

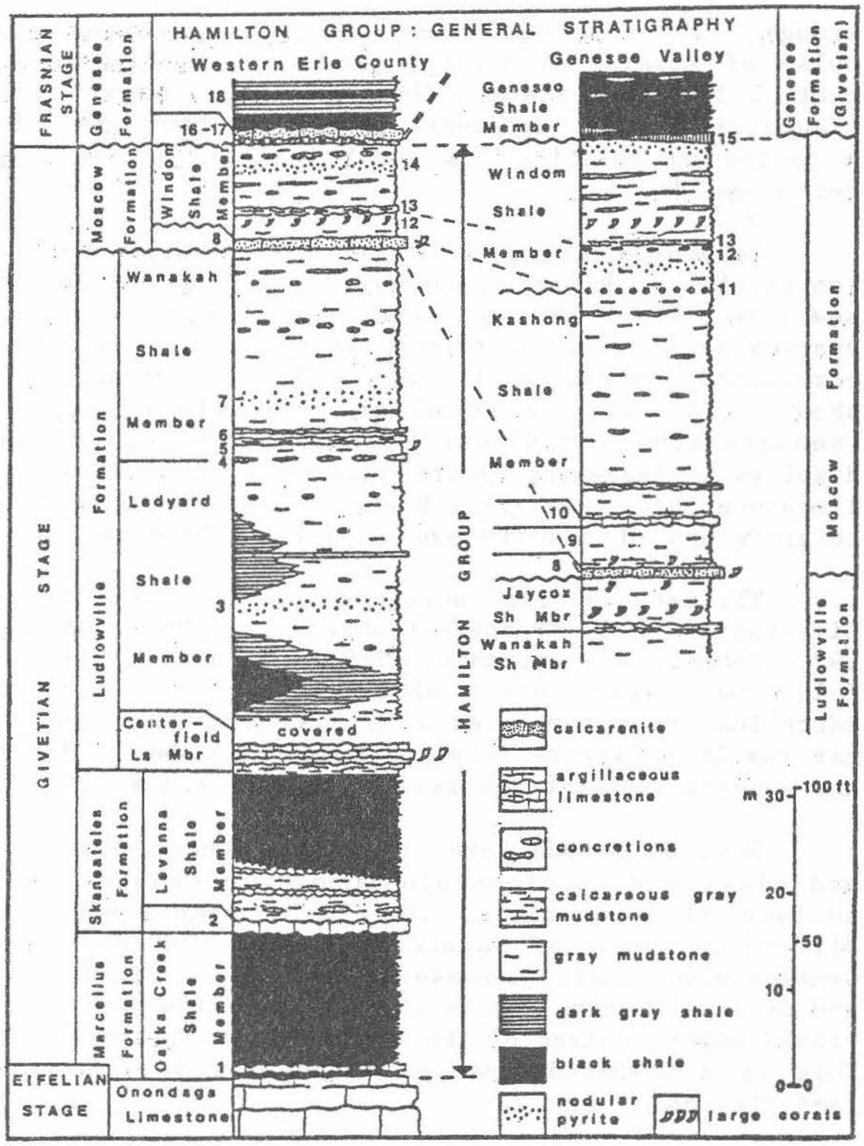


Figure 2. Stratigraphy of the Middle Devonian Hamilton Group and part of the overlying Genesee Formation. Upper Hamilton and basal Genesee beds in the Genesee Valley are correlated with condensed equivalent deposits in Erie County New York. Numbered units include: 1) basal Marcellus fossil-rich beds (concealed west of LeRoy, Genesee Co.); 2) Stafford Limestone Member; 3) Alden Pyrite bed; 4) Mt. Vernon Bed 5) Pleurodictyum beds; 6) Murder Creek trilobite bed; 7) lower Wanakah pyrite beds; 8) Tichenor Limestone Member; 9) Deep Run Shale Member; 10) Menteth Limestone Member; 11) Sub-Windom discontinuity-related phosphatic lag bed; 12) Bayview Coral Bed; 13) Smoke Creek trilobite Bed; 14) Penn Dixie Pyrite Bed; 15) Leicester Pyrite Member; 16-17) North Evans bone bed and Genundewa Limestone; 18) West River Shale Member.

trough. The same tectonism, possibly associated with a renewed pulse of Acadian thrusting, produced a synsedimentary bulge in central New York State ("Chenango Valley high") that served to trap siliciclastic sediments in eastern New York (Heckel, 1973). A period of relative sea level fall coincided with this minor tectonism (Fig. 3).

Carbonate sediments of the upper Givetian Tully Formation of central New York were deposited in the ensuing period of gradual sea level rise. Tully carbonates formed on a siliciclastic-starved shelf. The relatively sharp base of the Tully limestones corresponds approximately to a 3rd order sequence boundary. A sharp mid Tully disconformity surface may represent a transgressive ravinement surface. The upper Tully clearly displays a deepening-upward pattern from shallow, near-wavebase limestone into outer-shelf black limestones which, in turn, appear to grade upward into the overlying black Genesee Shale.

The Genesee black anoxic sediments constitute a major late Givetian to early Frasnian highstand (Taghanic onlap of Johnson, 1970; Johnson and Friedman, 1969). In many ways the change from Tully to Genesee black shales mimics the earlier Onondaga-Marcellus transition. As with the latter, it appears to be the net result of active foreland basin subsidence (Ettensohn, 1985) and a major eustatic sea level rise (Johnson et al., 1985).

West of Seneca Lake, the Tully/Genesee contact is a sharp and clearly disconformable submarine erosion or dissolution surface that truncates the Tully Limestone in a westward direction. West of Canandaigua Lake the Tully is absent and Genesee black shale (Geneseo Member) with associated reworked bone and detrital pyrite debris (Leicester Pyrite Member) occurs on the eroded upper contact of the Windom Shale (Brett and Baird, 1986). This is a combined sequence boundary and transgression surface (see Fig. 3B).

The Geneseo black and dark gray maximum-highstand shale facies is followed by an upward-shallowing trend through the gray silty Penn Yan Member. A fairly major sea level drop is marked by the Crosby Sandstone in the Finger Lakes region. Crinoidal bone-rich lag beds of the North Evans Limestone in Erie County (Figs. 2, 3; STOPS 2, 3, 8) may also correspond to this regression event. If so, the Crosby-North Evans event may represent a major subsequence boundary. Subsequent marine flooding (rapid deepening) produced condensed pelagic limestones of the Genundewa Limestone, followed by dark gray shales of the West River Member (see Brett and Baird, 1982; Baird et al., 1988).

DISCONTINUITY SURFACES AND CONDENSED DEPOSITS ASSOCIATED WITH INITIAL SEALEVEL DROP: "PRECURSOR BEDS"

As noted the Middle Devonian Hamilton Group has been subdivided into a series of shallowing-deepening cycles, marked in western New York (see Brett and Baird, 1985, 1986). Many of these cycles display abrupt bases along which relatively condensed, shell-rich, oxic facies are juxtaposed sharply on dark gray to black offshore, dysoxic shale deposits. This appears to be a case of abrupt shallowing and certainly a change from dysoxic to fully oxic environments sometimes with a diverse benthic fauna. These, sharply-based "precursor" beds appear to form the beginnings of several shallowing cycles and are traceable for up to 200 km between the Erie County region and the central Finger Lakes. These beds are normally a few centimeters to about a half meter thick and are abruptly overlain by dark gray mudstones or shales again containing a dysaerobic fauna. These beds then grade upward into the main central limestones (or corresponding siltstone or sandstone) of each cycle. Thus, for example, at the base of the well-known Centerfield cycle a relatively sharp separates a gray shell-rich bed (Peppermill Gulf Bed) from the underlying black Leiorhynchus-bearing Levanna Shale and provides a reference horizon at which the Centerfield lower boundary may be drawn (Gray, 1984, in press). A comparable bed (Stafford-Mottville "A") occurs at the base of the widespread Stafford-Mottville limestone interval. Minor cycles such as the lower Wanakah Pleurodictyum beds (see Miller, 1986, this volume) also display sharp precursor beds which are typically condensed shell-rich layers.

Precursor beds may contain faunal elements otherwise associated with the caps of the shallowing cycles. These common elements may simply record the existence of a fauna which is relatively intolerant of turbidity and therefore developed primarily during times of siliciclastic sediment shut-off. However, such faunas are usually better developed and more diverse in the cap beds of regressive or shallowing cycles.

Precursor beds are particularly well-developed in central and west-central New York and tend to die out toward the east into the thicker unconformity-capped siliciclastic, coarsening-upward cycles in central and eastern New York State. In western New York these are recorded as thin, calcareous, shell-rich markers, within shales; they are not particularly prominent in sections but they represent important condensed intervals.

Any model for the precursor beds must explain the facts that these horizons display sharp to disconformable bases, relative condensation, and an abrupt change from dysoxic to oxic, presumably deeper to shallower water. Finally, we must account for the fact that these beds appear to be connected closely in time with the development of more major shallowing cycles. In short, these are condensed and sometimes erosionally- based beds associated with initial sealevel drop or the beginnings of a shallowing cycle. However, it is also probable that such beds reflect a smaller-scale, shallowing-deepening cycle superimposed on the larger one. If so, some precursor beds may be thought of as accentuated caps of heretofore unrecognized small-scale cycles.

Keith Miller (personal communication) suggests that the abruptness of the bases of these horizons may result from the constructive interference of two different sealevel fall processes. For example, a small-scale Milankovitch band-induced eustatic sealevel fall might be superimposed on a larger scale cycle.

In the sequence stratigraphy model the precursor beds lie between early and late highstand, i.e., at the change from aggradational deep-water facies to progradational, upward-shallowing successions. The association of condensed shell-rich beds with sealevel drop is counter intuitive and demands an explanation. These beds are typically followed by thick sections of silty, sparsely fossiliferous mudstone that appear to record major influxes of siliciclastics associated with the continuing sealevel drop. The initial period of offshore sediment starvation (which is not as extensive as that for typical transgressive sediment-starved beds; see below), may record disequilibrium conditions associated with the rapid change in sealevel. For example, Posamentier et al. (1988) argue that rapid drops in base level may cause rivers to regrade to an equilibrium profile. During this period of readjustment of stream beds a considerable amount of sediment may actually be deposited in subaerial environments, a phenomenon referred to as subaerial accommodation; sediment is being trapped near the lower reaches of streams, resulting in a brief period of sediment-starvation in offshore areas. Erosion associated with the bases of precursor beds may, in part, record lowering of storm-wave base or increased scouring by gradient currents. Erosive surfaces of the bottoms of these beds are most accentuated in areas that appear to have had steep northwest-dipping slopes as in the case of shell-nodule-rich diastemic beds in the Ludlowville Formation in the Cayuga Lake region (see Baird, 1981; Baird and Brett, 1981).

EROSION AND CONDENSATION ASSOCIATED WITH REGRESSION MAXIMA (SEQUENCE BOUNDARIES)

A second type of sharp erosional surface and fossil lag bed is commonly associated with the caps of shallowing-upward cycles. This type of bed is well exemplified by the Tichenor Limestone (see Fig. 4; STOPS 2, 7). In western New York, these are discontinuity-floored coarse crinoidal and shell-rich gravel deposits. They appear to represent some of the shallowest (highest energy) deposits in the entire Devonian succession.

Such surfaces occur at the bases of thin, high-energy limestone beds in the Hamilton Group of Erie County which record

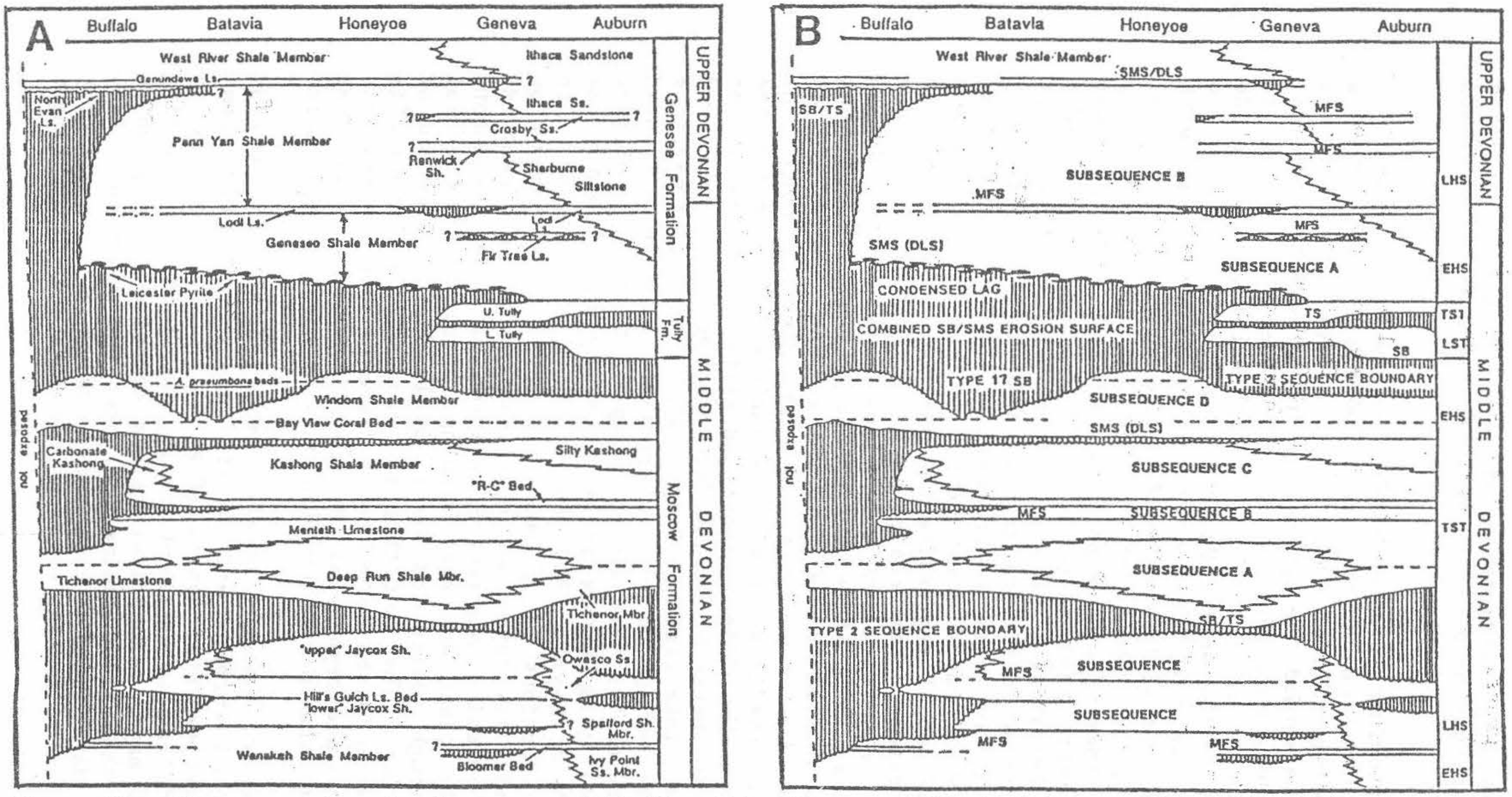


Figure 3A. Chronostratigraphy for uppermost Ludlowville, Moscow, Tully and Genesee Formations across western New York State. The most important changes from Rickard, (1975) involve major revisions of uppermost Ludlowville and lower Moscow strata (see Baird, 1978, 1979; Mayer 1989; Mayer et al. 1990, in prep.), and reinterpretation of the relationship of Leicester and North Evans lag deposits to surrounding beds and unconformities (see Brett and Baird, 1982; Baird and Brett, 1986a, b).

3B. Sequence stratigraphic interpretation of the upper Ludlowville, Moscow, Tully and Genesee Formations. The symbols include: CI=condensed interval; EHS=early highstand; LHS=late highstand; LST=lowstand; MFS=marine flooding surface; SB=sequence boundary (type 2 implies planar type erosion surgace); SMH/DLS= suface of maximum starvation or down lap surface; SB/SMS=combined sequence boundary and maximum starvation surface erosion surface (see text); TS=transgressive surface. The subsequence designation refers to sequence-like units of lesser temporal magnitude and lacking major erosional boundaries (see Brett et al. article, this guidebook for further explanation).

the immediate post-regressive maxima of cycles (Figures 3-5). The basal surfaces of such beds bevel underlying strata in a westward direction.

The most prominent erosion surface is the lower contact of the Tichenor Limestone which forms the base of the Moscow Formation by definition of Baird (1979). The Tichenor is a prominent and widespread, though very thin (10-40 cm) crinoidal packstone-grainstone unit (Fig. 4). The Tichenor occurs close to the regressive center (lowstand) of the largest-magnitude shallowing event in the entire Hamilton Group (Fig. 5). In the Seneca Lake region the Tichenor is nearly conformable with underlying calcareous silty mudstones of the upper Jaycox member and with very similar facies of the overlying Deep Run Member (Baird, 1979). These facies appear to represent slightly lower energy mud deposits that accumulated below normal wave base whereas the Tichenor pack- and grainstones reflect persistent physical reworking of carbonate gravels and sands in relatively high energy near-wave-base environments. Tichenor crinoidal debris accumulated immediately after a period of maximum shallowing. The actual regressive maximum may have been coarse siltstone or sandstone. Remnants of a sub-Tichenor siltstone have been discovered in one locality (Big Hollow Creek) between Seneca and Cayuga Lakes. The highest portions of the sub-Tichenor coarsening-upward cycle have everywhere been removed by an interval of submarine or possibly subaerial erosion. Hence, the Tichenor actually overlies an erosion surface which bevels the underlying upper Ludlowville mudstone and siltstones. The amount of section removed beneath this surface increases both east and west of the Seneca Lake region; in such areas, the upper portions of the Jaycox Member (3 to 10 m of section) have been removed (Fig. 4a). Progressive westward overstep of distinctive marker beds in the underlying Jaycox Shale member by the Tichenor has been demonstrated (Mayer, 1989; Mayer et al., in press). In extreme western sections along Lake Erie the Tichenor rests on Wanakah Shales with the Jaycox and uppermost Wanakah beds removed. The pattern of erosion suggests truncation of older sediments along the flanks (east and west dipping ramps) of the central Finger Lakes trough (Baird and Brett, 1981) during a period of extreme shallowing. The fact that the base of the Tichenor is unconformable, even in the basin center, reveals both the severity of the regression and removal of the eroded sediments by apparent southward current transport, along the axis of the foreland basin.

The Tichenor, itself, is a condensed bed consisting of multiply reworked, broken and abraded pelmatozoan ossicles, corals, and other skeletal debris (Fig. 4). In places, two or more graded beds can be observed within the Tichenor suggesting amalgamation of major tempestites (storm deposits) during which much or all of the relict sediment blanket was reworked. Very crude conodont data suggest that the Tichenor may be slightly diachronous, becoming younger outward from the axis of the Finger Lakes trough.

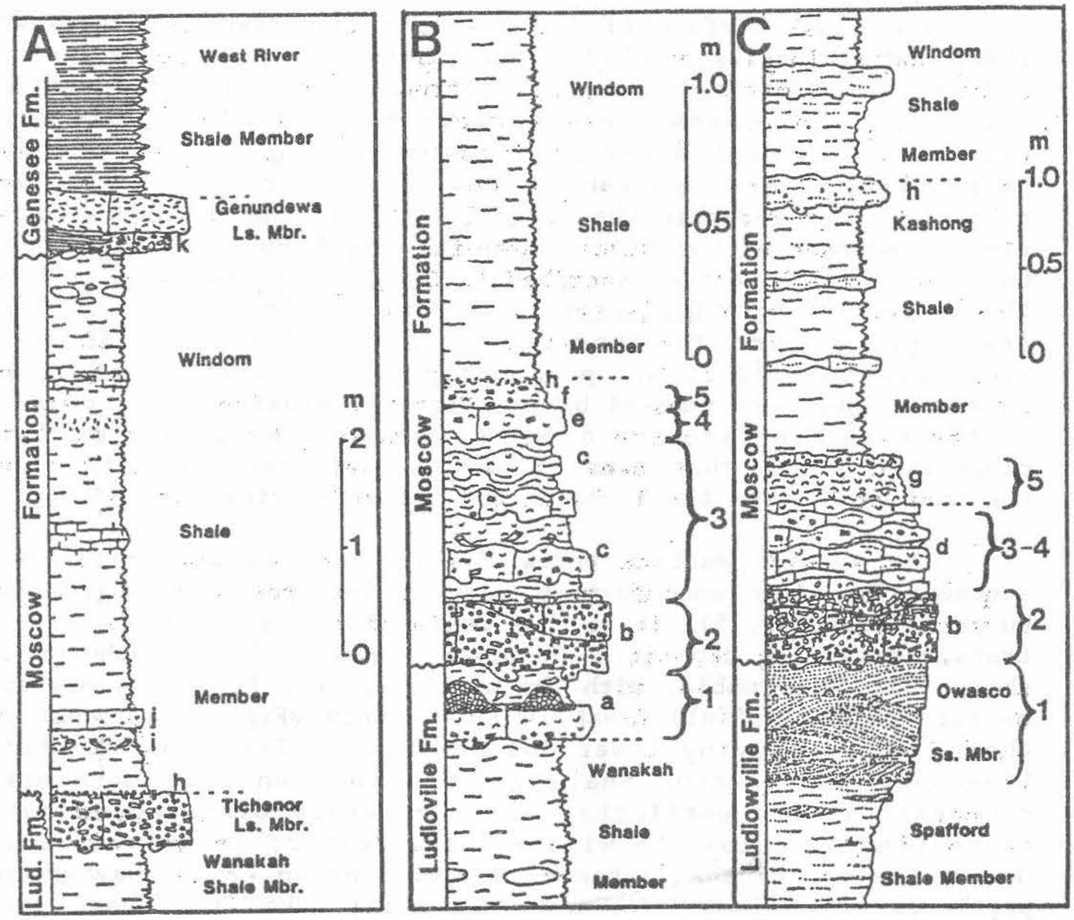


Figure 4. Stratigraphy of Moscow Formation and adjacent units. A. Stratigraphic section on Eighteenmile Creek east of (upstream from) Route 5 bridge (see STOP 2); B-C, Comparison of coeval condensed uppermost Ludlowville (Jaycox Member) and lower Moscow (Tichenor Member-Kashong Member) deposits on opposite flanks of broad depocenter in Genesee Valley-Cayuga Valley region; section B is on Buffalo Creek at Bullis Road (STOP 7) in Erie County; section C is generalized uppermost Ludlowville-lower Moscow interval for localities in the Owasco Lake Valley. Numbered divisions 1-5 denote coeval condensed chronostratigraphic units which are traceable across the depocenter (see Figure 2). The corresponding condensed units display similar facies except that Division 1 unit in west (lower Jaycox limestone bed) is represented by the Owasco sandstone east of the trough (see text). Numbered units include: a) Hill's Gulch Bed and overlying mudstone unit of Jaycox Member; b) Tichenor Limestone Member; c) condensed muddy carbonate beds equivalent to Deep Run Shale Member; d) condensed muddy carbonate beds equivalent to both Deep Run and Menteth members (see Figures 2, 3); e) Menteth Limestone Member; f) condensed calcareous mudstone facies of lower Kashong Shale Member; g) condensed facies of lower Kashong Member ("R-C" Bed of Baird, 1979); h) sub-Windom discontinuity surface marked by phosphatic debris; i) Bayview Coral Bed; j) Smoke Creek trilobite bed; k) North Evans bone-conodont bed.

The basal surface of the Tichenor Limestone is everywhere sharp and it locally displays large burrows(?) up to 10 cm across, and up to one meter in length, protruding from the sole surface (Fig. 4). In places these burrows may extend, as discrete exichnial "tubes," downward into underlying shales. These "megaburrows" are apparently devoid of scratch marks, but otherwise they resemble the large burrows on the analogous basal erosion surface of the Middle Devonian Hungry Hollow limestone in Ontario; these have been ascribed to Cruziana (probably burrows of the large trilobite Dipleura) by Landing and Brett (1987). Such prods prove that the underlying Jaycox-Wanakah muds were overcompacted and firm; presumably, up to several meters of mudstones had been removed by pre-Tichenor erosion. The details of the basal surface are commonly obscured by crusts of late diagenetic pyrite that seem to have formed preferentially along the contact between the Tichenor and the underlying mudstone.

The erosion surface below the Tichenor is analogous to a sequence boundary unconformity with a juxtaposed transgressive surface (Figs. 3b, 5); it is thus believed to represent an initial transgressive lag deposit. The upper contact of the Tichenor is sharp, but conformable, with the overlying Deep Run Shale perhaps as far west as Buffalo Creek in Erie County (Fig. 4b). West of there, the overlying lower Moscow units - Deep Run, Menteth Limestone and Kashong Shale grade into even more condensed carbonate layers until they are completely overstepped by a discontinuity below the Windom Shale Member; in western Erie County the top of the Tichenor is marked by an eroded hardground particularly at localities near and along Lake Erie Shore (see Fig. 4a; STOP 2). Hence the upper surface of the Tichenor is a disconformity representating depositional pinchout of muds onto the shallow western platform. Only the relatively major Windom deepening event allowed this disconformity to be overlapped and preserved (Figs. 3, 5).

The lower Moscow Formation (Tichenor, Deep Run Menteth and Kashong members) is approximately equivalent to a transgressive systems tract; it records a slight upward-deepening through a series of smaller-scale shallowing-upward units (Fig. 5). This interval is a highly condensed section in Erie County as a result of winnowing and bypass. Indeed, a few centimeters of limestone in the western Erie County sections may be the only vestige of this entire package which exceeds a net of 35 m (110 feet) of mudstone in the Genesee Valley-Canandaigua Lake Region (see Baird and Brett, 1981; Fig. 3). The very widespread sub-Windom phosphatic bed at the top of the Kashong Shale may represent a surface of maximum starvation (Fig. 4).

In addition to the sub-Tichenor unconformity, regressive erosion surfaces are seen at various other levels in the New York Devonian. For example, the base of the Jaycox Member which immediately (and unconformably) underlies the Tichenor in Erie County is represented by a thin (15-22 cm) crinoidal and coral-rich limestone unit (Hills Gulch bed) which mimics (and has been

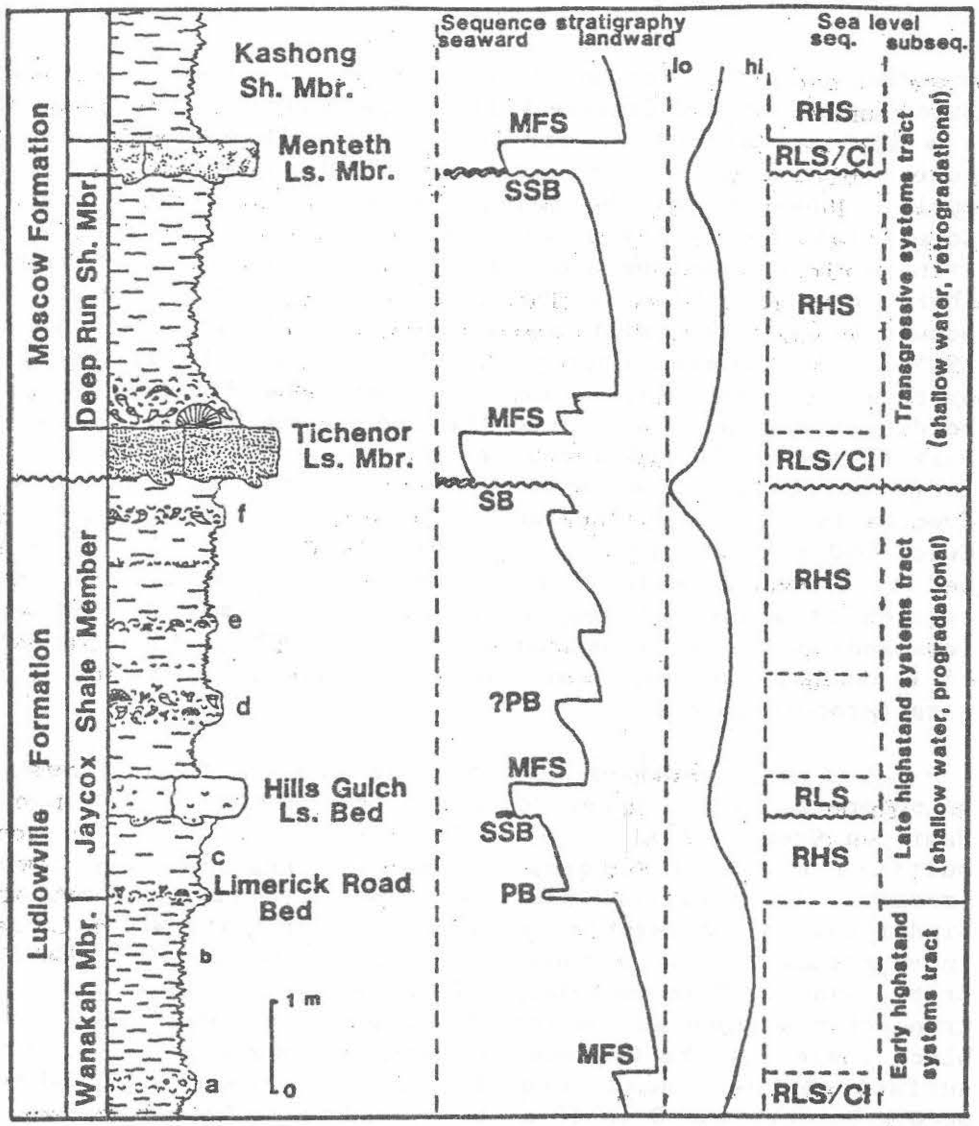


Figure 5. Sequence Stratigraphy Model applied to a portion of the upper Hamilton Group. Upper Ludlowville Formation divisions (uppermost Wanakah Member, Jaycox Member) and lower Moscow units (Tichenor, Deep Run, Menteth, and basal Kashong Members) are shown to be the result of rises and falls of sea level. Major regression event at base of Moscow Formation (discontinuity flooring Tichenor Limestone), traceable across most of New York State, probably marks a sequence boundary (SB). Other discontinuities (flooring Hill's Gulch and Menteth limestones) mark subsequence boundaries (SSB). PB = Precursor (PB) beds (see text; STOP 6). Remaining terms include: MFS=marine flooding surface; RHS=relative highstand; RLS=relative lowstand; CI=condensed interval. Units include: a) Bloomer Bed; b) upper Wanakah mudstone with diminutive dysaerobic fauna; c) barren, blocky mudstone unit; d) Green's Landing Coral Bed; e) Sponge-Megastrophia Bed; f) Cottage City Coral Bed.

mistaken for) the Tichenor itself. About 70 miles to the east of Erie County, in the Genesee Valley, the Hills Gulch bed appears as a silty calcareous, moderately fossiliferous mudstone that conformably overlies soft gray shale and appears to cap a small cycle. However, as the bed is traced westward from Livingston County (Genesee Valley area) it becomes a compact, silty, coral-crinoid rich packstone and, near Bethany, it begins to display a sharp, diastemic lower surface. Coarse crinoid and coral debris occurs in vaguely graded layers within the Hills Gulch bed (Mayer, 1989). In Genesee County the Hills Gulch horizon displays overstep of lower Jaycox beds and near the Erie-Genesee county border it begins to cut into the underlying Wanakah Shale. The base of the Hills Gulch bed resembles that of the Tichenor with large burrow prods extending down into the underlying shale. Eventually, the sub-Tichenor unconformity oversteps the Hills Gulch bed both at and west of Cazenovia Creek. The Hills Gulch bed is instructive in that it demonstrates that the pattern of erosion is evident in major sequence bases, may develop at the lowstands of lesser subsequences as well. Thus, the same pattern of erosional overstep near the basin margin is evident at many stratigraphic levels.

A final example of the regressive-type (lowstand) unconformity is the upper contact of the Moscow Formation of the Hamilton Group (Figs. 3, 6). In Erie County this is a complex multiple event unconformity, in part representing lowstand erosion. Previous work has shown that the upper contact of the Windom Shale is a regionally angular unconformity which increases in magnitude to the northwest (Brett and Baird, 1982; Baird and Brett, 1986). From Canandaigua Lake westward to Erie County, this truncation surface at the top of the Windom floors latest Givetian black shales of the Genesee Formation. However, this truncation surface can be traced into the Finger Lakes region, where it occurs beneath the 0 to 10 m-thick, middle to late Givetian Tully Limestone (see Heckel, 1973), which intervenes between the Moscow and Genesee Formations (Fig. 3).

It is evident, therefore, that some or much of the Windom truncation surface was developed prior to deposition of the Tully. Basal Tully carbonates are massive micrites representing shallow subtidal (and possibly lagoonal) shelf conditions as suggested by the occurrence of rare stromatolites (Heckel, 1973). Where the Tully is in contact with the Windom truncation surface the contact, like that of the Tichenor, is marked by large tubular burrows some of which extend downward 10-20 cm into the Windom Shale.

In western New York the entire Tully deposit has been removed by a still younger erosion surface; this latter discontinuity is of a very different nature and is associated with a period of sediment-starvation during rapid sea level rise to highstand conditions of the Genesee Formation (see Figs. 3, 6). Nonetheless, this latest unconformity is combined with the pre-Tully sequence boundary unconformity in western New York.

Sub-Tichenor, sub-Hills Gulch, and sub-Tully unconformities all involved the removal of stiff compact mud. We cannot rule out that some of this erosion, at least in basin margin areas, may have been subaerial. However, at least later stages of sediment removal were surely submarine. Dislodgement and resuspension of the firm muds may have been aided by active burrowing by organisms adapted to excavation of compact mud. Vestiges of this fauna are seen in the megaburrows at the bases of limestone beds. Abrasive scour of the seafloor may have been aided by tractional and saltational transport of skeletal sands and gravels during storms. In some cases, it is evident the preexisting burrows or furrows were present and widespread prior to deposition of the lowest calcarenite sediments. In fact, basal sediments of the limestone may have initially accumulated as tubular tempestites, i.e., infillings of deep burrows (see Wanless, 1988).

DISCONTINUITY SURFACES ASSOCIATED WITH RAPID SEA LEVEL RISE AND SEDIMENT STARVATION (SEE STOPS 1, 4, 8)

Black shale-roofed discontinuities

A third, and largely unrecognized, type of erosion surface is associated with the rapid-deepening phases and the bases of black shales (Figs. 3, 6-8). The lower contact of the black shales or lag beds is sharp and typically erosional and, indeed, regional truncation of the underlying strata is common. The erosion surfaces in such cases are nearly planar to undulatory and razor sharp. No burrowing of the underlying sediments is evident, as would be predicted, because the erosion apparently took place under anoxic or at least dysoxic conditions (see Figs. 6, 7). There is evidence for dissolution of carbonates at the surface and the overlying thin lag beds commonly contain chemically resistant particles such as phosphate nodules, conodonts, fish bones and teeth and in several instances, diaclasts of reworked early diagenetic pyrite (Fig. 7). Pelmatozoan ossicles may be present but other carbonate detritus is rare or absent in the lag beds. Lag beds typically range from thin sheets only millimeters thick to pods or lenses up to 20 cm thick and several meters across (Fig. 6). Internally, the lag beds may be laminated or vaguely cross laminated and may display thin partings of black shale. Small lenses of debris may occur, up to several centimeters above the erosional base, interbedded with black shales. Pyritic lag beds, typified by the Leicester Pyrite, have been described in detail elsewhere (Baird and Brett, 1986; Baird et al., 1988).

Black shale/limestone contacts (STOP 8)

Sharp, lower surfaces are characteristic of most Devonian black shale units; in many instances there is evidence for erosion and dissolution of underlying sediments and of lag beds above the erosion surfaces. Typically, the underlying beds are condensed outer shelf limestone facies. One such contact of black shale on carbonate, not seen on the present field trip, is the contact of the Union Springs (or Bakoven) black shale on the upper Onondaga Limestone (Seneca or Moorehouse members). This contact is rarely seen, but it is nearly always sharp and marked by concentrations of fish teeth and phosphate nodules on the upper surface of the Onondaga; where the succession is more nearly continuous, as in the Cayuga-Seneca Lake area, alternating 10-25 cm-thick, micritic, styliolinid ("ribbon") limestones and black shale beds (i.e., Seneca Member), underlie the black shale. Although these beds appear transitional between massive Onondaga carbonate and, overlying black, organic-rich shale, there is still a scattering of fish bones, quartz grains, and rare phosphatic granules above the uppermost ribbon limestone of the Seneca Member. East and west of this area, the basal contact of the Marcellus black shales is increasingly erosional and marked by abundant fish bones, conodonts, quartz pebbles and phosphatic nodules. Both east and west of the central Finger Lakes trough the transitional black micritic limestone/shale beds of the Seneca Member are cut out by the erosion surface, such that the phosphatic bone bed comes to rest on the beveled upper surface of the underlying Moorehouse member.

A similar but more cryptic contact, occurs at the upper surface of the Tully Limestone in the southern Cayuga Lake region. Here, again, the upper beds of the Tully (Fillmore Glen beds of Heckel, 1973) appear transitional, with decimeter-scale dark styliolinid micritic limestones alternating with dark gray to black shales through about one meter of section. The upper surface of the highest limestone bed displays a thin lag of styliolinids and silty pyritic debris.

As with the upper contact of the Onondaga Limestone, the transitional Fillmore Glen beds-and then successively lower units of the Tully Limestone, are truncated by the erosion surface to the west. Near Gorham, the lowest bed of the upper Tully Member (Bellona Coral Bed) is beveled and a thin lag of bones, crinoidal grains and minor reworked pyrite burrow tubes (Leicester Pyrite Member) rests sharply on the planar upper surface.

Still farther west, at Canandaigua Lake, the entire Tully is beveled and the overlying black Genesee Shale then rests sharply on the upper Windom Shale. As noted above, some upper Windom beds had already been truncated beneath the sub-Tully sequence boundary erosion surface. Hence, the unconformity between the Windom (upper Hamilton Group) and Geneseo is actually a compounded erosion surface marking the juxtaposition of the basal Tully, and upper Tully unconformities. How much additional erosion of Windom

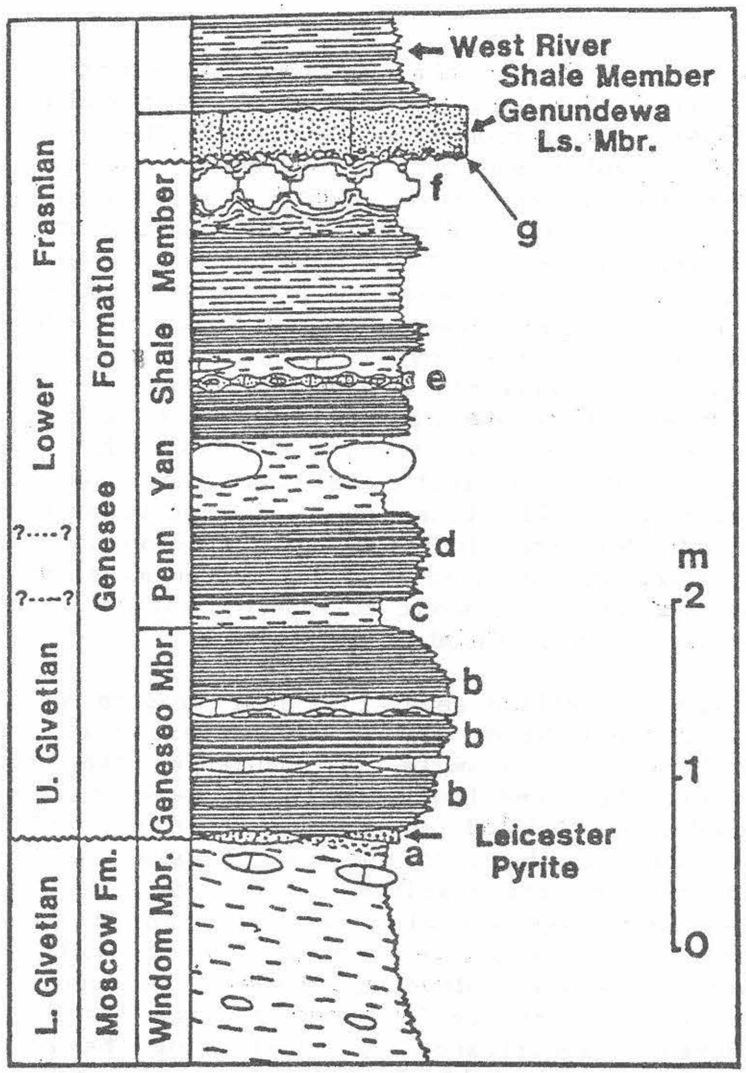


Figure 6. Stratigraphic section at waterfalls on Cayuga Creek south of (upstream from) Clinton Road bridge (see STOP 8). Important features in this outcrop include: manifest angularity of sub-Genesee unconformity within the outcrop, the Middle-Upper Devonian (Frasnian-Famennian) boundary (see interval of Question marks), and both the Leicester Pyrite and North Evans lag deposits. Lettered units include: a) brachiopod-rich bed (equivalent to Fall Brook Coral Bed?) which is overstepped (truncated) within the outcrop; b) calcareous black shale and concretionary black limestone rich in diminutive Devonochonetes and current-aligned Styliolina,; c) grey mudstone layer equivalent to Lodi Limestone Bed (to east); d) black shale unit probably equivalent to Renwick Shale (to east); e) Styliolina-rich concretionary layer ("Linden Bed" of Kirchgasser and House, 1981; Kirchgasser et al., 1988); f) grotesque concretions beneath North Evans-Genundewa limestone ledge; g) North Evans bone-conodont Bed.

beds can be ascribed to the last erosion event is not clear. However, some additional scour of the bottom during latest Givetian (post-Tully) time did take place. The sub-Tully erosion surface is irregular and heavily burrowed, whereas the combined unconformity separating Geneseo from Windom Shale is nearly planar and knife sharp. This indicates a modification of the old sub-Tully erosion surface by later processes. Also, the contact between the Windom and Genesee, like that between Tully and Genesee, is marked by lenses of fish bones, conodonts, pebbles and, above all, reworked pyrite debris (Fig. 6). The pyrite lenses have been referred to as the Leicester Pyrite Member of the Genesee Shale. They are clearly related to deposition of the black Geneseo muds as they are interbedded with the black shale (Fig. 6). Conodonts indicate also that the lenses are slightly younger than the Tully Limestone. The occurrence of reworked pyrite in the Leicester indicates that erosion and concentration of pyrite diaclasts, derived from the Windom mudstone, took place under low oxygen to (dysoxic-to-anoxic) bottom conditions (see Baird and Brett, 1986; Baird et al., 1988).

We have identified several similar erosion surfaces at the junctions between black shales and underlying concretionary carbonate beds. For example, we documented two thin limestone intervals (Fir Tree and Lodi) within the Genesee Formation which are beveled beneath black shales (Baird et al., 1988). Again, thin lenticular lag deposits occur at the sharp contacts between the carbonates and the overlying shale (Fig. 7). The pyrite-, conodont-, bone lags are also are interbedded with the basal laminae of the black shale proving that reworking of pyritic debris and black shale deposition were contemporaneous. One further observation of the Lodi and Fir Tree discontinuities is of considerable significance in interpreting the genesis of the erosion surfaces beneath black shales. In both cases the contact between the concretionary carbonates and the overlying shales is abrupt but gradational in areas where grey silty shales overlap the surface. However, as the overlying units grade, in presumed downslope direction, into black, laminated shales the contact becomes increasingly sharp and then erosional. Thus, the concretionary carbonates are truncated in an apparent downslope direction, being utterly missing in basinal section where both underlying and overlying black shales are in direct contact. These shales are separated by a cryptic discontinuity marked by a thin lag of fish debris, conodonts or silt. However, no major lenses of reworked pyrite are present, as flooring black shales contain little or no nodular pyrite.

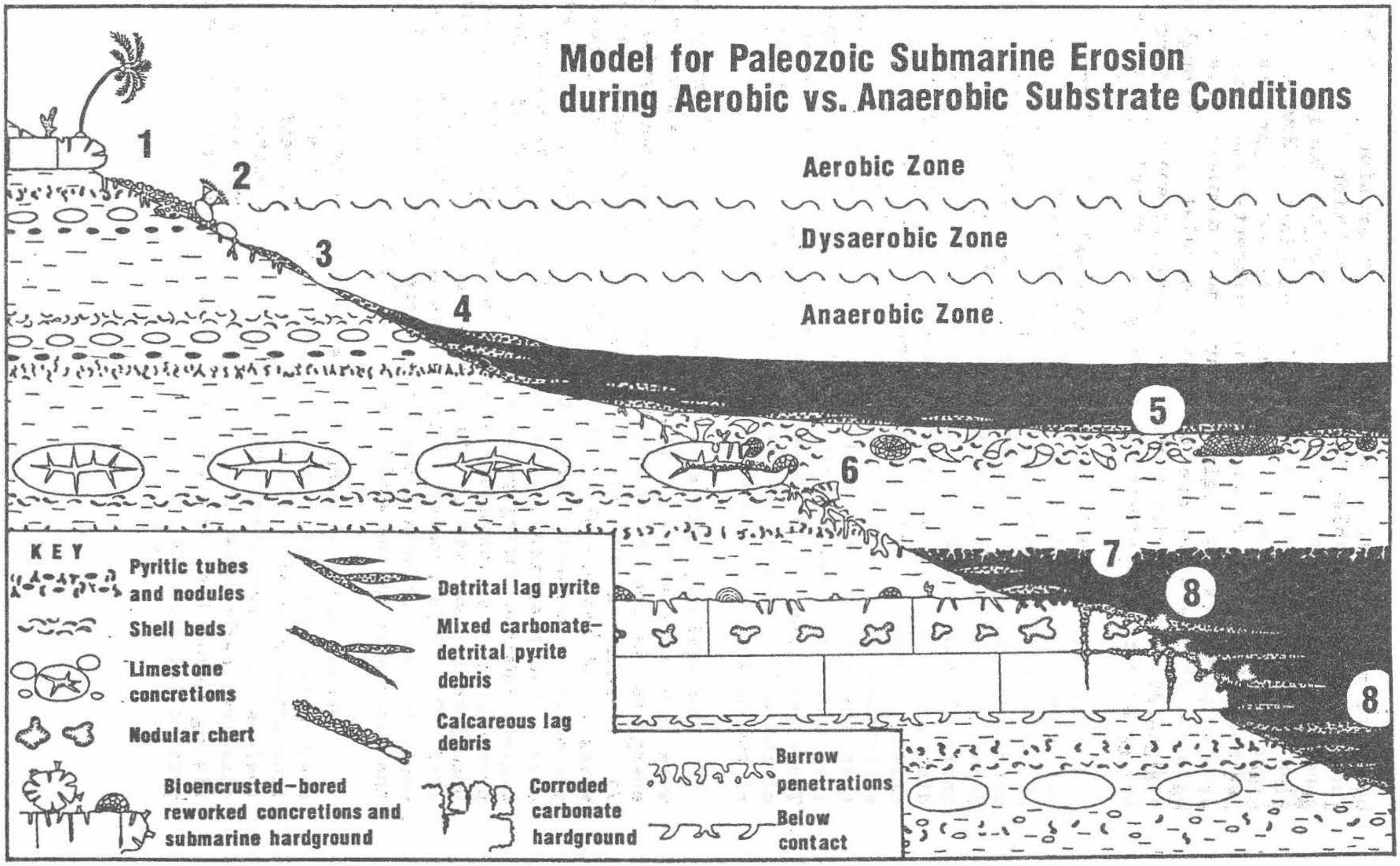
Any model for the genesis of black shale-roofed disconformities must explain the following features: 1) The erosion occurs during apparent intervals of sea level rise rather than fall; 2) they are nearly planar or runnelled surfaces overlain by dark gray or black laminated shales; 3) The surfaces are frequently underlain by concretionary argillaceous micritic carbonate or calcareous mudstones with distinctive deeper water biofacies (auloporid corals, small brachiopods, plus pelagic forms such as styliolinids and cephalopods); 4) surfaces are sharply overlain by lag deposits of geochemically resistant allochems such as phosphate, quartz, bone and conodonts, but lacking most carbonates; 5) reworked pyrite is commonly present, at least, where pyritic mudstones -serving as source beds - underlie the unconformities; pyrite should only be stable under anoxic conditions; 6) surfaces are sharp where overlain by black shales but seem to fade into conformity where overlain by gray dysaerobic deposits in the presumed upslope direction (Fig. 7).

From the standpoint of sequence stratigraphy the major black shale-roofed disconformities are not sequence boundaries but appear to correspond to surfaces of maximum starvation or downlap surfaces of seismic stratigraphers. As noted above, both the Onondaga and Tully limestones appear to comprise the bases of large-scale sequences. The upper nodular to tabular, argillaceous carbonates and interbedded shales appear to record a condensed section terminated by the abrupt change to deep-water black shales. Hence, the carbonates themselves comprise a transgressive systems tract; this sharp upper contact is a sediment-starved surface recording an increased rate of deepening to early highstand (deepest-water) conditions. During the rapid transgressive phase the carbonate factory was abruptly terminated and the offshore areas were also starved of siliciclastic sediment due to coastal entrapment. In the following highstand interval siliciclastics began to prograde seaward, providing a sedimentary wedge that downlaps onto the surface of starvation.

Rapid sea level rise also produced an elevation of the pycnocline (zone of density stratification) causing flooding of formerly shallow areas with deeper and slightly denser bottom water. Relative sediment-starvation and high productivity in surface waters enabled abundant organic matter to accumulate below the pycnocline, producing widespread oxygen deficiency on the seafloor. During shallow water intervals anoxic water was confined to basin centers but in major transgressions it expanded onto the basin margin ramps and shelves.

This pattern fits with the typical sequence model for development of surfaces of maximum starvation. A critical adjunct to the model, however, is that substantal submarine erosion may occur during times of rapid sea level rise in addition to sedimentary condensation. The thin concretionary beds that underlie the black shales reflect the onset of sedimentary condensation. Once sediment starvation reaches a critical point,

Figure 7. Generalized model for the exhumation and hydraulic dissolutional concentration of detrital pyrite on black shale roofed submarine discontinuities. A hypothetical submarine discontinuity cutting into a variety of oxic-dysoxic facies is shown being overlapped by both oxic and anoxic deposits. Discontinuity surfaces and associated lag deposits exposed respectively to oxic and anoxic waters are radically different owing to differing chemical stabilities of pyrite and carbonate in the two opposing settings (see Baird and Brett, 1986a, b; Baird et al., 1988). Features shown include: 1) Oxygenated discontinuity surface on sea bed with encrusted and bored hardground; 2) oxygenated seafloor covered by lag of coral-encrusted reworked calcareous concretions and associated shell and carbonate debris with absence of detrital pyrite; 3) dysoxic submarine substrate marked by burrows and reduced lag fraction composed partly of residual undissolved carbonate and partly of detrital pyrite and phosphatic component; 4) anoxic submarine substrate marked by absence of burrowers and bioencrusters and by complete dissolution of carbonate lag debris. Detrital pyrite is stable in this setting, but carbonate is prone to dissolution producing starved-lens concentrations of pyrite grains, bone debris, and conodonts; 5) black shale-roofed discontinuity truncating coral-rich shell bed; note that no carbonate debris survived to be concentrated on this surface despite the abundance of subjacent shell material; 6) grey mudstone-roofed erosional contact showing effects of burrowing, boring, and bioencrustation processes under oxygenated conditions. Again, pyrite is unstable and carbonate stable in this setting; 7) contact between black shale unit and overlying grey mudrock. Bioturbation associated with the onset of oxic conditions has mixed and blurred this contact. Note the dramatic stratinomic changes at the discontinuity contact timed with this change; 8) effect of prolonged exposure of limestone unit to oxygen-deficient waters; the carbonate undergoes solution producing surface pitting and solution along joints with attendant formation of a chemical lag placer of chert nodules. Detrital pyrite lenses are diachronously shingled reflecting progressive burial of the discontinuity by black basinal muds.


Model for Paleozoic Submarine Erosion
during Aerobic vs. Anaerobic Substrate Conditions
1
2
3
4
5
6
7
8
8
Aerobic Zone
Dysaerobic Zone
Anaerobic Zone
KEY
Pyritic tubes and nodules
Shell beds
Limestone concretions
Nodular chert
Bioencrusted–bored reworked concretions and submarine hardground
Detrital lag pyrite
Mixed carbonate–detrital pyrite debris
Calcareous lag debris
Corroded carbonate hardground
Burrow penetrations
Below contact

however, non-deposition may give way to erosion. One way of looking at this problem is that minor erosion, due to storm-generated gradient currents, and deep-flowing density currents, plus chemical corrosion is always taking place. However, during times of sediment input this erosion is more than balanced by sedimentation. At times of total sediment-starvation ambient erosion processes may begin to play a more dominant role and the balance shifts from one of slow accumulation through non-sedimentation to erosion without any change in energy. Hence, the key to this type of erosion is stoppage of new sediment input.

Part of the explanation for erosional loss of section may well involve dissolution of the older carbonates by corrosive (low pH, or carbonate undersaturated) bottom water. We have noted that carbonate grains are often conspicuously absent in the lag deposits that overlie disconformities (see Fig. 7). Nonetheless, there is also evidence for increased erosional energy in a distinctive pattern along basin margins since relatively heavy clasts, such as pyrite, were apparently dislodged from firm siliciclastic clays and concentrated on the sea bed. We argue that the erosion process is also concentrated along particular levels of the slope-to-basin profile and that it dies out upslope. These positions may be marked by thin pyrite lenses; in the case of the Lodi limestone, we observed pyrite lag beds on either side of the basin center (Baird et al., 1988).

Furthermore, this erosive process occurs in settings which were primarily anoxic. We postulate that wave and/or current energy may be focussed along internal water mass boundaries (Fig. 7). If interval waves propagated along the pycnoclines then these waves would impinge along the sea floor at the point where the pycnocline intersected sloping basin-margin ramps. In such a case a topographically narrow belt of erosional energy would migrate upslope during periods of rapid sea level rise when the pycnocline also expanded upward, producing a transgressive unconformity overlain by diachronous, anoxic, laminated deposits (Fig. 7). This process would produce a pattern of erosion that would be most intense along lower slope to mid slope regions of the basin margins and would die out upslope.

Hence, major erosion surfaces appear to have developed in deep water during times of relative sea level rise. The truncation probably involved: 1) sediment-starvation in distal regions; 2) development of corrosive anoxic bottom waters that dissolved carbonates; and, 3) possibly, internal waves along the rising pycnocline that eroded the seafloor and concentrated pyritic lag deposits.

Black shale - roofed furrowed contacts (see STOP 4)

Occasionally, shale-roofed discontinuities display numerous, low-relief erosional channels. This phenomenon is well displayed at two levels in Erie County as well as a few other contacts. In these cases, again erosional scours are associated with minor but abrupt deepening events. The first example, involves the junction of a black shale with an underlying gray mudstone unit in the Levanna Shale Member (lower Hamilton Group, Skaneateles Formation) at Buffalo Creek (Stop 4; Fig. 8). The contact is sharp and is marked by a series of small, low-relief channels or gullies each about 1/2 to 1 m across and with a total relief of about 35 cm which resemble submarine furrows (see Flood, 1983). These gullies are subparallel, evenly spaced, and oriented approximately N-S, perpendicular to the inferred paleoslope.

The basal contacts of the channels are delineated by very thin erosion lag deposits of crinoid debris, trilobite fragments and fish bones and teeth. A particularly unusual feature of the channels is that the contact between the gray and overlying dark gray shales is sharp at the rims, but appears slightly blurred in the floors of the gullies. As it is obvious that an erosion surface separates the gray and black shales, the apparent gradation between the two facies in channel bottoms is paradoxical. We suggest that during earliest phases of dark mud deposition in the channels, conditions remained marginally oxic. Burrowing organisms were able to mix dark, slightly organic-rich muds downward into underlying, still soft, gray muds.

The erosional channels themselves may have been produced as bypass chennels on a gently south-sloping ramp; vortical debris-laden currents developed during sustained unidirectional flow may have have initiated a ridge-and-furrow topography; later, currents carrying erosive agents such as shell debris, accentuated the erosional runnels scouring them somewhat deeper. Finally, the furrowed surface was blanketed by dysoxic muds; channel-filling alternated with episodes of minor scour resulting in the phenomenon of channels nested within the larger channels (Fig. 8c).

A second example of furrowing has been described in detail from the Wanakah Shale by K.B. Miller (1988; see discussion in article by Miller, this guidebook). In this instance, a series of broader and deeper channels (with widths up to 30 m and depths up to 1 to 2 m) were cut into a gray fossiliferous mudstone. In Erie County the channels are filled with a slightly darker, blue gray fissile to platy, barren mudstone. Farther east, in the Finger Lakes region, these channels still occur at the same horizon, but they are infilled with a very dark gray to black fissile shale. Miller carefully considered various alternatives and concluded that the Wanakah "channels" were erosional forms rather than lows between mud bars or ripples.

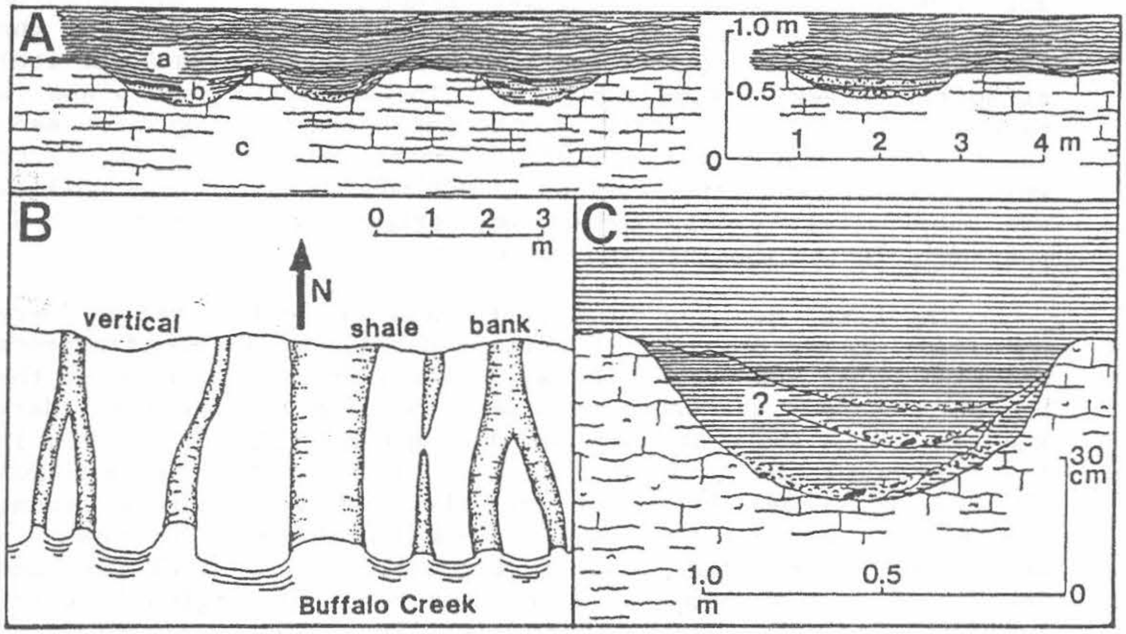


Figure 8. Submarine discontinuity within Levanna Shale Member on Buffalo Creek at Union Road (see STOP 4). A) along-bank profile of a series of erosional runnels (troughs) into calcareous mudstone which are filled with brownish-black shale of upper unit; B) vertical ("map") view of channels on exposed creek bed bordering shale bank. Note southward bifurcation of some channels suggestive of southward current-flow; C) complex history of episodic scouring and filling of mud within channels. Sharp scoured contacts with associated lag debris of fish bones and shells grade laterally to extinction (continuity) over very short distances. Lettered units include: a) black, laminated shale with Leiorhynchus, Styliolina, and palynomorphs; b) brown-black shale filling in troughs with associated scoured contacts and brachiopod-trilobite fish bone lag debris; c) calcareous gray to dark grey blocky to chippy mudstone with Ambocoelia, Devonochonetes, and Phacops rana.

The Wanakah channels are somewhat accentuated by the development of early diagenetic concretions which follow the contours of the channel profiles (the concretion horizons appear to move up and down along the outcrop face as they outline the otherwise cryptic channels). Again, a minor lag of shell debris is present locally along the bases and margins of the channels and furrows. Here, as in the Levanna example, the development of the channeled (furrowed) mud surface appears to have taken place during interval of sediment-starvation during rapid relative sea level rise (see Miller: FIELD TRIP: this volume).

CONDENSED INTERVALS ASSOCIATED WITH BENTONITES

Finally, some metabentonite beds appear to have at their bases thin, condensed bone- lag deposits. This may indicate that rather than representing a catastrophic pulse of ash influx the general interval of increased volcanism and ash may have had an influence on the sedimentary systems in producing a sediment-starved surface, over which ash, presumably from many episodes of volcanism, gradually accumulated. Some metabentonites appear to be a type of condensed deposit analogous to bone beds; indeed many erosion-related bone-lag deposits are enriched in pyroclastic debris (see Conkin and Conkin, 1984; Conkin et al., 1980) which one would expect within "time-dense" marine lag units (see STOP 5).

At present, it is unclear whether the sediment-starvation interval was produced by a minor sea-level rise that coincided with volcanic activity or by a curtailment of carbonate production. The latter would perhaps result from intense episodes of ash input.

CONCLUSIONS

Significant discontinuities occur, predictably, at three positions within Middle and Upper Devonian marine shale and carbonate sequences of western New York. Pronounced erosional unconformities, commonly with irregular, burrowed contacts, occur on the bases of shallow water carbonate beds corresponding to rapid lowering of relative sea level. These contacts (e.g., basal Tichenor, basal Tully) correspond to sequence and subsequence boundaries. In some cases they are composites of lowstand submarine (and possibly subaerial) erosion surfaces and transgressive ravinements.

A second type of important discontinuity occurs at the bases of major highstand deposits, roofed by black shales. These are typically planar disconformities (no burrowing and only minor very low-relief furrowing), marked by concentrations of phosphate, pebbles, glauconite, conodonts, bones and/or reworked pyrite. Such surfaces are associated with condensed sections formed during times of rapid sea level-rise; as such, they correspond to accentuated surfaces of maximum sediment-starvation or downlap surfaces of sequence models. Erosional processes may include deep storm waves, density currents, or interval waves propagated along pycnoclinal water mass boundaries.

The third category of discontinuity and condensed interval occcurs at the boundary between early deepest water highstand deposits and progradational late highstand deposits. As such they appear to be associated with the inflection point between latest phases of sea level rise and early stages of regression. They are overlain by shallowing-upward intervals of gray mudstone to silty calcareous mudstone that may culminate in a sequence or subsequence bounding unconformity below shallow water transgressive deposits. These mid-highstand beds commonly display reworked concretions and relatively shallow water biofacies. They appear to initiate cycles of rapid shallowing and mimic some characteristics of cycle-capping carbonates (limestones above sequence or subsequence boundaries) - hence, we term them "precursor" beds. Such beds are not predicted by most sedimentary models. We infer that they may represent brief sediment-starved intervals during periods of sediment disequilibrium resulting from sea level lowering. Submarine erosion probably involves a combination of bioturbation and storm-generated gradient currents.

Finally, some diastems may be associated with ash beds and may or may not be related to sea level fluctuations. Some ash layers may be condensed beds.

All four types of discontinuities and associated condensed beds provide outstanding regional and roughly isochronous markers that enable detailed physical correlations of strata. They also subdivide the stratigraphic column into bounded genetically related bundles. Mapping of these discontinuities facilitates interpretation of sea level variations and basin dynamics.

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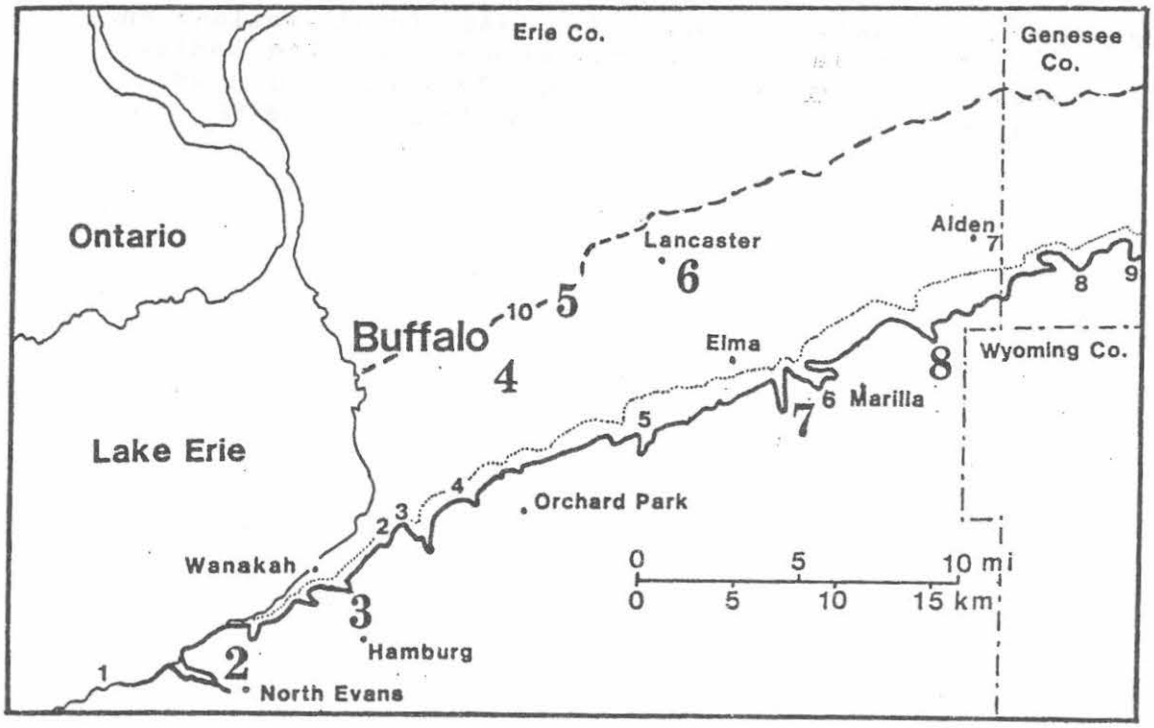

Figure 9. Field trip stops in Erie County, New York. (STOP 1: Point Gratiot at Dunkirk, Chautauqua County, not shown). Outcrop belt of the Middle Devonian Hamilton Group and localities examined. Dashed line denotes contact of Onondaga Limestone and Marcellus Formation; stippled line is base of Moscow Formation; heavy dark line is base of Genesee Formation. Key reference sections include: 1) Lake Erie bluffs at Highland-On-The-Lake; 2) unnamed creek south of Big Tree Road; 3) Bayview Shale Pit (formerly Penn Dixie Quarry); 4) Smoke Creek south branch near Blasdell; 5) Cazenovia Creek at Elma; 6) Little Buffalo Creek at Marilla; 7) Spring Creek at Alden; 8) Elevenmile Creek near Darien Center; 9) Murder Creek at Darien; 10 Federal Crushed Stone Corp. Quarry in Cheektowaga. Field trip stops (large numbers) include: Eighteenmile Creek (2); abandoned shale pit at Cloverbank (3); Buffalo Creek at Union Road (4); Cayuga Creek in Depew (5); Cayuga Creek at Como Park (6); Buffalo Creek at Bullis Road (7); Cayuga Creek at Clinton Road (8).

ROAD LOG FOR DEVONIAN DISCONTINUITIES

(see Figure 9)

TOTAL MILES	MILES FROM LAST POINT	ROUTE DESCRIPTION
0		Leave Fredonia Campus at the Temple Street exit. Turn right (N) onto Temple St.
0.4	0.4	Y-intersection; bear right (N) on Brigham Road.
0.8	0.4	Cross New York State Thruway
1.5	0.7	Enter City of Dunkirk
1.6	0.1	Pass Al-Tech Corporation Factory (on right).
2.7	1.1	Junction of Brigham Road with Lake Shore Drive (Route 5) turn left (SW) onto Lake Shore Drive.
2.9	0.2	Junction of Lake Shore Drive (Route 5) with North Point Drive. Turn right (N) onto North Point Drive.
3.1	0.4	Turn right onto Cedar Beach Parking area. Niagara Mohawk coal-powered generating station straight ahead (to NE). Proceed north on foot for approximately 500 feet along beach to northeast-facing lake shore outcrop near lighthouse museum at Point Gratiot.

STOP 1. TYPE SECTION OF DUNKIRK SHALE MEMBER, POINT GRATIOT AT DUNKIRK.

This outcrop is excellent for viewing the sharp contrast between the grey-green bioturbated, but non-shelly, mudstone of the Hanover Shale Member and the black, organic-rich, laminated facies of the overlying Dunkirk Member. A conformable, bioturbated contact between Hanover and Dunkirk can be seen below the 15 to 18 cm thick (6 to 7 inches) basal Dunkirk black bed which dips southward below the water at this section. However, a sharp, erosional discontinuity with associated reworked debris marks the contact between the 12-13 cm (5 inch) thick grey-green bioturbated bed above the 18 cm (7 inch) basal bed and the overlying continuous black shale succession.

Close examination of this contact shows that abundant reworked (detrital) pyrite is present along it with lesser amounts of carbonized wood, conodonts, fish bones, and pyritic goniatite steinkerns (Baird and Brett, 1986a); much of this material is probably derived from the 12-13 cm (5 inches), grey-green mudstone unit which is conspicuously rich in pyrite cemented and overgrown burrow tubes, although the abundance of wood suggests that the basal few inches of the overlying black shale is unusually condensed, recording the descent of numerous logs from the water surface over a long period of time. This lag unit also records bioturbation, which at this section, was sufficient to flux the broken pyritic tubes into random orientations.

As this discontinuity is traced northeastward to the vicinity of Java Village, Wyoming County, more and more beds progressively appear beneath it such that this break passes essentially to extinction (see Fig. 5; Baird and Lash; FIELD TRIP SAT. A, this volume). Instead several black shale beds alternating with bioturbated and non-bioturbated grey-green mudstone make up an intervening sequence several meters-thick. Most of the thin black shales, however, display minor diastemic basal contacts with the grey-green beds marked by minor detrital pyrite. Collectively, these diastems downcut underlying units as they are traced southwestward such that higher discontinuities downcut through lower ones until only a single 5 inch (12-13 cm) grey-green bed remains at this locality. This illustrates the pervasiveness of submarine erosion associated with the transgressive grey-to-black facies change beneath even very thin black shale units. It also illustrates the distinctive character of condensed sedimentary deposits involving alternations between dysoxic and anoxic facies. For additional information about this outcrop, see Baird and Lash; FIELD TRIP LOG SAT A: STOP 2 (this volume).

3.5	0.4	Reboard vehicles and return to Lake Shore Drive (Route 5). Turn left (NE) onto Lake Shore Drive. Dunkirk Harbor Complex visible (to left) for next mile.
4.6	1.1	Junction of Lake Shore Drive with Main Street (Route 60). Turn right (5) onto Main Street.
5.2	0.6	Junction (Y-intersection bifurcation) of Main Street and Route 60. Bear left onto Route 60.
5.6	0.4	Cross Norfolk and Western Railroad tracks.

5.7	0.1	Leave Dunkirk, New York
6.7	1.0	Thruway overpass
7.0	0.3	Thruway entrance at red light. Turn left to enter Thruway. Bear right to go towards Buffalo.
15.1	8.1	Cross Walnut Creek. Hanover-Dunkirk contact is at base of bridge. Stebbins Road bridge (being repaired to right) collapsed in 1987, killing one person, when an overweight vehicle caused the bridge to plunge.
16.2	1.1	Cross Silver Creek, Dunkirk Shale at base of bridge.
19.4	3.2	Dunkirk Shale above Hanover Shale in Thruway cut immediately beyond (downhill from) the Silver Creek exit.
19.8	0.4	Cross Cattaraugus Creek floodplain. Sand and gravel pits have been opened on this bottom in the vicinity of the Thruway.
20.5	0.7	Cross Cattaraugus Creek. Begin to cross Seneca Indian Reservation.
27.4	6.8	Cross Big Sister Creek. Angola Shale Member of West Falls Formation exposed below bridge.
27.7	0.3	Exit for Thruway rest area and restaurant facilities. Keep going straight.
29.7	2.0	Turn off Thruway at Eden exit.
30.4	0.7	Thruway exit junction with Eden-Angola Road. Turn right (w) towards Angola.

32.4	2.0	Junction of Eden-Angola Road with U.S. Route 20. Continue straight on Eden-Angola Road.
34.7	2.3	Turn right onto Old Evans Center Road.
35.1	0.4	Junction of Old Evans Center Road with North Main Rd. Bear right onto North Main Rd.
35.3	0.2	Junction of North Main Road with Route 5. Turn right (NE) onto Route 5.
		Enter village of Highland-On-The-Lake.
38.7	3.4	Cross Eighteenmile Creek.
38.8	0.1	Turn right onto first side street north of Route 5 bridge. Park vehicles and proceed down path at end of street to large cutbank section on north side of Eighteenmile Creek 200 ft. east of (upstream from) Route 5 bridge.

STOP 2. MIDDLE AND UPPER DEVONIAN MARINE DEPOSITS ALONG EIGHTEENMILE CREEK.

This large outcrop shows to maximum advantage the Tichenor Limestone, the overlying Windom Shale Member, and the major discontinuity at the top of the Windom (marked by North Evans bone-conodont-rich debris) which marks the base of the Upper Devonian series in this area (Figs. 3, 4A). We will see the North Evans to better advantage at the next stop (see STOP 3) and will, thus, focus on the Tichenor and basal Windom shale at this stop.

The Tichenor is a 0.7 m (2 ft.)-thick, widespread crinoid-brachiopod grainstone-packstone unit which is also noteable for large corals (Heliophyllum, Eridophyllum, Favosites), large bivalves (Plethomytilus, Actinopteria) and large fragments of the trilobite Phacops rana. As is obvious from the texture, this is a medium to high energy deposit which may have accumulated within the depth-range of fairweather wavebase. It is also extremely condensed and time-rich; in the western Finger Lakes region, deposits equivalent to the western Tichenor (mostly Deep Run Shale Member) reach a thickness of almost thirty five meters. Through a combined affect of westward stratigraphic thinning and westward lateral facies change from mudstone to shelly carbonate, the Deep

Run is replaced by very thin clean skeletal carbonate in Erie County. The base and top of the Tichenor at this locality are sharp, reflecting erosional processes. The base marks a major disconformity seperating deposits of the Ludlowville Formation from the overlying Moscow Formation; the Jaycox Shale Member of the Ludlowville Formation is progressively bevelled below this contact from the Genesee Valley westward such that only the base of the Jaycox is visible at Buffalo Creek in eastern Erie County and none is visible west of the north branch of Smoke Creek in south Buffalo. This bevelling was produced by a major regression event which caused synchronous submarine (and possibly subaerial) erosion in central and eastern New York State (see McCave, 1973; Baird, 1979; Baird and Brett, 1981) and this contact may be a bona fide sequence boundary. Examine overturned Tichenor blocks for large, abrasion-enlarged, hypichnial trace fossil markings produced by large arthropods; these resting-(or dwelling) excavations into firm Wanakah marine muds were later filled-and casted by the Tichenor skeletal sands.

The top of the Tichenor is also marked by a submarine discontinuity, perhaps of similar hiatal magnitude. Submarine erosion that preceded deposition of the Windom, removed most of (or all of) three units (Deep Run-equivalent carbonate beds, Menteth Member, Kashong Member) which overlie the Tichenor east of Buffalo. This erosion produced a submarine hardground at this locality and at other western Erie County Tichenor sections). Examine this surface closely for auloporid corals and crinoid holdfasts which encrust this contact and for the presence of phosphatic nodules and steinkerns reworked from below (see Brett, 1974; Brett and Baird, 1974 for additional description of this surface).

The overlying Windom Member records transgressive deepening to quiet, open-shelf conditions minimally affected by storm wave-reach. Fifty centimeters (16 in.) above the base in a unit (Bayview Coral Bed) which is rich in large brachiopods, particularly Spinatrypa, and which locally yields large rugose corals, including Cystiphylloides and Heliophyllum along this bank. Above it is a calcareous mudstone unit (Smoke Creek Bed) which is well known for complete enrolled and outstretched specimens of the trilobite Phacops rana (see Brett and Baird, 1982 for additional information on this unit).

		Return to vehicles. Turn right onto Route 5 and proceed northeast towards Wanakah, N.Y.
41.2	2.4	Cross Weyer Creek. Fossiliferous Middle Devonian Wanakah Shale exposed mainly downstream (north) of Route 5 bridge.

41.5	0.3	Enter town of Wanakah, New York
41.6	0.1	Junction of Route 5 and Old Lake Road. Proceed straight (NE) on Route 5.
42.6	1.0	Cross Amsdell Road Amsdell Creek, further up Amsdell Road, has been an important source for conodonts and fish fossils from the North Evan bone-conodont bed.
42.8	0.2	Enter town of Cloverbank.
43.1	0.3	Turn right (SE) onto Cloverbank Road by the Cloverbank Hotel.
43.4	0.3	Cross Amtrak railroad tracks
43.5	0.1	Park on shoulder pull-off just south of the railroad tracks. Proceed on foot 0.3 mile southwest along a path bordering tracks to the abandoned Lehigh Cement Co. Shale quarry which is southeast of the tracks.

STOP 3. NORTH EVANS BONE BED AND GENUNDEWA LIMESTONE AT THE CLOVERBANK QUARRY.

This abandoned shale pit, developed by the Lehigh Cement Co. as a source of claystone for the mill (now defunct) in Lackawanna, contains a stratigraphic succession from the Middle Devonian in the Upper Devonian. The Quarry walls about 16 m (50ft) high expose the Upper Devonian Middlesex-Cashaqua Shale. The quarry is floored mainly by the shaley upper contact of the Genundewa limestone and the West River Shale. In a narrow pit the Genundewa is breached and a section extends down some 2.5-3 m (8-10ft.) to, or just below, the Amsdell (Praeumbona) bed of the Windom shale. The Windom here is in contact with the North Evans Limestone and the contact is an erosion surface showing a characteristic "rip-up" horizon. We will focus on lag deposits (North Evans Bone-Conodont Bed) associated with an erosional contact between the grey Windom Member (Givetian) and the overlying Genundewa Limestone of Late Devonian (early Frasnian) age. For additional information on these units, see: Sass, 1951; Huddle, 1981; Brett, 1974; Brett and Baird, 1982; Baird and Brett, 1986a.

The North Evans Limestone, or "Conodont bed" of older literature, is typically a 0.5 to 6 inch-thick packstone-grainstone unit composed of reworked crinoid ossicles, conodonts (including many mixed from older zones), fish teeth and armor fragments, as well as calcitic brachiopod, coral, and trilobite fossils derived from the underlying Windom or from intervening beds now removed. Conspicuous within the North Evans at this locality and also at the abandoned Penn Dixie Shale Pit at Bayview, New York (see Brett and Baird, 1982: STOP 2) are reworked limestone concretions from the underlying Windom; These are often stacked like shingles and they typically have a green exterior patina of glauconite as well as surface dissolution pits produced following exhumation on the seafloor.

The overlying Genundewa Limestone is composed almost entirely of Styliolina fissurella, a problematic millimeter-long conoidal calcitic shell which may be of tentaculitid affinities or the shell of an unknown protistan organism (Yochelson and Lindemann, 1986). Wood debris, goniatitid and orthocerid cephalopods, and the bivalves Buchiola and Pterochaenia comprise the remainder of a low diversity biota. The Genundewa appears to be a classic example of the pelagic Cephalopodenkalk facies of the European and North African literature (Tucker, 1973). As such, it records very slow sedimentation in an offshore, sediment-starved, dysoxic environment.

Although the North Evans rests on fossiliferous Middle Devonian deposits at this locality and would appear to record a simple transgression over the oxic, shell-rich Windom facies, a more complex story emerges when the same bed is viewed in eastern Erie County (see STOP 7); at that section, the North Evans overlies brown-black anoxic facies of the Upper Devonian Penn Yan Shale Member. Hence, an apparent regression with attendant seafloor erosion is recorded after deposition of the Penn Yan and prior to final accumulation of the North Evans lag. The North Evans-Genundewa succession is, thus, a transgressive interval culminating in the deposition of brown-black anoxic deposits of the overlying West River Shale Member which is visible here above the Genundewa Limestone. The North Evans and Genundewa beds probably correspond ,respectively, to the transgressive surface and overlying condensed interval in the sequence stratigraphy model (see text); they probably correspond, in part, to other sediment-starved condensed units, such as pebbly greensands and bone beds identified by sequence workers in younger sedimentary systems (see Loutit et al. 1988; Baum and Vail, 1988).

The North Evans lag deposit was apparently reworked into the dysoxic Genundewa outer shelf-slope setting because the encrinitic-bone-conodont hash layer grades upward into Genundewa facies and it underlies the Genundewa throughout Erie County except for exposures along Lake Erie near Highland-On-The-Lake where a brown-black shale subfacies of Genundewa overlies the North Evans (Brett and Baird, 1982). Hence the North Evans is rich in carbonate debris with only minor amounts of detrital pyrite; compare the North Evans with the pyrite-dominated lag that we saw at STOP 1 and, particularly, what we will see in the

Leicester Pyrite deposit at STOP 8. Exhumed Windom calcareous shell material was apparently dissolved in the largely anoxic Geneseo basin setting to produce the residual detrital pyrite lag deposit of the Leicester (Baird and Brett, 1986a). Conversely, detrital pyrite was differentially stable in this anoxic or minimally dysoxic setting. Carbonate undersaturation and/or low pH conditions of the basal Geneseo substrate environment are clearly not evident for the North Evans-Genundewa setting to anywhere the same degree. Only where a black shale subfacies of Genundewa directly overlies North Evans along the Lake Erie shore, does the North Evans lag deposit begin to become rich in detrital pyrite, poor in carbonate debris, and laterally discontinuous (lenticular) in outcrop, the way the Leicester always appears.

Fossils to look for in the North Evans are crushing teeth (tritors) of ptyctodonts, an extinct fish order, placoderm dermal armor and jaw fragments, tricuspate cladodid shark teeth, as well as reworked Windom calcareous fossils, including the trilobite <u>Phacops rana</u>.

43.9	0.4	Return to vehicles. Return to Route 5 and turn right (NE) onto Route 5.
44.8	0.9	Cross Morse Creek. One of many shore area localities in the richly - fossiliferous Middle Devonian Wanakah Shale Member.
45.3	0.5	Excellent view of Lake Erie, Buffalo-Lackawanna skyline for next 0.6 mile.
45.7	0.4	Enter town of Athol Springs.
47.7	2.0	Exit Route 5 onto traffic circle by Ford automotive plant. Bear right to get onto Route 179.
47.8	0.1	Turn right onto Route 179.
48.8	1.0	Cross Route 62 (South Park Ave.). Keep going straight.
50.0	0.2	Cross Mile Strip Road and enter New York State Thruway at Blasdell entrance.
50.5	0.5	Mudstone (probably Wanakah) exposed along Thruway entrance ramp.

51.4	0.9	Cross Smoke Creek, Ledyard Shale Member exposed to right (upstream) from Thruway.
52.4	1.0	Proceed through Thruway Toll plaza.
53.3	0.9	Cross Cazenovia Creek. Middle Devonian black Levanna Shale Member exposed upstream (to right) from Thruway bridge.
53.7	0.4	Exit from Thruway onto Route 400. Proceed east on this expressway to Union Rd. exit.
55.4	1.7	Exit from Route 400.
55.7	0.3	Junction of route 400 exit ramp with Union Road. Turn left (N) onto Union Road.
56.5	0.8	Pull off from Union Road to the right onto a dirt road and small parking area in vacant lot immediately before bridge over Buffalo Creek and immediately after passing junction of Indian Church Road on the left. Proceed north, on foot to creek. Cross creek if water is not high.

STOP 4. SUBMARINE DISCONTINUITY WITHIN MIDDLE DEVONIAN LEVANNA SHALE MEMBER ALONG BUFFALO CREEK.

Along this cutbank exposure one can observe two key lithologic divisions of the Middle Devonian Levanna Shale Member of the Skaneateles Formation which are currently unnammed. Just above water level is a calcareous, dark grey-shale division which yields the diminutive brachiopod Ambocoelia and specimens (often complete) of the trilobite Phacops rana. A submarine discontinuity (prominent undulatory outcrop reentrant) separates this lower unit from a fissile, black shale upper division, rich in the brachiopod Leiorhynchus and the aformentioned problemmatic small conical fossil Styliolina. This boundary is traceable as far east as Oatka Creek near Pavilion in Genesee County. The units in this section record oxygen-deficient outer shelf-to-basin conditions with the lower division recording dysoxic to minimally oxic conditions and the upper division recording lower dysoxic to near-anoxic conditions ("exaerobic" zone of Savrda and Bottjer, 1987) along the seabed.

This discontinuity is distinctive for its distinctly undulatory appearance; troughs between 0.5 and 2.0 meters (1.5-6.5 ft.) in width and between 12 and 45 cm(5 to 16 in) in depth alternate with intertrough ridges and platforms (Fig. 8A). The troughs are erosional runnels cut into division 1 deposits which are aligned in a nearly north-south direction transverse to the creek channel (Fig. 8B). Some runnels bifurcate but most remain simple and linear. Trough bottom deposits often include calcareous brachiopods, Phacops, and Styliolina debris admixed with fish teeth and dermal plates. These lags are often at channel bottoms but they can occur in axial channel sediments above channel bottoms. Some troughs appear to have been repeatedly filled with sediment and scoured out by currents; these troughs display nested erosional scour surfaces with the sharpness of scour contacts varying from clear to diffuse (Fig. 8C). Evidently some episodes of scour removed only water-rich surface mud while others cut into firm muds.

Clearly, this section records a type of sedimentary condensation where repeated sediment accumulation and scour were dominant sedimentary processes. The overall upward-change from division 1 to division 2 appears to be transgressive with the consequent development of an erosional surface; the complex channel-fills appear to correspond to the interval of maximum sediment-starvation and sedimentary condensation which overlies the transgressive erosion surface.

These erosional runnels are probably submarine furrows (sensu Flood, 1983), which are rarely reported from the stratigraphic record. Furrows are believed to form through the action of abrasive horizontal, debris-laden current vortices which scour the bottom into linear runnels within a sustained unidirectional current regime (Flood, 1983). The complex "cut-and-fill" histories of the Levanna runnels is a testament to the unidirectional character of the currents which produced them. We are currently studying these features at this locality to establish which way the currents flowed and are also examining all other similar discontinuities to determine if similar runnels are distributed along them.

		Return to vehicles. Turn right (N) onto Union Rd. and proceed toward towns of Gardenville and Cheektowaga.
56.6	0.1	Cross Buffalo Creek and enter Gardenville, New York.
57.3	0.7	Enter town of Cheektawaga.

58.6	1.3	Cross Cayuga Creek. Middle Devonian Onondaga Limestone is exposed below bridge and upstream (to east).
59.8	1.2	Junction of Union Road and Broadway (Route 130). Exit Union Road to turn right onto Broadway.
59.9	0.1	Junction of turn lane with Broadway. Turn right (E) onto Broadway.
61.2	1.3	Enter town of Depew.
62.3	1.1	Junction of Broadway (Route 130) with Rowley Road. Turn right (S) onto Rowley Road.
62.5	0.2	Cross Cayuga Creek.
62.6	0.1	Junction of Rowley Road and Borden Road. Bear right and stay on Rowley Road.
62.8	0.2	Exposure of Onondaga Limestone along Cayuga Creek (to right). Park on asphalt driveway next to first house on the right. Proceed carefully down slope to south side of creek.

STOP 5. VOLCANIC ASH LAYERS IN UPPER ONONDAGA LIMESTONE ALONG CAYUGA CREEK.

This cutbank exposes two thin metabontonite layers within the upper part of the Onondaga Limestone Formation (Middle Devonian: Eifelian) which comprise part of the "Tioga Ash" (metabentonite) complex of beds discussed in Devonian literature (see Dennison and Textoris, 1978; Conkin and Conkin, 1984; Rickard, 1984; Sparling, 1988). Dennison and Textoris (1978) and Dennison (1983) believe that the tuff originated in what is now northern Virginia and that Devonian prevailing winds carried the winds predominently westward (in the present sense) into the U.S. midwestern region.

The Cayuga Creek section exposes two metabentonite (K-rich mixed-layer, illite-smectite) beds which are about 16 inches apart with the lower one just below the water level. The higher metabentonite is probably the Onondaga Indian Nation ("O.I.N.") metabentonite of Conkin and Conkin (1984) which corresponds to the "Tioga B" metabentonite of Rickard (1984). The lower metabentonite is probably the Cheektowaga (No. 2) metabentonite of Conkin and Conkin (1984); both of these ashes are exposed in the nearby Federal Crushed Stone Corp. Quarry (see Conkin and Conkin, 1984). Although most workers place the boundary between the Moorehouse Member and the overlying Seneca Member of the Onondaga at the horizon of the O.I.N. (Tioga B) ash (see Rickard, 1975, 1984), Conkin and Conkin (1984) place it about 0.5 m higher at the position of a bone bed which is visible in the quarry and which may be present in this section. Uncertainty exists with surface correlations because outcrops in the upper Onondaga-through-Marcellus interval are nearly absent in western Genesee and Erie counties. In any case, this section and one in the nearby Federal Crushed Stone Corp. Quarry west of this stop, are the only outcrops showing any part of the Tioga complex of ashes in this region.

The upper metabentonite is a brown mudstone layer with a bronze-yellow micaceous luster which shows some evidence of bioturbation. The lower, less ash-rich unit, contains abundant fossils including rugose corals, bryozoans, pelmatozoan debris, and the trilobite Phacops. The corals, interestingly, are highly abraded and fragmental; this suggests that the lower "ash" might not be the record of a single "mega-eruption" or closely-spaced series of "eruptions" but is rather a condensed unit within Onondaga where pyroclastic debris and other terrigenous sediment became concentrated over a long period of time relative to carbonate. The occurrence of the uppermost Tioga unit ("Restricted Tioga" division of Conkin and Conkin, 1984; "Tioga A" Bed of Rickard, 1984) above the basal-Marcellus transgressive bone bed lag on uppermost Onondaga deposits, suggests a similar story of selective pyroclastic-enrichment associated with sediment-starved bottom conditions (Baird and Brett, 1986a, b).

This brief stop simply illustrates another unusual type of sediment associated with apparent sediment starvation. What is needed is detailed study of sedimentary structures and sedimentary petrography associated with the Tioga deposits to obtain answers concerning sedimentation rates and paleoenvironmental conditions associated with the formation of these enigmatic event-beds.

63.3	0.5	Board vehicles. Return to junction of Rowley and Broadway. Turn right onto Broadway and proceed east towards Lancaster.
63.8	0.5	Junction of Transit Road (U.S. Route 20) with Broadway (Route 130). Route 20 turns here to follow Broadway. Proceed straight (E) on Route 20.
64.4	0.6	Cross Cayuga Creek

64.5	0.1	Enter town of Lancaster, N.Y.
65.0	0.5	Cross Cayuga Creek. Middle Devonian black and dark grey shales of the Oatka Creek Member are intermittently exposed along creek in this area.
65.3	0.3	Junction of Lake Avenue with Route 20. Turn right (S) onto Lake Avenue.
65.5	0.2	Junction of Old Lake Avenue with Lake Avenue. Bear left (SE) onto Old Lake Avenue.
65.6	0.1	Junction of Old Lake Avenue with Pardee Avenue. Turn left onto Pardee Avenue.
	0.1	Turn right off of Pardee Avenue into a parking area at Como Park. Proceed on foot about 400 feet west to Lake Road bridge downstream from small dam on Cayuga Creek.

STOP 6. "PRECURSOR BED" AT BASE OF MIDDLE DEVONIAN STAFFORD LIMESTONE MEMBER AT COMO PARK.

Along the banks and bed of Cayuga Creek between the dam and base of the small waterfalls lip at the Lake Avenue bridge are exposures of the Stafford Limestone Member, the basal division of the Skaneateles Formation. Downstream from the water falls are intermittent exposures of the black, fissile, organic-rich Oatka Creek Member of the underlying Marcellus Formation which is mostly covered. Near the falls and bridge, the topmost few feet of the Oatka Creek Shale can be examined on the south side of the creek; these uppermost Marcellus beds are dark grey-brown in color and they yield a meager dysoxic biota consisting of the rhynchonellid brachiopod Leiorhynchus, Styliolina, and numerous flattened composite molds of an orthoconic nautiloid.

The Stafford, in Erie County, is a three-part member consisting of a basal, thin, shell-rich muddy limestone bed (Stafford "A" bed), a middle, shaley interval several feet thick which contains nodular micritic concretionary beds, and an upper cherty limestone division, termed the Stafford "B" bed, which is 0.6 - 1.3 m (2 to 4 feet) in thickness and fossiliferous (see Meyer, 1985). In central New York, the equivalent Mottville Member has a shell-rich "A" bed division, succeed by a variably-thick middle "shale" division followed by a micritic or siltstone regressive capping unit which corresponds to the Erie County, chert-rich ("B") micritic division visible by the Como Park dam (Grasso, 1986; Meyer, 1985). Despite significant thickness variations of the "middle shale" and "B" bed divisions along the Stafford-Mottville outcrop strike between Buffalo and the Chenango Valley, the "A" bed remains relatively thin, usually between 8 and 30 cm (0.2 and 1.0) foot in thickness, and it is typically a densely fossiliferous calcareous mudstone, both overlain and underlain by sparsely fossiliferous deposits. Although the "middle shale" usually grades upward into fossil-rich shaley micrites of the "B" bed, the "A" bed often rests abruptly on dysoxic to anoxic dark shales as it does at this section.

The "A" bed is a prime example of what we term a "precursor" bed, a layer which records what appears to be a sediment-starved regression event linked to, but clearly preceding, a subsequent longer-term regression which culminates in fossil-rich, regressive, limestone, siltstone, and even sandstone facies (see text). Such beds are enigmatic in terms of existing models of cyclic sedimentation, because they are followed by apparent deepening events associated with synchronous and subsequent influxes of sediment which then produce a regressive filling sequence that culminates in the "B" unit (see text discussion).

At this locality the Stafford "A" Bed yields numerous small brachiopods, including Ambocoelia umbonata var. nana, Truncalosia truncata, Devonochonetes scitulus, and small variety of Tropidoleptus. Other fossils include the large bivalve Panenka, occasional Leiorhynchus, orthoconic nautiloids often encrusted by the reptate biserial tubular organism Reptaria stolonifera, which may have "hitchiked" on the living cephalopod (see Baird et al., 1989), and wood debris.

This faunal association is rather typical of precursor beds we have seen in other units and it is nearly identical to that associated with the lower Wanakah "Darien Center" cycle at nearby localities (see Miller, FIELD TRIP SUN C, this guidebook). The diminutive brachiopod assemblage in the Stafford "A" bed appears to represent only a slight increase in bottom oxygenation relative to the underlying Oatka Creek Shale. This assemblage falls between the "Leiorhynchus" and "Ambocoelia-chonetid" biofacies of Brett et al., 1986; Vogel et al., 1986; which is indicative of non-turbid upper dysoxic to minimally oxic bottom conditions (see text).

66.0	0.4	Board vehicles and return via Pardee, Old Lake, and Lake avenues to Route 20. Turn right (E) toward Alden.
67.0	1.0	Leave town of Lancaster
67.3	0.3	Junction of Route 20 with Bowen Road. Turn right (S) onto Bowen Road.

67.7	0.4	Cross Cayuga Creek. The lower calcareous part of the Middle Devonian Levanna Shale Member is exposed along creek near bridge. One particularly prominent ledge upstream (east) from the bridge yields occasional excellent enrolled specimens of the trilobite <u>Phacops rana</u>.
70.1	2.4	Junction of Bowen Road and Clinton Road. Proceed straight (S) on Bowen Road.
70.6	0.5	Cross Buffalo Creek at Elma, N.Y. The Middle Devonian Ledyard Shale Member is exposed in the bed and banks of the creek. Pond Brook, a north-flowing tributary of Buffalo Creek just to the east of Bowen Road south of the bridge crossing has good exposures of the richly fossiliferous Wanakah Shale Member.
71.3	0.7	Junction of Bowen Road and Bullis Road, turn left (E) onto Bullis Road.
71.4	0.1	Cross the upper end of Pond Brook.
72.9	1.5	Junction of Bullis Road with Girdle Road.
73.1	0.2	Intersection with old Bullis Road (loops to south over old bridge). Turn right onto old road.
73.35	0.25	Park near old bridge over Buffalo Creek. Walk out onto bridge for brief overlook, then proceed down bank at west end of bridge and walk about 100 feet north (downstream) to limestone exposure adjacent to the new Bullis Road bridge.

STOP 7. CONDENSED CARBONATE DEPOSITS OF LOWER MOSCOW FORMATION AT BUFFALO CREEK.

In the low stepped falls interval between the old and new Bullis Road bridges one can observe a succession of thin carbonate beds representing condensed facies of the lower Moscow Formation and uppermost Ludlowville Formation (Fig. 4B). The Tichenor Limestone is visible here as at STOP 2, but it is both overlain and underlain by additional limestone layers; the underlying layer is the basal Hill's Gulch Bed of the largely-bevelled Jaycox Shale Member of the Ludlowville Formation and the overlying beds are in ascending order, the thin, condensed phases of the Deep Run, Menteth, and Kashong members (Fig. 4B). In western Erie County the Jaycox is entirely absent and the overlying complex of condensed units is absent or nearly absent due to further westward bevelling, such that the Tichenor is directly underlain by Wanakah Shale and is overlain by the Windom Member (compare Figure 4A and Figure 4B) .

Three discontinuities are present in this section; one at the base of the Hill's Gulch Bed which cuts into the Wanakah Shale; one below the Tichenor which cuts into the Hill's Gulch Bed, and one below the Windom Shale which bevels into a thin remnant of the Kashong Shale Member. The two lower discontinuities are marked by hypichnial, carbonate-casted burrow prods produced by arthropods excavating into underlying muds prior to burial of the discontinuity surface. The sub-Windom discontinuity is marked by phosphatic nodules, phosphatic steinkerns of Kashong fossils, and assorted shelly debris which have been churned and mixed by bioturbation processes during the onset of Windom deposition (Baird, 1978).

This condensed section is almost a "mirror-image" to that involving equivalent beds in central New York (Fig. 4c). Detailed mapping by Baird (1979), Baird and Brett (1981), Mayer (1989), Mayer et al. (1990) shows that each major bed in this outcrop has its time-stratigraphic counterpart in the condensed Jaycox-Kashong succession in the Owasco Lake-Ithaca region. Even the same discontinuities are represented in this latter area, though with the trend of increased bevelling and condensation in the eastward direction instead of westward, as is observed for the deposits here at Buffalo Creek. In the intervening Genesee Valley-Cayuga Lake region, each one of the componant divisions in this section balloons into thicker, mud-dominated facies, with each respectively higher division -- Jaycox, Tichenor, Deep Run, Kashong reaching maximum thickness west of that for the previous division (Brett et al., 1986). Hence, this intervening region records a westward-shifting depocenter and an aggregate maximum thickness for the Jaycox-Kashong interval exceeding 35 meters (110 ft.)!

Thus, the "mirror-image"-stacking of corresponding condensed beds in these widely-seperated regions is all the more significant given the complexity of depocenter shifts in the intervening region. It strongly suggests that eustatic sea-level changes were responsible for the succession of units, both within the depocenter areas, and on the adjoining shelf regions. Such a pattern makes all the more relevent the discussion of sequence stratigraphy applicability to the New York Devonian System (see text).

From the old Bullis Road bridge one can see the upstream bank of grey chippy Windom mudstone deposits. These rest on the sub-Windom (post-Kashong) phosphate debris-rich discontinuity which can be reached below water-level just upstream from the bridge foundation. Near the top of the Windom bank, the Bayview Coral Bed and the overlying Smoke Creek Bed can be seen. Enrolled Phacops rana can be collected from the Smoke Creek Bed further upstream in the floor of the creek. The giant blastoid Placoblastus sp. is a rare find at this locality; it occurs in the Deep Run-Menteth ledges above the Tichenor.

		Reboard vehicles. Return to new Bullis Road.
73.6	0.25	Junction of old Bullis Road with New Bullis Road. Turn right (east) onto Bullis Road and proceed toward Marilla.
75.95	2.35	Junction of Two Rod Road (Route 358) in Marilla. Turn left (north) onto Two Rod Road.
76.05	0.1	Cross Little Buffalo Creek. Middle-Upper Devonian disconformity is exposed downstream from (to northwest of) road crossing.
77.1	1.05	Intersection of Two Rod Road and Clinton Road (Route 354). Turn right (east) onto Clinton Road.
78.1	1.0	Intersection of Clinton Road with Four Rod Road. Continue straight on Clinton Road.
79.1	1.0	Intersection of Clinton Road with Three Rod Road. Continue straight on Clinton Road.

79.7	0.6	Cross Cayuga Creek. Pull off onto driveway of first house on right beyond the bridge or onto right shoulder of Clinton Road if parking space is limited.

STOP 8. MIDDLE-TO-UPPER DEVONIAN CONDENSED BASINAL DEPOSITS ALONG CAYUGA CREEK (See also Brett and Baird, 1982: NYSGA Buffalo meeting).

At this section we will first examine the Leicester Pyrite and its relationship to synjacent beds and then we will focus on the North Evans bone-conodont bed which marks the base of the Genundewa Limestone above the last falls riffle about 120 feet upstream from the bridge.

As with the lag deposit we observed below the Dunkirk at STOP 1, the Leicester Pyrite Member of the Genesee Formation is a detrital pyrite-bone-lag accumulation which directly underlies a laminated black shale unit (Geneseo Shale Member) and which occurs on a submarine discontinuity marking the base of the Geneseo. However, the Leicester is a more dramatic example of this lag type because it is made up of coarser grains and it is typically much thicker than the Dunkirk pyrite bed. Moreover, it rests on the Middle Devonian Windom Shale Member which is a grey mudstone unit usually rich in shelly fossils.

The Leicester is composed of pyrite burrow tube fragments, pyrite nodules, and pyrite fossil steinkerns derived from the Windom Member plus fish bone-and conodont debris of Windom and post-Windom age. These were exhumed under conditions of submarine anoxia or temporary dysoxia by episodic strong currents of unknown character. Reworked Windom (and Tully) lag debris was initially carbonate-dominated reflecting the overall calcitic and aragonitic character of Windom fossils. However, this carbonate debris underwent selective dissolution in a negative pH (or carbonate undersaturated) basin setting; a continuous blanket of reworked Windom carbonate debris, resembling the North Evans deposit at STOP 2, would hypothetically have been reduced to a placer lag of pyrite and bone debris only a small fraction of the original volume. Hence, the laterally discontinuous Leicester lenses represent only a remnant fraction of total Windom debris which was exhumed (Baird and Brett, 1986A). In actuality, during Geneseo time, no continuous carbonate debris blanket probably ever formed because dissolution would have removed carbonate as it was exhumed, allowing no carbonate to build up on the surface.

At this section as at other Leicester localities, some Leicester debris lenses occur within the basal Geneseo, not just at the base. This indicates that pyrite clast-transport occurred during the period of initial black mud accumulation. Morever, conodont examination by Huddle (1981) shows that the age of the youngest (Genesee-age) conodonts in the Leicester becomes progressively less as this unit is traced westward from the Seneca Valley into eastern Erie County; this westward progressive overlap of Geneseo black mud and lag debris onto the widespread Windom-Genesee disconformity surface tracks the major Taghanic Onlap Event which is now believed to mark a major eustatic transgression in the late Givetion (Johnson, 1970). This overlap cannot be followed westward indefinately; the sub-Genundewa discontinuity oversteps all lower Genesee strata in central Erie County and the Leicester is apparently cannibalized by this younger erosion surface between Cazenovia Creek and the north branch of Smoke Creek, southwest of Elma, Erie County (Brett and Baird, 1982; Baird and Brett, 1986A).

Evidence for reworking of Windom Pyrite clasts includes: 1, identical character of Windom and Leicester pyrite grains; 2, evidence of mechanical breakage of pre-formed pyrite grains; 3, abundance of pyritic Windom fossil steinkerns in Leicester; and 4, the reorientation of early diagenetic stalactitic pyrite which formed initially in voids within in-situ Windom pyrite tubes and steinkerns (see Baird and Brett, 1986a,b). Ongoing laboratory sulfur isotope studies indicate a hodgepodge pattern of variable isotopic weights between adjacent pyritic grains which further suggest exhumation and mixing of the pyrite material (see Lyons, 1990).

The mechanisms for physically exhuming and reworking pyrite in what would normally be thought of as a euxinic environment are difficult to reconstruct, given that there is no known modern example of this specific marine condition. Deep-storm waves are always a possibility as are various possible bottom current processes. Baird and Brett (1986A; Baird et al. (1988), offer an erosion model involving transgressive upslope migration of a water density-stratification boundery (pycnocline) along which storm generated internal waves are propagated. Impingment of the pycnocline with the basin slope at an given time allows for the presence of a higher energy wave-shoaling zone coincident with the slope-pycnocline intersection producing a swath of bottom erosion at a critical water depth/contour. Continue transgression would displace the wave-shoaling zone upward allowing basinal black muds and associated bone-pyrite debris to settle on the scour surface produced during earlier internal wave-shoaling. Overall westward Geneseo black mud overlap of the erosion surface may have been interrupted by brief episodes of major current flow and bottom scour events; these may explain the occurrence of Leicester lenses which are interbedded with basal Geneseo black shale deposits.

The Windom-Geneseo contact is a regional disconformity (combined sequence boundry,transgressive and down lap surface) which overlies different Windom beds at different western New York out crops. Generally, towards the north, the unconformity truncates progressive lower Windom beds. Conversely, towards the south, progresively higher Windom layers appear beneath the Leicester-Geneseo contact (Brett and Baird, 1982). At Cayuga

Creek one can observe a Windom shell-rich bed become progressivly truncated as it is traced from the falls south of the bridge northward. Near the falls, this Mediospirfer and Pseudoatrypa-rich mudstone layer, probably equivalent to the Fall Brook Coral Bed in the Genesee and Wyoming valleys, is well developed (Baird and Brett, 1983).

Above the Windom-Genesee contact there are approximately eleven feet of organic-rich black shale, dark grey shale, and concretion-bearing horizons which comprise the lower part of the Genesee Formation. This sequence of largely anoxic and minimally dysoxic basinal facies is extremely condensed; at Ithaca, New York, the equivalent stratigraphic interval is in excess of 150 m (500 feet) (deWitt and Colton, 1978; Baird and Brett, 1986A). Fossils which can be collected from the basal three feet of the Cayuga Creek Geneseo section include current-aligned Styliolina, the brachipod Devonochonetes, and scattered wood fragments.

At the highest falls, dark, organic-rich and conspicuously laminated beds of the Penn Yan Shale Member are abruptly overlain by the 20-25 cm (8 to 10 inch) thick ledge of the Genundewa Member and its associated 1-2.5 cm (0.5 to 1.0 inch) thick basal lag veneer of North Evans reworked pelmatozoan, conodont, and bone debris. Further east in Genesee County, this lag unit apparently disappears and the base of the Genundewa become conformable. Although the North Evans at this locality is a bit less conspicuous than it is at STOP 2, it still yields glauconite-coated reworked concretions and a great abundance of conodonts. As at STOP 2, the Genundewa is a dense, grainstone to packstone blanket accumulation of Styliolina shells. The grotesque Penn Yan concretionary bed below the North Evans contact is also developed at other adjacent sections; it may have formed as a geochemical response to the proximity of the North Evans erosion surface which was being scoured out from above.

END FIELD TRIP