SEDIMENTOLOGY, FACIES AND DEPOSITIONAL ENVIRONMENTS OF THE ROCHESTER SHALE (SILURIAN; WENLOCKIAN) IN WESTERN NEW YORK AND ONTARIO[1]

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ABSTRACT: In western New York and Ontario, the Rochester Shale (Silurian; Wenlockian; Clinton Group) is everywhere divisible into lower (Lewiston) and upper (Burleigh Hill-Stoney Creek) members; thin units within these members are traceable east to west for distances exceeding 100 km, without substantial change in lithology; or fossil content. In contrast, abrupt lateral facies changes occur within the Rochester Shale along short north-south sections (for example, Niagara Gorge). Such stratigraphic evidence suggests that Rochester shale facies belts are elongate east-west, parallel both to a northern paleoshoreline and also to the present outcrop trend.

The Rochester Shale consists of sparsely to richly fossiliferous, gray, shaley mudstone with abundant interbedded carbonates, including intrasparrudites, lenticular biosparites and biomicrites (= calcarenites) and laminated pelmicrites (= calcisiltites). Such interbeds provide evidence for episodic concentration and transport of carbonate sediments by storm-wave action on a gently southwards-sloping shelf. Calcarenite lenses were formed as erosion-lag deposits in regions within storm-wave base. Finer debris, winnowed from such areas, formed suspension clouds which flowed downslope, depositing storm silt- (calcisiltite) and mud layers.

A crinoidal bank facies (Wiarton) accumulated in the area of the Algonquin Arch during Rochester deposition. Adjacent shelf areas, to the south, received a mixture of terrigenous muds from southeastern source areas (Taconics) and detrital carbonate sediments from the Wiarton shoal, forming argillaceous carbonates and/or calcareous shales (Stoney Creek-upper Burleigh Hill). During times of low sedimentation this area became the site of abundant bryozoan growth—"bryozoan belt" (Lewiston B, D and E). Farther southward (basinward), facies comprise a mixture of sparsely fossiliferous mudstones and storm-silt layers (Lewiston C, lower Burleigh Hill).

Vertical facies changes in the Rochester Shale are attributed to north-south shifting of environmental belts, due to migration of the northern paleoshoreline. As a whole, the formation comprises two (eustatic?) trangressive-regressive cycles. The Lewiston Member represents a nearly symmetrical cycle of deepening (units A–C) and shallowing (units C–E), while the upper units (Burleigh Hill, Stoney Creek) reflect aspects of an asymmetrical, shallowing-upward hemicycle. During the last event, allodapic carbonate sedimentation was considerably increased, as a result of migrating crinoidal bars, inhibiting the growth of bryozoans and other organisms.

The Rochester Shale provides a paradigm for interpreting numerous marine units in western New York which exhibit layer-cake arrays of facies.

INTRODUCTION

Lower Paleozoic sedimentary rocks of New York State and adjacent Ontario have provided a major source of data on the depositional environments of ancient epeiric seas; indeed, certain extensively studied rock units form the basis for paleoenvironmental models (Laporte, 1967, 1969; Walker and Laporte, 1970; Anderson et al., 1978; Cisne and Rabe, 1978). However, most previous studies in New York have concentrated either on near-shore carbonate environments (for example, Black River and Helderberg groups: Walker, 1972; Walker and Laporte, 1970; Laporte, 1967, 1969), or on deltaic settings (for example, Queenston and Catskill deltaic complexes; Bretsky, 1969, 1970; Sutton, Bowen, and McAlester, 1970; Thayer, 1974; McGhee and Sutton, 1981). Relatively little emphasis has been placed on nondeltaic, open marine paleoenvironments. As a consequence, some of the most fossiliferous, and thus, paleontologically best known, rock units have received very little paleoenvironmental study.

The relatively thin marine rock sequences of western New York and Ontario are particularly

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difficult to interpret in terms of conventional facies models. Stratigraphic sequences such as the Silurian Clinton, Lockport, and Salina groups exhibit vertical successions of lithic and faunal subdivisions (facies), each of which is typically widely traceable as a stratigraphic unit. These vertical facies rarely intergrade with one another laterally along the east-west trending outcrop belt (Belak, 1980; Kissling and Moshier, 1981; Koch, 1981). This "layer-cake" aspect (*sensu* Levorsen, 1943) of New York stratigraphy has facilitated local correlations but has also hampered attempts to decipher facies relationships and depositional environments.

The medial Silurian Rochester Shale (Wenlockian; Clinton Group) is a classic unit in American stratigraphy, being among the first formally designated formations in North America (Hall, 1839, p. 20). This formation has been widely correlated in the northern and central Appalachian region, and serves as an important stratigraphic marker in subsurface studies (Schuchert, 1914; Chadwick, 1918; Caley, 1940; Gillette, 1940, 1947; Berry and Boucot, 1970). The Rochester Shale is also noted as an important source of fossils; over 200 species of invertebrates have been reported from the formation, including some of the best preserved Silurian fossils in North America (Hall, 1852; Ringueberg, 1888, 1897; Grabau, 1901; Sarle, 1901; Bassler, 1906; Springer, 1920, 1926; Brett, 1978).

Yet, despite its historical, stratigraphic, and paleontologic significance, the Rochester Shale has received little attention in recent literature. Preliminary studies of Rochester depositional environments and paleoecology were undertaken by Thusu (1972) and Narbonne (1977); however, these papers are restricted in geographic scope, and their conclusions are necessarily generalized and tentative.

Recent detailed stratigraphic and paleontologic studies (Brett, 1978, in press) provide a general background for the present paleoenvironmental interpretation of the Rochester Shale. Most importantly, these studies indicate that facies belts within the Rochester Shale extend east-west, subparallel to the modern Niagara Escarpment outcrop belt in western New York and the Ontario peninsula (Brett, in press). This single factor provides a key for the development of a depositional model for the Rochester Shale, and perhaps also other units with apparent "layer-cake" stratigraphy.

In the present paper, data on the sedimentology, paleoecology, and stratigraphic relationships with other rock units have been synthesized in interpreting Rochester Shale sedimentary environments. Depositional environments of the synjacent Irondequoit, DeCew, and Gasport Formations have also been considered to provide a general framework for interpreting the paleoenvironmental setting of the Rochester Shale. A model of storm-influenced sedimentation along a gently sloping shelf is presented to explain many of the sedimentologic features observed within the Rochester Shale.

GEOLOGIC SETTING AND FACIES RELATIONSHIPS OF THE ROCHESTER SHALE

In Ontario and New York State, the Rochester Shale constitutes the middle unit of three formations of the upper Clinton Group (Bolton, 1957) (Figs. 1, 2). Throughout much of its extent, the Rochester is underlain conformably by the upper member of the Irondequoit Limestone, a light gray to pinkish gray crinoidal biomicrite or biosparite.

From Hamilton, Ontario, eastward to Rochester, New York, the Rochester Shale is overlain by fine-grained, buff-colored DeCew Dolostone. Early workers (Ulrich, 1911; Schuchert, 1914; Chadwick, 1918) postulated a major disconformity between the Rochester and DeCew, but the completely gradational nature of the contact in nearly all localities argues against this. For this reason, the boundary between the Clinton and Lockport groups is now generally placed at the sharp upper contact of the DeCew with the overlying Gasport Limestone in western New York (Gillette, 1947; Bolton, 1957).

Northwest of Hamilton, Ontario, the DeCew Dolostone is absent, and the Gasport Limestone rests directly on a condensed Rochester Shale section. Where the Rochester Shale pinches out, the Gasport overlies the Irondequoit Limestone (Figs. 1, 3). The two rock units represent nearly identical facies types, and together they appear to merge northwestward into the crinoidal, dolomitic limestone of the Wiarton Formation of the Amabel Group (Sanford, 1969).

In north-south cross sections (Fig. 1), the Irondequoit and Gasport limestones appear as tongues of the crinoidal shoal facies that ex-

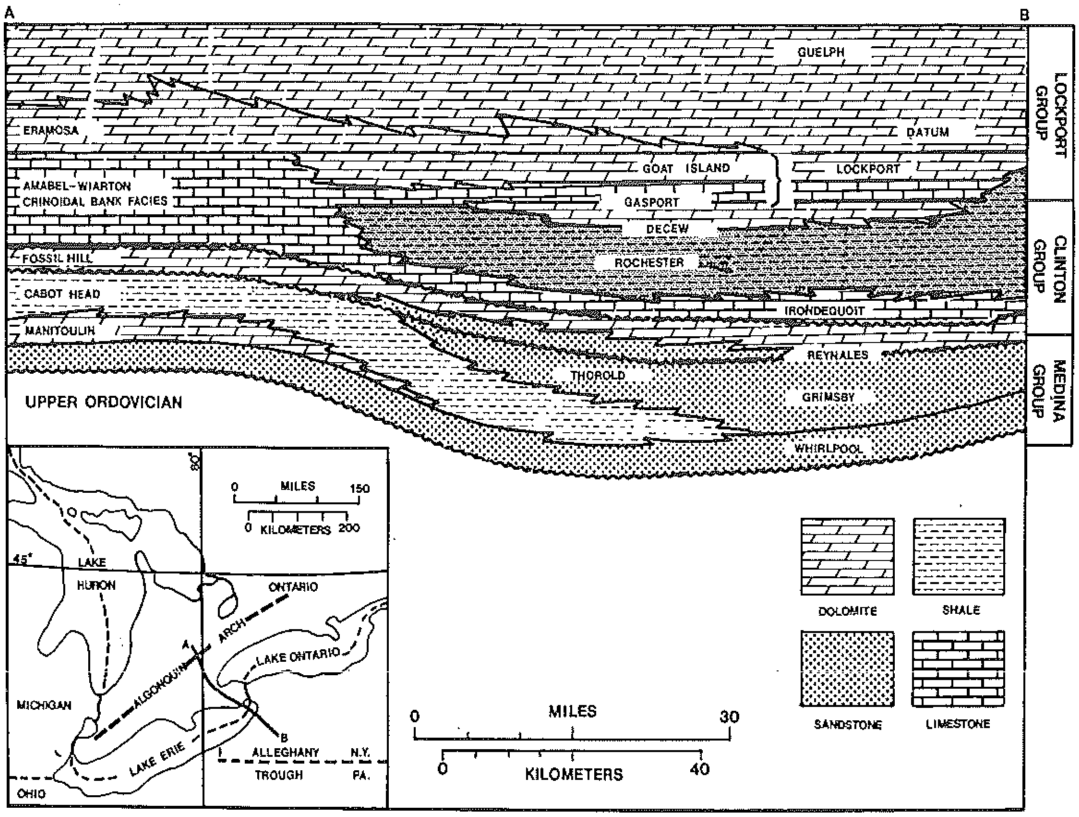


FIG. 1.—Cross-sectional diagram of the upper Clinton-lower Lockport groups in Ontario and western New York; orientation of section line is indicated on inset. Modified from Sanford (1969).

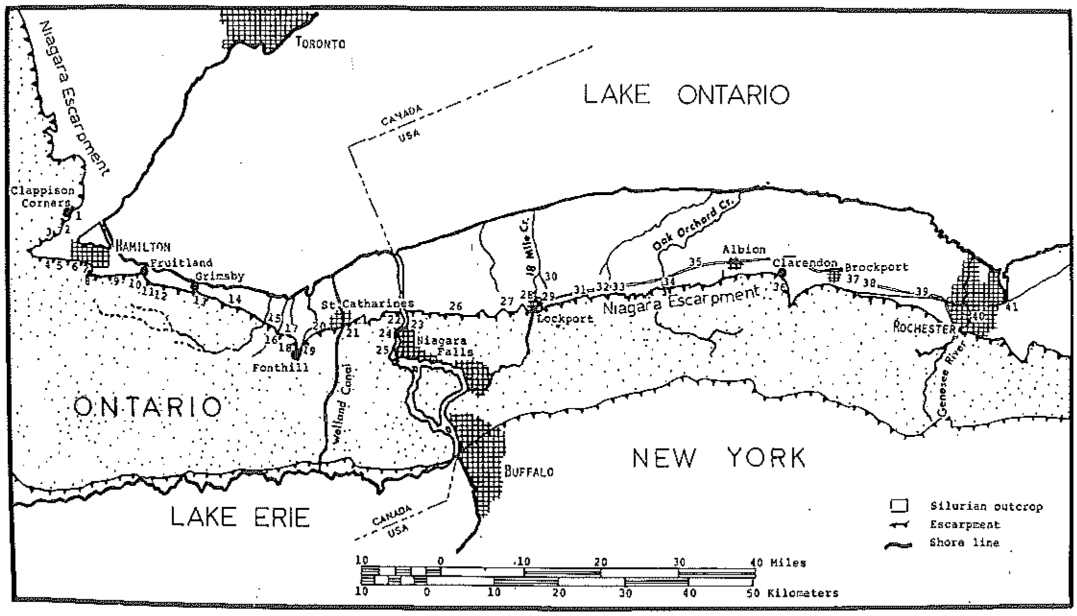


FIG. 2.—Location map for stratigraphic sections of the Rochester Shale in western New York and Ontario. Numbers refer to localities described in Brett (1978a).

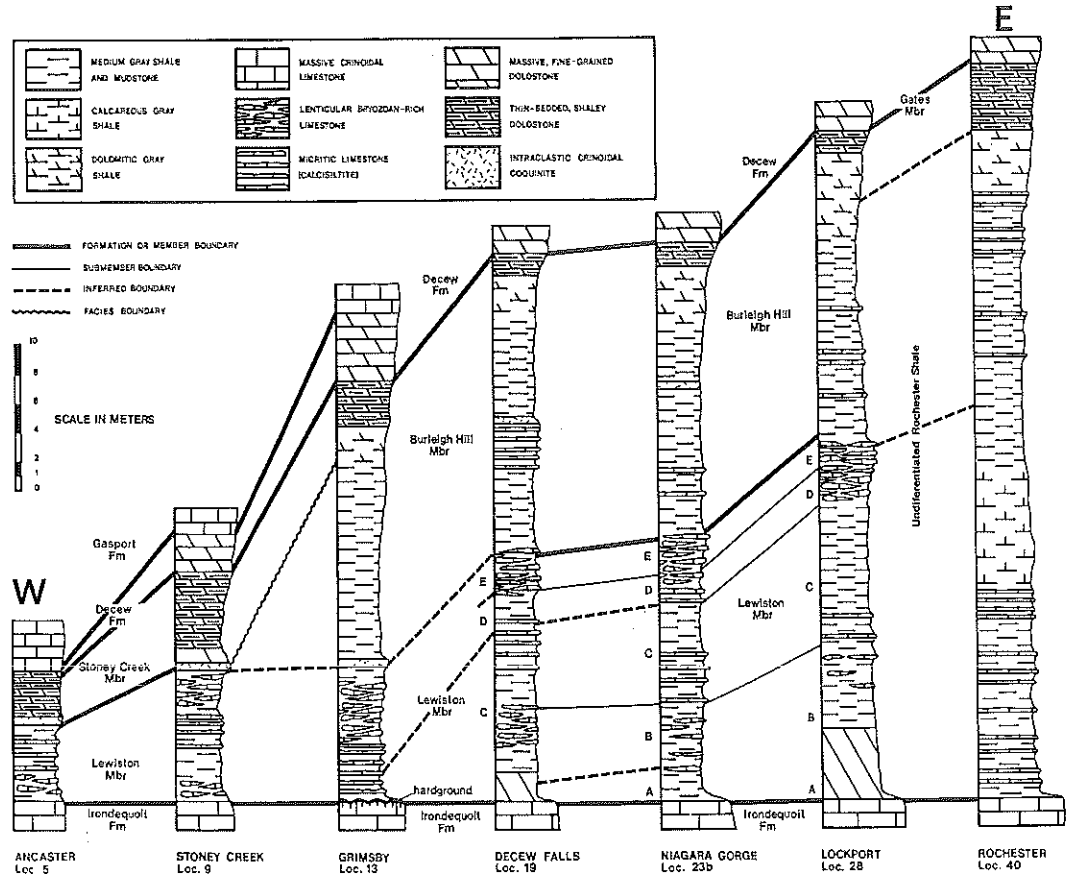


FIG. 3.—Stratigraphic sections of Rochester Shale at seven localities in Ontario and western New York. Locations of numbered sections are shown in Fig. 2.

tend southeastward into the Appalachian Basin. These tongues are separated by mudstone and argillaceous dolostone of the Rochester and DeCew formations.

In Ontario and New York State, the Rochester Shale consists of medium to dark gray calcareous shale and thin-bedded limestones, including micrites, pelmicrites, biomicrites, and intramicrites (Thusu, 1972). Along the outcrop belt in New York and Ontario, the Rochester thickens southeastward from a minimum of 0.6 m (2 ft) at Clappisons Corners, Ontario, to a maximum of about 37 m (122 ft) near Wolcott, in central New York. Subsurface data reveal that the Rochester is thickest in an elongate northeast-southwest trending area of west central New York from North Victory (Cayuga County), to Geneva (Ontario County), where it attains a maximum thickness of 44.8 m (147 ft) (Gillette, 1940; Figs. 1, 14). Well logs indicate a southward thickening in western New York from 15–21 m (57–70 ft) in Niagara-Orleans counties to thicknesses of 30–35 m (100–115 ft) in southern Erie, Genessee, and Livingston counties (Kreidler et al., 1972).

The Rochester Shale maintains a thickness of 12–15 m (40–50 ft) in the subsurface along the southern side of the Ontario peninsula westward to Windsor, Ontario. However, well logs also reveal relatively rapid thinning and pinch-out of the Rochester into Wiarton crinoidal dolostone within 24–32 km northeast of this belt (Caley, 1940; Fig. 1).

This northward-thinning is apparently due to facies change with only minor, if any, erosive overstep of the Rochester (Bolton, 1957; Sanford, 1969). The Wiarton crinoidal facies is thus the northern equivalent of the entire Irondequoit-Gasport sequence. The line of abrupt facies change approximately coincides with the

Algonquin Axis, an area of relative uplift during the Paleozoic.

The Rochester Shale persists in the subsurface southward from Ontario into eastern Ohio and Kentucky, but grades westward into argillaceous dolostone (Bisher Formation) in the Ohio outcrop belt (Hunter, 1970). In southwestern Pennsylvania, the Rochester thins to 6–12 m (20–40 ft) of dark gray shale, which overlies and interfingers southeastward with the Keefer Sandstone (Swartz, 1934, 1935; Hunter, 1970). These shales are generally sparsely fossiliferous, compared with the Rochester Shale in western New York, but contain many of the same faunal elements (Swartz, 1923). Local bioherms have been reported from the upper Rochester and overlying McKenzie formations near Lock Haven, Pennsylvania (Cuffey and Davidheiser, 1979).

In Maryland and West Virginia, the so-called Rochester Formation consists of nearly black, laminated, pyritic shales lacking a normal marine fauna, and interpreted by Folk (1962) as lagoonal deposits formed in a restricted environment landward of an offshore sand bar, a tongue of the Keefer Sandstone.

In east-central New York, the Rochester Shale exhibits sandstone tongues, and in Oneida County, New York, the formation grades into the Herkimer Sandstone. The Herkimer has been further subdivided into two laterally adjacent members (Zenger, 1966). A western Joslin Hill Member consists of brownish-gray calcareous and fossiliferous sandstone with some gray shale layers. In contrast, the Jordanville Member consists of silica-cemented quartz arenite and quartz pebble conglomerate. Body fossils are absent or rare in the Jordanville, but trace fossils are abundant in some units (Zenger, 1966).

STRATIGRAPHY OF THE ROCHESTER SHALE IN ONTARIO AND WESTERN NEW YORK

Although local subdivisions of the Rochester Shale were recognized by early workers (Ringueberg, 1888; Grabau, 1901), subsequent authors have treated the Rochester Shale as a uniform lithologic unit, lacking mappable subdivisions (Gillette, 1940; Bolton, 1957; Thusu, 1972). Detailed stratigraphic study of the Rochester Shale indicates the existence of several widely traceable units within the formation, and four new members have recently been proposed (Brett, in press; Fig. 3).

In western New York and Ontario the Rochester Shale is divisible into lower and upper members of roughly equal thickness, generally separated by a sharp contact (Fig. 3). The lower or Lewiston Member is further subdivisible into five mappable submembers; it exhibits a cyclic repetition of facies which bryozoan-rich biosparites (submembers A, E) and biomicrites (submembers B, D) at the base and top of the member separated by an interval of sparsely fossilferous shale and calcisiltites (submember C). The upper or Burleigh Hill Member comprises barren or slightly fossiliferous shales and calcisiltites resembling submember C of the Lewiston and grades upward into dolomitic (or calcareous) shales and argillaceous dolostones of the DeCew Formation. West of Grimsby, Ontario, the Burleigh Hill Member is replaced by an argillaceous dolostone facies, the Stoney Creek Member.

Lithologic subdivisions of the Rochester Shale, including the submembers of the Lewiston Member, are laterally persistent for over 100 kilometers along the east-west trending Niagara escarpment (Figs. 2, 3). However, abrupt facies changes are observed in short north-south sections, such as along Niagara Gorge (Brett, 1982; Fig. 4, herein). Here, fossiliferous portions of the Lewiston Member (submembers B, D, and E) thin and pinch out southward in only 8–11 km, whereas the middle, sparsely fossiliferous shale interval (submember C) thickens rapidly and comes to comprise most of the Lewiston Member in the south (Table 1). The Burleigh Hill Member thins slightly to the south and becomes entirely barren shale with the loss of calcisiltites and argillaceous dolostones (Fig. 4; Table 1).

Rapid southward facies change is also corroborated by field data from stream exposures of the Rochester Shale in the Fonthill Reentrant, an 8-km (5-mi) southward embayment in the Niagara Escarpment just west of St. Catharines. Here again, the Lewiston Member thickens and grades southward into a more monotonous, sparsely fossiliferous shale interval. Bryozoan-rich beds of unit E, well represented in the north, again diminish and are replaced by calcisiltite beds capped by one or two thin beds of crinoid-brachiopod-rich calcarenite.

A third area where abrupt north-south changes are observable in the Rochester Shale is the Burlington Bay Reentrant, at the western end of Lake Ontario. Here the Niagara Escarpment

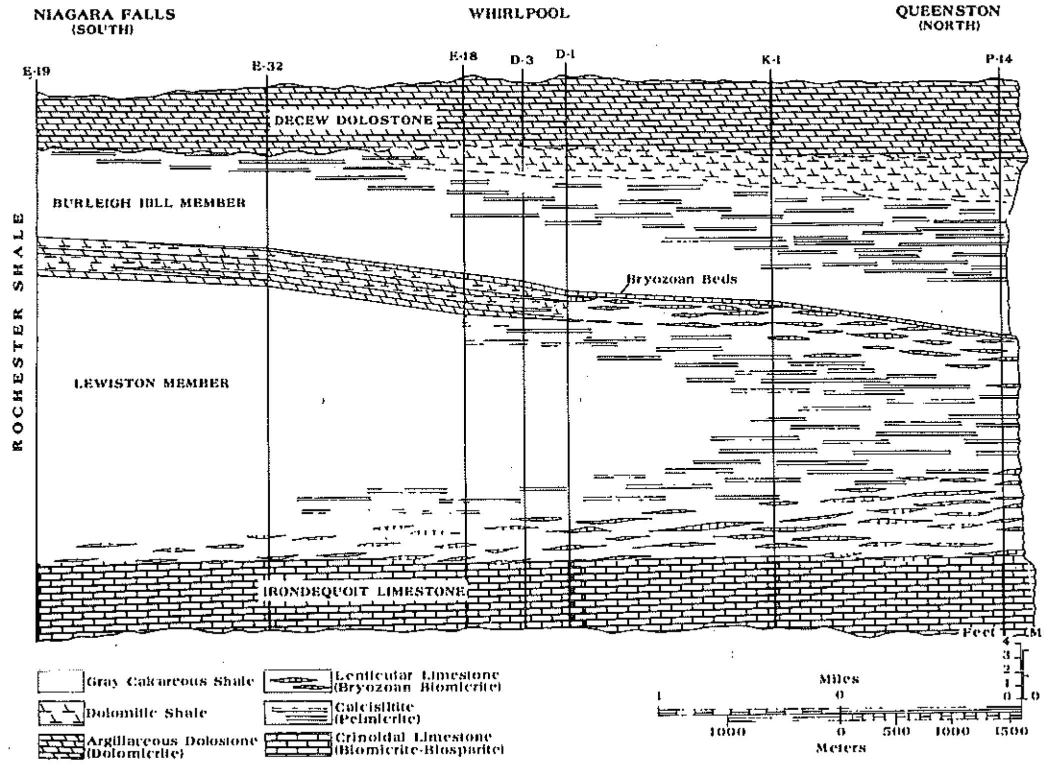


FIG. 4.—North-South stratigraphic relationships of the Rochester Shale and synjacent units in Niagara Gorge; vertical lines indicate positions of measured sections from diamond drill cores, logged by Bolton (1957; Appendix B, p. 107–141); numbers correspond to codes utilized by Bolton.

TABLE 1.—*Measurements of Rochester Shale subunits in diamond drill cores adjacent to west side of Niagara Gorge from Adam Beck Power Plant (P-1-4) to Niagara Falls, Ontario (N-14). Core codes refer to those given by Bolton (1957). Thicknesses in feet; abbreviations: LEW-AB, Lewiston submembers A,B; LEW-C, Lewiston submember C; LEW-DE, Lewiston submembers D,E; LEW TOTAL, total thickness Lewiston Member, measured to topmost bryozoan-bearing limestone bed; BH TOTAL, total thickness of Burleigh Hill Member; ROCH. TOTAL, total Rochester Shale thickness. Note consistent southward thickening of Lewiston Member, due to thickening of Lewiston C, despite thinning of Lewiston-AB and DE subunits. Variable thicknesses of total Rochester reflect variability of Burleigh Hill measurements. Cores are spaced approximately 1 km apart; total north-south distance from P-1-4 (north) to N-14 is about 9.5 km.*

	Core #	LEW-AB	LEW-C	LEW-DE	LEW Total	B.H. Total	ROCH. Total
North	P-14	12.7	7.7	10.4	30.8	27.3	58.1
	F-1	10.8	17.0	6.3	33.1	21.5	54.6
	K-1	9.4	20.9	5.7	36.0	21.7	57.7
	C-2	6.3	27.6	3.9	37.8	18.8	56.6
	D-1	4.0	30.1	3.7	37.8	20.3	58.1
	E-18	2.8	33.0	4.2	40.0	18.1	58.1
	E-32	3.1	39.7	1.3	44.1	12.4	56.5
	E-29	4.4	40.1	0.5	45.0	13.4	58.4
South	N-14	3.9	39.6	0.5	48.0	13.2	61.2

makes an abrupt bend from east-west to north-south; exposures of Rochester Shale occur on both north and south sides of the 8-km (5-mi) wide reentrant (Fig. 2). On the south side of the reentrant, the Rochester Shale is 4.3 m (14 ft) thick and is divisible into Lewiston and Stoney Creek Members; 8 km (5 mi) to the north of this area at Clappison Corners (Loc. 1) the Rochester consists of 0.6 m (2 ft) of intraclastic sandy limestones and calcareous shales. North of this locality, the Rochester is represented by a shaly parting or is absent altogether. As noted previously, this rapid northward-thinning and pinch-out of the Rochester Shale can be recognized in the subsurface as far west as the Windsor area of Ontario.

The rapid and substantial north-south facies changes of the Rochester Shale across the Burlington and Fonthill Reentrants and in the length of Niagara Gorge contrast with the east-west persistence of facies. This indicates that, in western New York and adjacent Ontario, Rochester facies belts are elongate east to west, probably parallel to a northern paleoshoreline and subparallel to the modern Niagara Escarpment. The rare north-south outcrop sections are approximately perpendicular to depositional strike and thus show rapid changes in short distances.

SEDIMENTOLOGY OF THE ROCHESTER SHALE

Mudstones

The bulk of the Rochester Formation in western New York and Ontario consists of medium to dark gray calcareous to dolomitic mudstone. Most of this unit lacks distinct lamination or primary fissility and is burrow-mottled locally, suggesting thorough bioturbation of the sediment. Carbonate content ranges from about 40 percent in the barren middle portion of the Lewiston Member (submember C) to over 60 percent in argillaceous limestones and dolostones of the upper Burleigh Hill-Stoney Creek Members.

Rochester mudstones contain both clay and fine silt-sized particles. Quantitative grain-size analyses by Narbonne (1977) indicate a variability in both median and maximum grain size within the Rochester Shale. Samples from the middle Lewiston Member at St. Catharines yield median diameters of 6.5 microns with little sediment exceeding 16 microns. An abrupt increase in grain size takes place within the Burleigh Hill Member; median grain size is approximately 8 microns and about 16 percent of the grains in the upper beds are greater than 16 microns (Narbonne, 1977).

Fossil content of the Rochester mudstones is variable. Many intervals, particularly in the Burleigh Hill Member, are nearly barren, with only scattered brachiopods and trilobite fragments. Locally, within the Lewiston Member, mud-supported accumulations of bryozoans and brachiopods form discontinuous beds or lenses, here termed bryozoan clusters (Fig. 5). These are distinguishable from biomicrites by their better fossil preservation, relatively low carbonate content of the matrix muds, and consequently different weathering properties. Clusters tend to be crumbly and, therefore, weather into reentrants. Biomicrites are more indurated, and hence, weather out as projecting ledges.

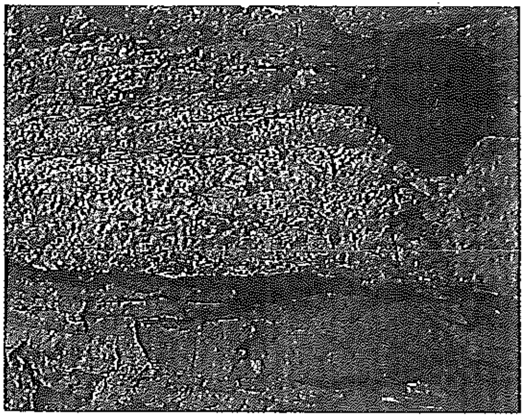


FIG. 5.—Rochester Shale mudstones; note typical blocky, sparsely fossiliferous mudstone overlain by a lens of bryozoan-rich calcareous mudstone. Lens cap is 57 mm; Lewiston Member, Niagara Gorge (Loc. 23).

Rochester mudstones are interbedded with a variety of carbonate lithologies including intraclastic limestones (intrasparites), calcarenites (biomicrites and biosparites), and calcisiltites (pelmicrites). Such interbeds reveal abundant evidence for sporadic, storm-generated sedimentation. Carbonate storm layers or tempestites (Ager, 1974) can be distinguished from background sediments by a combination of features including a) sharply defined basal surfaces with sole marks such as scours and gutter casts, b) internal sedimentary structures, including parallel and cross-lamination and vaguely grading bedding, and c) rippled upper surfaces (Kreisa, 1981; Aigner, 1982). In addition, taphonomic evidence may point to the existence of otherwise unrecognizable storm mud layers in fine-grained sequences.

Intraclastic Limestones

Intraclast-bearing carbonates are rare within the Rochester Formation as a whole, being almost restricted to sections in the Stoney Creek Member near Hamilton, Ontario. Such units are best developed at Clappison Corners (Loc. 1). These consist of beds 5–10 cm thick, containing large (up to 10 cm in diameter) angular clasts of shale and calcisiltite in a matrix of crinoid debris and coarse quartz sand grains with sparry calcite cement (Fig. 6). Intraclastic units indicate rip-up of indurated carbonate-rich muds, probably due to submarine erosion by storm waves. Imbrication of clasts and winnowing of particles smaller than medium sand size suggest deposition of the intrasparites under shallow, highly agitated conditions. As

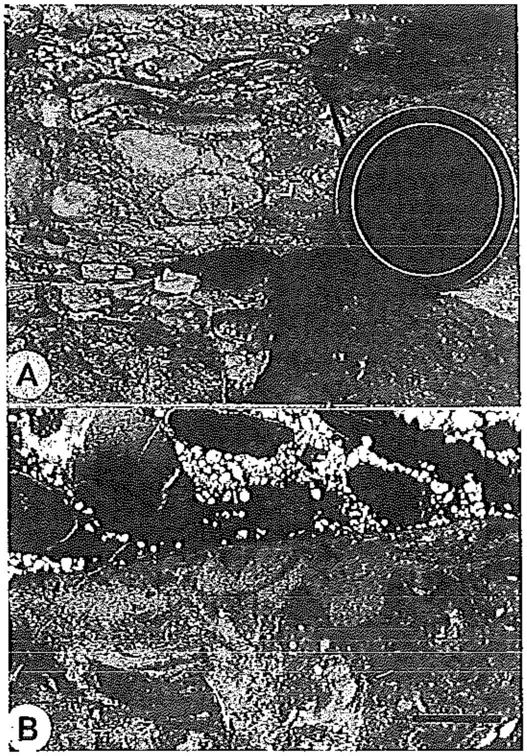


FIG. 6.—A) Sandy, intraclastic limestone (intrasparite) bands in outcrop of Rochester Shale at Clappisons Corners, Ontario (Loc. 1). B) Photomicrograph of same; note large burrow-mottled dolostone clast in matrix of quartz sand and skeletal grains, with sparry cement; bar scale indicates 5 mm.

noted above, intraclast-bearing limestones are clearly associated with the Algonquin Axis.

Calcarenites

The second category of Rochester carbonates consists of thin (5–15 cm), lenticular layers of disarticulated and broken fossil debris, rarely also including rip-up clasts of shale. Fossils, including brachiopod, bryozoan, pelmatozoan, and trilobite fragments, usually belong to the same species, which occur scattered through the underlying mudstones from which the debris layers were probably derived by the winnowing action of storm waves (compare with Sutton et al., 1970; Bowen et al., 1974). Winnowed mud and silt must have been removed and deposited elsewhere. These layers show sharp basal surfaces, rarely with well-preserved fossils intact; they are sometimes overlain by evidently autochthonous remains of epifaunal organisms that may have used the shell layers as settlement substrates. Closed brachiopod shells frequently exhibit randomly oriented geopetal infillings of mud resembling sediment of the underlying mudstone units, suggesting their reworking from below. Breakage and occasional abrasion of the fossils as well as the occurrence of intraclasts suggest bursts of high energy impinging on the Rochester sea floor. Certain calcarenites occur as a series of isolated lenses with tapering extremities, suggestive of starved ripples (compare Potter, Maynard, and Pryor, 1980; Fig. 7 herein).

Similar shelly and intraclastic limestones have been described from the Silurian of Arctic Canada (Jones and Dixon, 1976), and from the Upper Ordovician of the south-central Appalachians (Kreisa, 1981). In both cases, the limestones were interpreted as randomly occurring, storm-generated debris layers.

Certain calcarenites in the Rochester Shale show slight size grading from coarse-grained

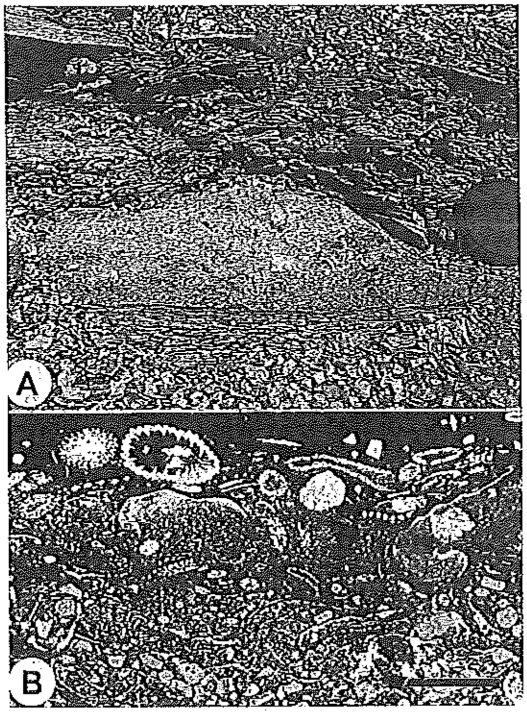


FIG. 7.—A) Lens of bryozoan-pelmatozoan-rich calcarenite interpreted as a starved ripple; Lewiston Member (Loc. 23B). B) Photomicrograph of bryozoan-rich biomicrite; bar scale indicates 5 mm; Lewiston Member (Loc. 9).

skeletal material at the base into finer-grained debris, for example, crinoid ossicles, at the top. Such debris layers may also grade vertically or laterally into a third type of finer storm-generated layer: laminated calcisiltites.

Calcisiltites

In outcrops, calcisiltites appear as sharply defined, buff-weathering and laterally persistent beds (Fig. 8). These beds contain numerous sedimentary structures indicative of deposition from waning currents. Weathered surfaces exhibit wavy cross- and planar-lamination, typically in alternating sets; brown, silty mud layers alternate with darker laminae of carbonate peloids (Figs. 8, 9). Undersurfaces of calcisiltites are sharply defined and exhibit sole marks such as flute, groove, and ridge molds indicative of scour of muds by sediment-laden currents (Fig. 10). Such lineations suggest a southerly current flow in many cases, presumably drainage from carbonate shoals to the northwest. Upper surfaces of the calcisiltites typically show low-amplitude ripple marks and cut-and-fill structures. Internally, the calcisiltites frequently exhibit small spherical blebs of disseminated pyrite. These may represent infillings of bubble cavities. Gas bubble cavities of comparable size have been found in similar rhythmically laminated silt-clay layers deposited from suspension clouds on the Rhine Delta in Lake Constance, Switzerland (Reineck and Singh, 1975, p. 109).

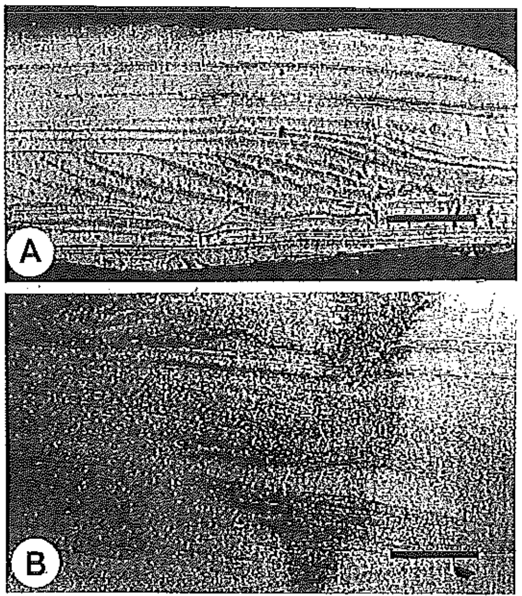


FIG. 8.—A) Weathered surface of calcisiltite band, showing alternating sets of planar- and cross-lamination; lower Rochester Shale at South Greece, New York (Loc. 39); bar scale indicates 1 cm. B) Thin section of calcisiltite; Lewiston Member; Niagara Gorge (Loc. 23B); bar scale indicates 5 mm.

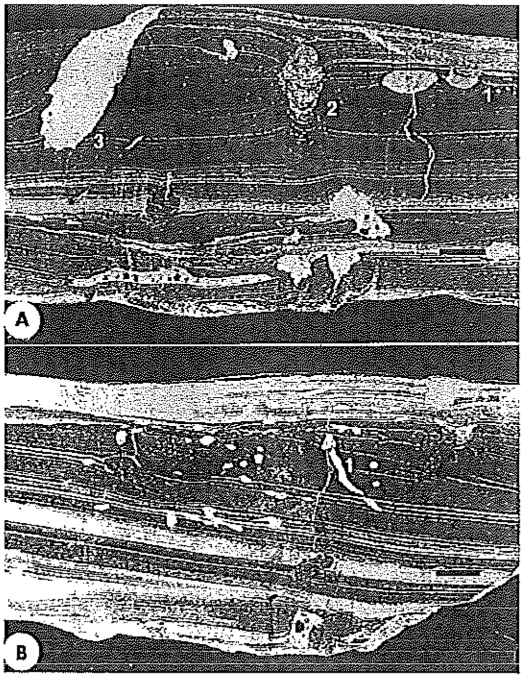


FIG. 9.—A, B, Polished sections of calcisiltite bands; note irregular alternating dark and light laminae and abundant burrows, including *Chrondrites* (1), *Teichichnus* (2), and large vertical burrows, possibly escape structures (3); bar scales indicate 1 cm; lower Rochester Shale at South Greece, N.Y. (Loc. 39).

Fossil fragments and, rarely, well-preserved fragile fossils (for example, crinoids) may occur at the bases of calcisiltites, but apparently the scouring action of the currents was typically too great to preserve in-place fossil communities. Although body fossils are usually lacking within or atop calcisiltites, these units show a variety of well-preserved ichnofossils, including possible escape burrows with short straight walls bordered by disrupted laminae. Upper portions may be intensely bioturbated by *Chondrites*, *Planolites*, and *Teichichnus spreiten* (Fig. 9). These provide evidence for rapid colonization of silt layers by infaunal-deposit feeding communities rather than by shelly forms.

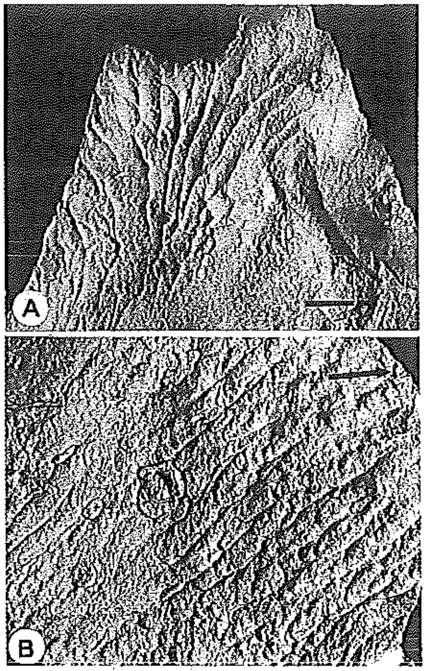


FIG. 10.—Undersurface of calcisiltite beds exhibiting sole marks: A) Lobate flow marks, bar scale indicates 1 cm; B) Groove and ridge molds, same scale, arrow indicates north orientation. Both specimens from lower Rochester Shale at South Greece, N.Y. (Loc. 39).

Calcisiltites in the Rochester Shale are very similar to storm silt-and-sand layers described by Reineck and Singh (1972) from outer parts of the North Sea shelf, and are thus interpreted as storm-generated silt layers deposited from moving suspension clouds.

Mud Layers

In turn, silt layers grade laterally and vertically into storm-generated, silty mudstone beds. This fourth type of episodic sedimentary package is recognized primarily on taphonomic criteria, indicating so-called "smothered bottoms" (Fig. 11). These consist of unfossiliferous, vaguely laminated mudstone layers up to several centimeters thick that abruptly overlie well-preserved fossil assemblages. The bases of such units may be sharply demarcated by shell beds. Although evidence of scouring is usually lacking, indications of slight disturbance of the sea floor immediately prior to mud deposition may be present. In some cases, brachiopod valves (seen convex downward on the undersurface of a bed in Fig. 11B) were evidently overturned immediately prior to burial, since they bear attached, inverted epifaunal organisms (for example, bryozoans and edrioasteroids; Brett, 1978, p. 397–398).

Silty mudstones immediately overlying such shell beds may also contain unusually well preserved fossils, such as complete crinoids, still attached to brachiopod shells (Fig. 11A). These fossils may show vaguely preferred orientations indicative of slight current action at the time of burial (Brett and Eckert, 1982). Obviously, extremely rapid or even live burial of these organisms is indicated. Further evidence for local rapid burial of the bottom is provided by well-preserved vagrant organisms, particularly stelleroids (Fig. 11C). Schäfer (1972) found that some recent ophiuroids can escape burial in up to 5 cm of silt. Thus, well-preserved stelleroids found in barren mudstone slightly above the base of smothered horizon provide direct evidence for essentially immediate burial by substantial mud layers.

Smothered bottom assemblages tend to occur at closely spaced intervals in local stratigraphic sections, indicating that conditions necessary for their formation recurred frequently in certain environments. For example, the *Homocrinus* band at Lockport, New York, a 40-centimeter interval in the middle portion of the Lewiston Member of the Rochester Shale, contains five such assemblages.

Storm-generated Sedimentation in the Rochester Shale

Studies of recent and ancient shelf environments have revealed the importance of episodic, relatively rare storm events in the deposition and shaping of sedimentary packages (Hayes, 1967; Ball, 1971; Reineck and Singh, 1975; Ager, 1974; Aigner, 1979, 1982; Kreisa, 1981; Kreisa and Bambach, 1982; Seilacher, 1982). Furthermore, the concept of proximality has been extended to the interpretation of tempestite sequences (Aigner, 1979; 1982). Because the intensity of storm effects decreases away from shore, proximal storm deposits are characteristically thicker and coarser than distal tempestites. The former are commonly calcarenites or calcirudites; proximal shell lags may be multiply reworked to form composite or amalgamated beds. In contrast, distal deposits are calcisiltites or mud layers and represent single-event beds (Aigner, 1982, p. 187).

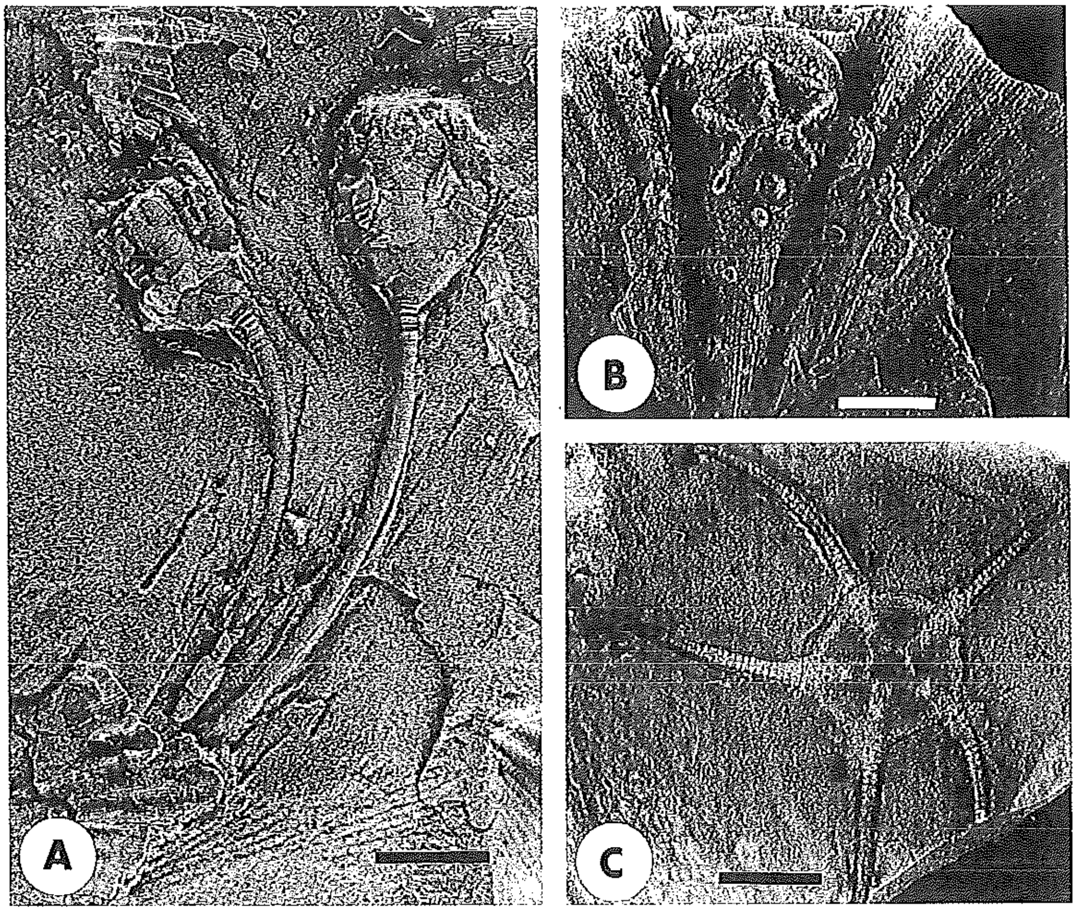


FIG. 11.—Well-preserved fossils from a "smothered-bottom assemblage." A) Complete specimens of the flexible crinoid *Asaphocrinus ornatus* Hall; note attachment to a spiriferid brachiopod. B) edrioasteroid (*Hemicystites*) attached to the shell of *Striispirifer* on the underside of a mudstone slab, indicating inversion of the brachiopod shell to a concave-upward orientation prior to burial; C) ophiuroid, *Protaster*, found in barren mudstone overlying "smothered bottom assemblage." All specimens from Lewiston Member at Lockport, New York, (Loc. 28). Bar scales indicate 5 mm.

The Rochester Shale contains four distinct but intergrading types of episodic deposits or event deposits (*sensu* Seilacher, 1982, p. 161): intraclastic limestones, wave-winnowed calcarenites, calcisiltites, and mud layers. Detailed field observations suggest that all types can be regarded as genetically related units generated as a side effect of a storm-wave action on a shallow, but gently sloping shelf. In this model, areas of sea bottom within storm-wave base (proximal regions) were scoured, producing parautochthonous debris layers and forming clouds of suspended carbonate and terrigenous silt and mud. Under the influence of gravity, these suspension clouds then flowed downslope, depositing calcisiltites proximally and mud layers distally (Fig. 12; compare Aigner, 1982, Fig. 10).

Presumably, any of the four types of storm deposits could have been generated in shallow water depending upon the intensity of and duration of storm waves. However, in deeper water settings, only calcisiltites and silty mud layers would have been deposited. The frequency of the four types of tempestites may thus provide a rough index of paleobathymetry (compare Kreisa, 1981; Aigner, 1982), and variations in their relative abundance in vertical sections of the Rochester Shale suggest variation of water depth.

Along the Niagara Escarpment outcrop belt of western New York and Ontario calcarenites

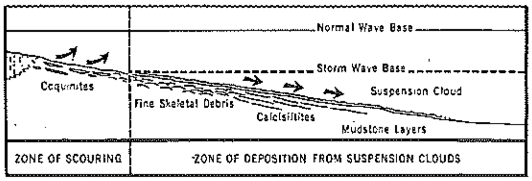


FIG. 12.—Schematic diagram of storm-generated sedimentation on a shallow, gently-sloping shelf. Areas of sea floor within storm wave base, about 10–60 m, experience scouring and winnowing of fine-grained sediments, generating coquinites. Winnowed sediment then moves down slope in suspension clouds (density flows), depositing finer skeletal debris, carbonate silts, and muds in successively deeper water.

("bryozoa beds"), interpreted as proximal tempestites, are abundant at the base and, again, near the top of the Lewiston Member, whereas the middle portion of the Lewiston is characterized by calcisiltites and silty mudstones (distal tempestites; Table 2). Composite crinoidal bryozoan-rich beds of variable thickness invariably mark the top of the Lewiston Member. Multiple episodes of reworking and condensation of bioclasts within this interval are strongly suggested by a mixture of well-preserved and broken, abraded, and biocorroded fossil material. Local occurrence of glauconite within the topmost bed also suggests very low rates of clastic sedimentation. These data indicate that a shoaling event of regional scale, accompanied by long-term reworking and winnowing, occurred toward the end of the Lewiston deposition. Similar features characterize the basal beds (Unit A) of the Lewiston Member. In the context of a storm depositional model, this sequence implies implies a transgressive-regressive cycle within the Lewiston Member (compare Kreisa, 1981; Meyer et al., 1981).

In the same region, the lower half of the Burleigh Hill Member contains few interbeds of any kind; however, thin calcisiltites appear near the middle of the member and increase in frequency and thickness (Table 2) toward the top of the unit where they become closely spaced and grade upward into argillaceous dolostone of the DeCew Formation. Thicker beds toward the top of the Burleigh Hill, particularly at its type section in Ontario, display hummocky cross-stratification, wave-rippled upper surfaces and grading, with fine crinoidal sand and rare intraclasts concentrated near the base of the units. This stratification sequence strongly suggests that the Burleigh Hill records upward shallowing. The Stoney Creek Member displays a comparable sequence, although calcisiltite bands occur even at the base of this unit.

Such interpretations based on single out-

TABLE 2.—*Numbers of calcarenite and calcisiltite bands per meter of measured section in outcrops and cores along Niagara Gorge; sampling sites are arranged from north (LEW) to south (E-19) and are spaced about 1 km apart. Total Rochester Shale thicknesses (in meters) is listed below each locality designation. Symbols: LEW; outcrop along east wall of Niagara Gorge 0.5 km north of Robert Moses Power Plant and 2.3 km south of Lewiston, New York WP: outcrop at Niagara Falls Sewage Treatment Plant: 1.2 km south of Whirlpool Bridge; SK: outcrop at site of (collapsed) Schoelkopf Power Plant 0.8 m north of niagara Falls, New York, F-4, C-2, E-18 and E-19 refer to drill cores adjacent to west well of Niagara Gorge; designations refer to codes utilized by Bolton (1957); see Figure 4. Note that positions of calcisiltites could not be determined for core data. Dashes indicate no data because of covered interval. ++ indicates numerous limestones interbedded with calcareous fossil-rich shale.*

		Calcarenites							Calcisiltites		
	T:	LEW 17.5	F-4 17.6	C-2 17.2	E-18 17.7	WP —	SK 17.7	E-19 17.8	LEW 17.5	WP —	SK 17.7
Sampled Meters above Base of Rochester Shale	18	0	0	0	0	0	0	0	15	3	0
	17	0	0	0	0	0	0	0	5	0	0
	16	0	0	0	0	0	0	0	—	1	1
	15	0	0	0	0	0	0	0	—	2	1
	14	1	0	0	0	0	4	2	0	1	0
	13	0	0	0	4	5	0	0	2	9	3
	12	0	0	4	4	0	0	0	1	6	6
	11	0	0	3	1	0	0	0	1	3	4
	10	7	7	0	0	0	0	0	2	3	3
	9	7	3	1	0	—	0	0	2	—	1
	8	4	0	1	0	—	0	0	1	—	1
	7	2	1	0	0	—	0	0	5	—	3
	6	0	0	0	0	—	0	0	10	—	2
	5	0	1	0	0	—	0	0	5	—	3
	4	2	5	0	0	—	0	0	4	—	2
	3	6	7	0	0	—	2	0	0	—	0
	2	8	4	4	5	—	5	0	1	—	0
	1	++	++	++	++	—	++	++	0	—	2

crops are further supported by lateral facies relationships within the Rochester Shale along north-south oriented cross sections perpendicular to the presumed depositional strike. For example, the stratigraphic profile of the Lewiston Member along Niagara Gorge (Fig. 4) closely resembles a "text book" transgressive-regressive cycle (see, for example, Raup and Stanley, 1978, p. 215). Note that bryozoan-rich lower and upper portions of the Lewiston converge toward the north (Fig. 4; Table 1).

To further document this relationship, the number of carbonate interbeds per meter of vertical section was determined at several sections along a north-south transect of the Rochester Shale (Table 2; Fig. 13). All measured sections of the Lewiston Member exhibit a nearly symmetrical distribution of interbeds centered on a middle shaly interval (Unit C). Calcarenites at the base and the top of the Lewiston Member decrease in number and thickness toward the south, while calcisiltites increase in the corresponding intervals. Thus, for example, the bryozoan calcarenites of Unit E, except for the topmost bed, are replaced southward by thin to medium beds of cross-laminated, storm-rippled calcisiltite (Figs. 4, 13).

Similarly, the number of calcisiltite bands in the middle unit (C) of the Lewiston Member and in the lower Burleigh Hill Member decrease toward the south, where both of these intervals are represented by sequences of nearly barren, dark gray to black mudstone. Present data are insufficient to quantify the occurrence of storm mud layers, but qualitative observations on the taphonomy of the Rochester Shale strongly corroborate interpretations based on other lithologies. Most notably, all exceptionally well preserved fossil occurrences discovered to date are associated with shale and calcisiltite sequences in Unit C of the Lewiston Member or in the middle to upper portions of the Burleigh Hill Member (Brett, 1978; Brett and Eckert, 1982). These observations suggest that "smothered-bottom" layers are, indeed, more numerous in certain portions of the Rochester than in others.

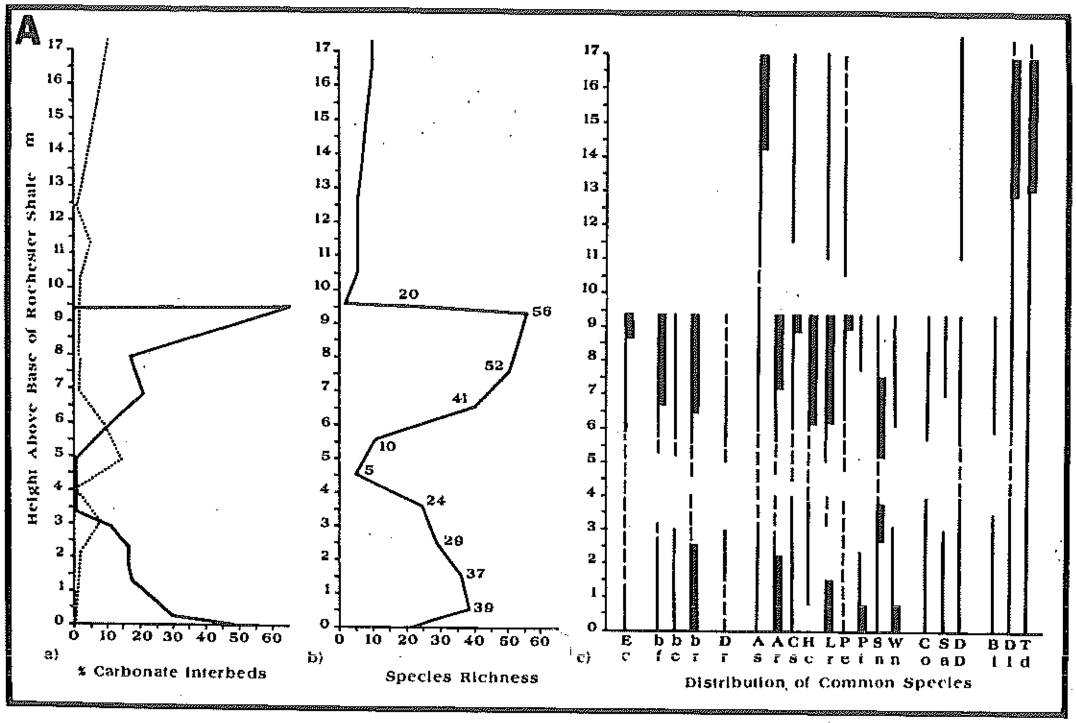
PALEONTOLOGY AND PALEOECOLOGY

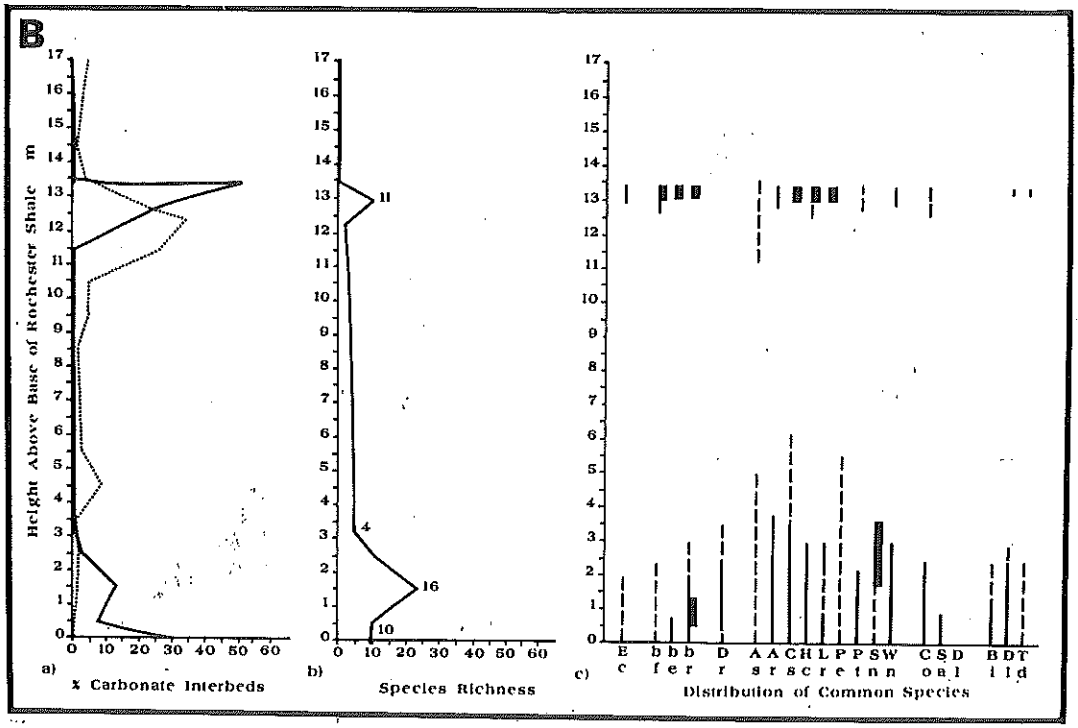
Although the Rochester Shale is noted for its diverse and well-preserved invertebrate faunas, fossils are by no means uniformly distributed within the formation. Certain limestones and biostromes, especially within the Lewiston Member, are extraordinarily rich in fossils, but the bulk of the formation is moderately to sparsely fossiliferous. Boucot (1975) referred the entire Rochester Shale fauna to the "*Striispirifer* community," a high diversity brachiopod-dominated association which he assigned to Benthic Assemblage 3—that is, an offshore, quiet-water setting. Detailed studies of Rochester Shale faunas (Brett, 1978) reveal that the *Striispirifer* association is restricted to certain portions of the formation. In fact, several distinct, though intergrading, fossil associations, evidently reflecting specific paleocommunities, recur cyclicly within the Rochester Shale (Fig. 13).

Ichnofossil Association.—The simplest association consists primarily of trace fossils. The ichnogenera *Chondrites*, *Planolites*, and *Teichichnus* occur abundantly in calcisiltites and argillaceous dolostones. These beds rarely contain abundant body fossils; rather, this appears to represent an association of soft-bodied, burrowing organisms that were rather closely restricted to silty substrates, inhospitable to most skeletonized benthic forms. The ichnofossil assemblage is found in barren silty shales and calcisiltites at many horizons in the Rochester Shale, particularly in the middle unit (C) of the Lewiston Member, and throughout the upper Rochester and DeCew Dolostone.

Amphistrophia-Dalmanites Association.—This low-diversity, brachiopod- and trilobite-dominated association, with about 25–30 species, characterizes the less fossiliferous shales of the Lewiston and Burleigh Hill Members. Most abundant fossils include the thin, flat-shelled orthids and strophomenid brachiopods *Amphistrophia striata*, *Coolinia subplana*, *Leptaena rhomboidalis*, *Parmorthis*, *Stegerhynchus*, the small inarticulate *Pholidops*, the trilobites *Dalmanites limulurus* and *Trimerus delphinocephalus* and the ostracode *Parachaemina*. Crinoids including *Dendrocrinus* and *Dimerocrinites* occur in clusters associated with this fauna. This fossil association appears to represent a mud-tolerant community typical of deeper, lower energy sea floors. Small, low-density skeletons of organisms may reflect adaptations to soft, unstable mud bottoms.

Striispirifer Association.—A somewhat more diverse (35–40 species) *Striispirifer* association contains many of the same elements as the


A
Height Above Base of Rochester Shale m
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
0 10 20 30 40 50 60
a)
% Carbonate Interbeds
b)
Species Richness
20
56
52
41
10
5
24
29
37
39
c)
E b b b D A A C H L P P S W C S D B D T
c f c r r s r s c r e t n n o a D l l d
Distribution of Common Species


B
Height Above Base of Rochester Shale m
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
0 10 20 30 40 50 60
a)
% Carbonate Interbeds
b)
Species Richness
11
4
16
10
c)
E b b b D A A C H L P P S W C S D B D T
c f e r r s r s c r e t n n o a l l l d
Distribution of Common Species

Amphistrophia-Dalmanites assemblage, but has, in addition, a great abundance of spiriferid and atrypid brachiopods, fenestellid bryozoans, dendroid graptolites, trilobites such as *Calymene* and *Arctinurus*, and echinoderms such as *Asaphocrinus*, *Homocrinus*, and *Caryocrinites*. Sporadic beds of *Striispirifer* occur as extremely high density shell pavements. This is the typical "*Striispirifer* community" of Boucot (1975).

Atrypa-Bryozoan Patch Association.—Bryozoan clusters (Fig. 5) constitute the most diverse fossil assemblages of the Rochester Shale; 60 to over 100 species may be present. These occur as lenticular masses of ramose and fenestellid bryozoans, frequently dominated by *Chilotrypa ostiolata* and *Hallopora elegantula*. Virtually all of the fossils found in the *Striispirifer* assemblage can also be found in this association, although these forms are relatively rare. Brachiopods are dominated by *Atrypa*, *Plectatrypa*, *Whitfieldella nitida*, *Howellella crispa*, *Dicoelosia biloba*, and *Sceninoides*. Trilobites are typified by *Bumastus*, with lesser numbers of *Dalmanites* and *Calymene*. The echinoderms *Caryocrinites ornatus* and *Stephanocrinus angulatus*, commonly associated with bryozoan patches, are frequently directly attached by holdfasts to bryozoan zooaria (see Brett, 1978b). Low-sedimentation rates combined with generally low-energy settings probably favored the growth of local thickets of bryozoans on skeletal substrates (Brett, 1978a).

Encrinite Association.—Local thin beds in the base and top of the Lewiston Member contain crinoidal biosparites similar to those of Irondequoit and Gasport Limestones. A survey of disarticulated plates and holdfasts of pelmatozoan echinoderms (Brett, 1978a) reveals an abundance of the camerate crinoids *Eucalyptocrinites*, *Dimerocrinites*, and *Saccocrinus*, flexibles such as *Lecanocrinus*, the rhombiferans *Caryocrinites* and *Callocystites*, and large specimens of the coronoid *Stephanocrinus*. The brachiopods *Atrypa*, *Whitfieldella*, *Coolinia*, and large specimens of *Leptaena* are also abundantly associated. Fragmentary ramose and fenestellid bryozoans are relatively common though not as abundant in lower Rochester bryozoan patches. The generally disarticulated and sometimes abraded nature of fossils, association with well-washed biosparites, and sedimentary structures including planar- and cross-lamination indicate that this faunal association occurred in very shallow, agitated waters, crinoidal shoals, or banks.

Fistuliporoid Bioherms.—These comprise small mounds of laminate fistuliporoid bryozoans, often with a large component of structureless micrite, possibly algal boundstones (Hewitt and Cuffey, in prep.). A *Whitfieldella*-atrypid brachiopod association characterizes these mounds, and shale-filled pockets within the mounds may contain large specimens of the trilobites *Calymene* and *Bumastus* (see Mikulic 1981). Pelmatozoans including *Eucalyptocrinites* and *Stephanocrinus gemmiformis* were associated with and attached by holdfasts to the surfaces of these mounds.

The lamellar growth forms of these bryozoans, possible algal structures (including rare receptaculitids), and the association of bryozoan mounds with well-washed biosparites again suggest that the mounds grew in shoal settings.

Distribution of faunal associations within the Rochester Shale closely parallels that of lithofacies (Fig. 13). Along the Niagara Escarpment, encrinites and fistuliporoid mound associations occur in the basal Rochester and

FIG. 13.—Graphical summary of vertical changes in lithology and fauna of the Rochester Shale at two locations along east side of Niagara Gorge. *A*) 0.5 km north of Robert Moses Power Plant, and 2.3 km south of Lewiston, New York. *B*) Exposures at site of (collapsed) Schoelkopf Power Plant, 0.8 km north of Niagara Falls, New York. Location A is about 6.5 km north of Location B. Features shown for each location are as follows: *a*, percentage thickness of two types of carbonate interbeds, (thickness of interbed lithology per meter of section); solid line: calcarenites (biomicrites and biosparites); dotted line: calcisiltites (pelmicrites and pelsparites); *b*, species richness (number of species collected in bulk samples of approximately 10 kgm); *c*, vertical distribution of common fossil species, solid thin line denotes presence of species; thick line denotes abundant occurrence (5% or more of total assemblage); dashed line indicates probable occurrence, unconfirmed by bulk sampling. Symbols for fossil species include: rugose coral, Ec: *Enterolasma caliculum*; bryozoans, bf: fenestrate bryozoans, be: encrusting bryozoans, br: ramose bryozoans; graptolite, Dr: *Dictyonema retiforme*; brachiopods; As: *Amphistrophia striata*, Ar: *Atrypa "reticularis"*, Cs: *Coolinia subplana*, Hc: *Howellella (Heidina)crispa*; Lr: *Leptaena "rhomboidalis"*; Pe: *Parmorthis elegantula*; Pt: *Plectodonta transversalis*; Sn: *Striispirifer niagarensis*; Wn: *Whitfieldella nitida*; pelmatozoan echinoderms, Co: *Caryocrinites ornatus*; DD: *Dendrocrinus* spp. and *Dimerocrinites* spp.; trilobites; Bi: *Bumastus ioxus*; Dl: *Dalmanites limulurus*; Td: *Trimerus delphinocephalus*.

Irondequoit transition, and again, rarely, near the top of the Lewiston Member. The bryozoan-patch facies occurs symmetrically in units B and D of Lewiston, respectively. The *Striispirifer* association occurs in the transition zones between Unit C and the underlying and overlying units, whereas the sparse *Amphistrophia*-trilobite association typifies the middle portion (C) of the Lewiston Member and the lower two-thirds of the Burleigh Hill Member. Southeastward from the Niagara Escarpment in the Niagara Gorge, the bryozoan-rich assemblages of the Lewiston Member tend to be replaced by the less diverse *Striispirifer* association. Near the southern end of Niagara Gorge nearly the entire Rochester Shale is very sparsely fossiliferous and contains only rare members of the *Amphistrophia*-trilobite association. The ichnofossil association occurs sporadically in calcisiltites and thicker beds of argillaceous carbonate (DeCew Dolostone).

The various faunal assemblages also tend to show a close association with particular types of storm deposits. Thus, for example, remains of ramose bryozoan patch association typically occur in wave-winnowed calcarenites, interbedded with relatively undisturbed samples of bryozoan patches. In contrast, members of the *Striispirifer* and *Amphistrophia* associations commonly occur at the bases of calcisiltites or mud layers.

The five main body fossil associations also show varying degrees of taphonomic disturbance. Preservation of fossils is poorest in the encrinite associations of the basal and upper portions of the Lewiston Member. Very high disarticulation ratios of brachiopods (>80%), as well as fragmentation, are observed within this fossil association. Biosparite beds near the base and, again, near the top of the Lewiston Member contain shells with reworked geopetal fillings. Abrasion and biocorrosion of fossils and glauconitic staining in these units also suggest prolonged periods of exposure and winnowing on the sea floor.

Atrypa-bryozoan patch associations in Units B and D of the Lewiston show somewhat better preservation of fossils (Brett, 1978a, p. 346–353). Disarticulation ratios in brachiopods are still moderately high (40–60%), but breakage and biocorrosion are relatively infrequent. Echinoderms and trilobites are largely preserved as disarticulated elements although whole trilobites and crinoid calyces do occur rarely. Pelmatozoan holdfasts, brachiopods, and some bryozoans within these beds occur preserved in life position, suggesting that certain bryozoan patches have simply been buried in place and not later reworked.

The best-preserved fossil horizons contain abundant, complete crinoids, trilobites, and graptolites, as well as many articulated brachiopods occurring in the *Striispirifer* and *Amphistrophia* associations, particularly in Unit C of the Lewiston Member or in the middle to upper Burleigh Hill Member (for example, *Homocrinus* band, *Eucalyptocrinites* bed; Brett, 1978a; Brett and Eckert, 1982). These apparently represent patch communities that were rapidly buried by muds and were not later disturbed in any way. This is suggestive of a low-energy, muddy environment near the lower limit of storm affects.

Taken together, qualitative preservational data indicate a rough taphonomic gradient from the *Amphistrophia* to the encrinite association. This spectrum of fossil preservation appears to reflect the increasing frequency of bottom disturbance by waves and currents in going from deeper basinal areas to high-energy shoal settings. As such, taphonomic interpretation accords well with bathymetric inferences based on the frequencies of storm deposits.

DEPOSITIONAL ENVIRONMENTS OF THE ROCHESTER SHALE

General Depositional Setting of the Rochester Shale

The sediments of the upper Clinton Group were deposited in a relatively shallow epeiric sea near the northern end of the gently sloping Appalachian Basin. A tectonically active (Taconic) source area southeast and east of New York State supplied terrigenous sediments to the adjacent epeiric sea basin. Slight uplift of this Taconic landmass immediately prior to deposition of the Rochester Shale may have produced an increased influx of terrigenous sediment into the basin.

Subsurface data suggest that, during Rochester Shale deposition, the northeast-southwest trending axis of maximum subsidence of the Appalachian Basin lay in central New York State (see p. 963; Fig. 14). The Rochester Shale thins slightly southeast from this area as it grades into the Herkimer-Keefer sandstones (Fig. 14). The western Joslin Hill facies of the Herkimer

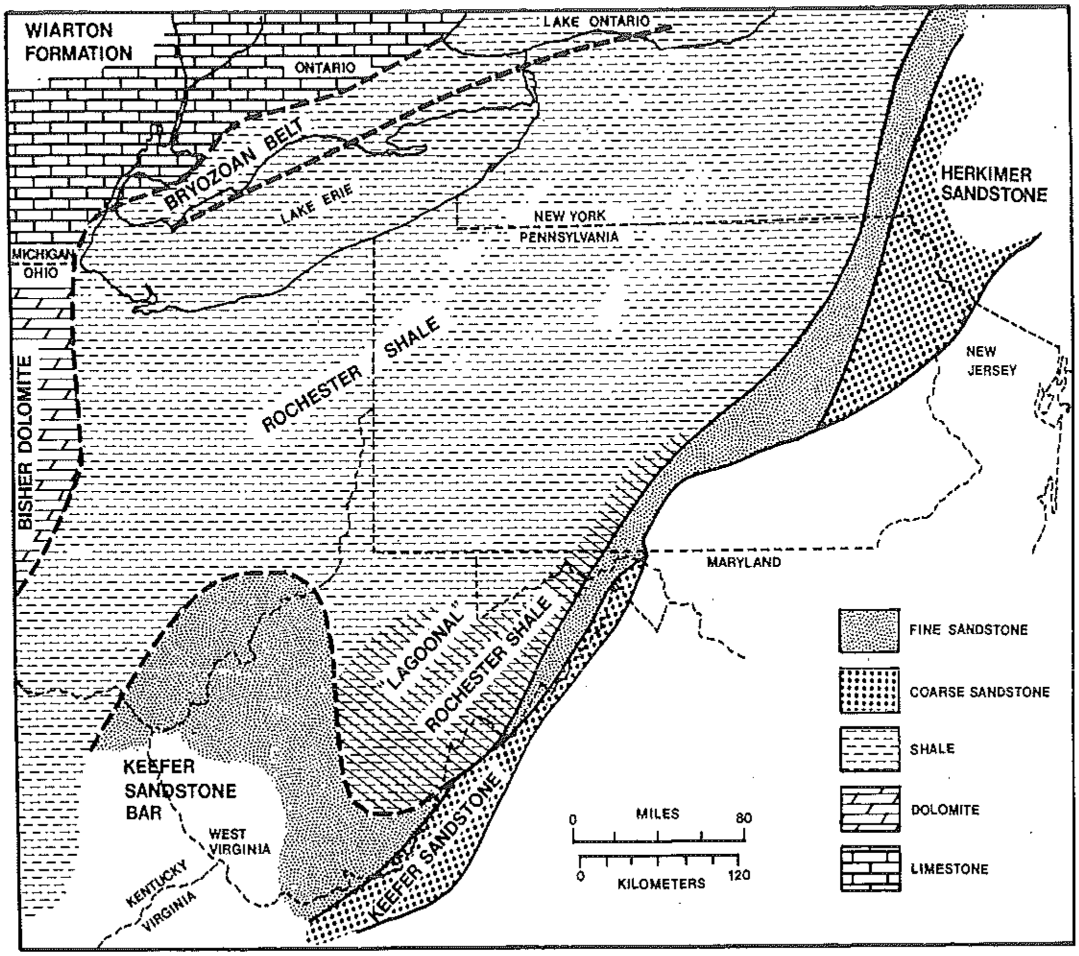


FIG. 14.—Generalized facies map of the Rochester Shale and associated, coeval facies, in the Appalachian Basin. Modified from Hunter (1970).

is interpreted as a shallow subtidal, sandy deposit, whereas the more eastern Jordanville Member represents beach and bar deposits (Zenger, 1966). Distribution of these sandstones suggests a northeast-southwest orientation of the eastern paleoshoreline. The source area for the Herkimer-Keefer and Rochester clastic sediments lies to the east and southeast of New York State. Westward migration of the eastern shoreline during the Irondequoit-Rochester transition may have resulted from progradation of sediment from the Taconic source area (Gillette, 1947).

During Rochester deposition, the Appalachian Basin was bordered on the northwest by a carbonate platform-crinoidal shoal complex in the area of the Algonquin Arch (Bolton, 1957; Caley, 1970). This area evidently provided some allochthonous carbonate to the basin, but essentially no terrigenous sediments (Figs. 12, 14). Toward the west and northwest, the Rochester Shale also thins and interfingers with the carbonate platform sediments of the Irondequoit, Wiarton (Amabel), and Gasport Formations (Hunter, 1970). These formations yield abundant sedimentologic evidence—such as winnowing of fines and cross-stratification of comminuted crinoidal debris—suggesting deposition in high-energy shoal environments, frequently above wave base (Crowley, 1973). Thus, these carbonates are generally considered to represent shelf settings shallower than gray shale and fine-grained dolostone facies (Hunter, 1970).

Aside from the anomalous black shale facies (lagoonal?) of West Virginia (Folk, 1962), the Rochester Shale represents the deposition of muds in a normal marine, relatively shallow subtidal (inner neritic) setting. Sedimentologic and taphanomic evidence indicates a generally low-energy environment punctuated by occasional bursts of higher energy sedimentation, probably during storms (Thusu, 1972; Narbonne, 1977). Paleogeographic reconstructions of North America during the Silurian (Seyfert and Sirkin, 1973; Ziegler et al., 1977; Bambach et al., 1980) indicate that New York lay about 15° south of the paleoequator, thus in a tropical climatic belt. A tropical position for the Appalachian Basin could have placed the epeiric seas within the pathway of severe tropical storms (hurricanes) (see Kreisa, 1981). The Rochester Shale and synjacent units yield evidence for storm-influenced shelf sedimentation, as noted above.

Slight latitudinal shifting of North America and/or orographic effects during the medial Silurian may have resulted in a change from humid to arid tropical conditions. Hunter (1970) noted a marked decrease in iron content in the uppermost Clinton rocks and a virtual absence of iron-rich rocks in the overlying Lockport Group. He further suggested, as a cause, decreased rainfall, possibly related to lowered relief of the Taconic uplands. Associated with this greater aridity is possible evidence of a slight increase in salinity during the latest Clinton deposition. Rochester Shale sediments were certainly deposited in seas of normal salinity in most areas, as indicated by widespread occurrence of stenohaline organisms (for example, crinoids). But restricted fauna and possible primary dolomite in the overlying DeCew Formation may indicate slightly hypersaline conditions at the end of Rochester deposition (Hunter, 1970; Nairn, 1973; Crowley, 1973).

Irondequoit-Lower Rochester Sequence

Carbonate sediments of the Irondequoit Limestone accumulated over a rather broad region during a time of low clastic sedimentation. Conditions favorable for the growth of crinoids, bryozoans, brachiopods, and other benthic invertebrates existed over much of New York State and adjacent Ontario at this time. Petrological studies by Freedenberg (1975) suggest that the Irondequoit represents a crinoid bank deposit, formed in shallow, moderate- to high-energy environments, as indicated by poorly to well-washed biosparite, presence of small-scale cross-laminae, intraclasts at the base of the unit, and the comminuted nature of most fossils. The occurrence of small bioherms formed of lamellate fistuliporoid bryozoans and algae is further indicative of shallow-water deposition. The Irondequoit Limestone appears to merge with the overlying crinoidal carbonates of the Amabel Group, indicating a persistence of the crinoid biofacies during Rochester mud deposition farther southeast (Figs. 14, 15).

Gradation of the Irondequoit into Unit A of the Lewiston Member of Rochester Shale at most western New York localities, and the persistence of Irondequoit fauna, including its fistuliporoid bryozoan bioherms, from the limestone into the overlying shale, suggests a rather gradual transition to more muddy initial Rochester depositional conditions. Farther west, near Grimsby and Hamilton, Ontario, the Irondequoit/Rochester contact is sharply defined, and the development of local encrusted hardgrounds on the upper surface of the Irondequoit at Grimsby (Brett, in press) indicates that a discontinuity surface exists at this contact.

The highly condensed section of the Rochester Shale (Lewiston Member?) at Clappison Corners, Ontario, probably accumulated near the crest of Algonquin Arch. Intraclasts of dolomitic shale were probably derived locally by erosion of previously deposited Rochester sediments. The provenance of rounded quartz grains is unknown; these grains may have been moved by longshore transport from southeastern source areas or they may be derived from the Precambrian shield nearby to the north. A high-energy environment probably existed along the Algonquin Arch throughout much of Rochester Shale deposition farther southeast; the winnowing of fine-grained sediments resulted in a very thin shale section. As noted below, this condensed crinoidal intraclastic facies of the Wiarton shoal grades southeastward into dolomitic shales and argillaceous limestones or dolostones (argillaceous carbonate belt, see below).

The most fossiliferous sections (B, D, and E submembers) of the Lewiston Member, which crop out along the Niagara Escarpment between Brockport, New York, and Grimsby,

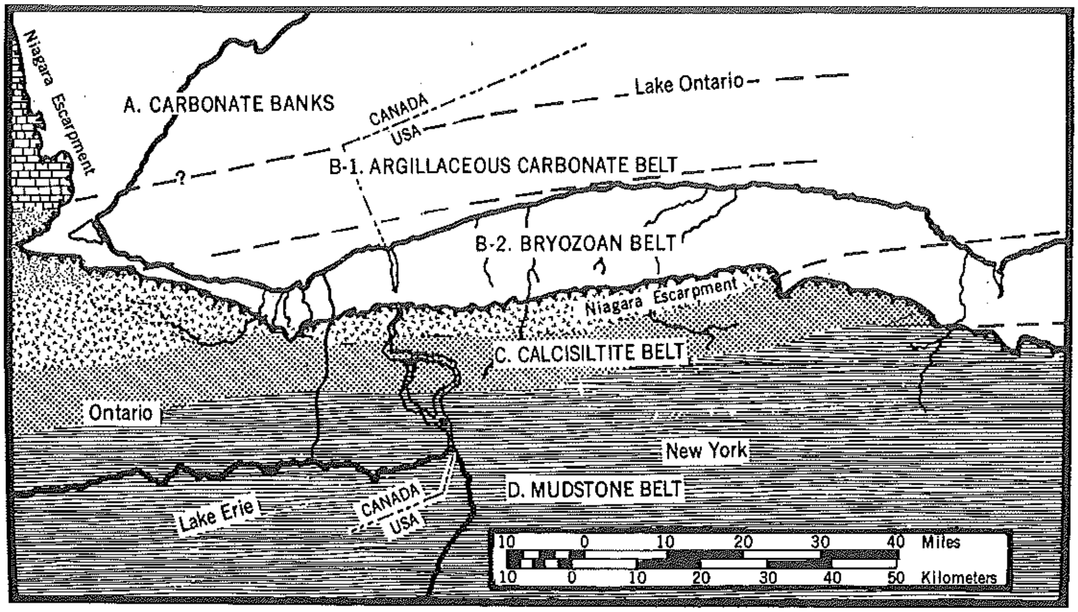


FIG. 15.—Facies map for Rochester Shale in Ontario and western New York State. Reconstruction shows approximate geographic position of facies belts during deposition of the upper part of the Lewiston Member (Submember E). Note parallelism between facies belts and present Niagara Escarpment.

Ontario, are interpreted as deposits that accumulated in the northeast-southwest trending environmental belt (bryozoan belt), which was particularly favorable to bryozoan growth (Fig. 15). This region of the Rochester sea floor probably lay below normal wave base but well within reach of deeper storm waves, as indicated by lenticular bryozoan-rich biosparites and occasional intraclasts within the limestones. The location of this belt was controlled largely by depth or sedimentation, and it fluctuated slightly during Lewiston deposition. Recent bryozoans are often sensitive to siltation, and this was likely an important factor in controlling the distribution of Silurian forms as well. This Silurian bryozoan belt strikingly resembles bryozoan-rich zones off the modern Rhône delta (Lagaaij and Gautier, 1965, p. 46).

Unfortunately, the northern edge of bryozoan belt has been largely removed by post-Silurian erosion, but some indication of its nature can be inferred from the westernmost outcrops of the Rochester Shale in the vicinity of Hamilton, Ontario. A maximum development of the bryozoan facies in the lower Rochester was observed near Grimsby, Ontario, where the entire lower member of the formation (except for the basal meter) is richly fossiliferous and contains numerous bryozoan-rich limestones. West of this location, the character of the Lewiston Member changes rapidly, and at Fruitland, only 10 km west of Grimsby, it consists dominantly of silty dolomitic shale with only a few dolomitized bryozoan limestone lenses. This aspect of the Lewiston Member (argillaceous carbonate belt), which persists into the Hamilton area, suggests that bryozoan growth was somewhat restricted in the northwestern depositional area. An increase in burrowed silty dolostone (originally calcisiltite) or fine calcarenite in this area indicates that the controlling factor may have been the deposition of silt- to fine sand-sized carbonate sediment. Interbedded stringers of well-sorted crinoidal debris, which grade upward into dolomitic siltstones, reflect intermittent influx of current-winnowed skeletal debris from the so-called Wiarton crinoid banks that lay immediately northwest of the Hamilton area during Rochester deposition. Crowley (1973) has determined a similar source for the DeCew Dolostone. At times when the influx of debris from the northwest became less intense, the sea floor was populated by bryozoans and other organisms.

Outcrops near the south end of Niagara Gorge and in the southern end of the Fonthill Reentrant, as well as those in west-central New York, indicate that the area lying immediately southeast of the bryozoan belt was a lower energy, muddy, basinal area characterized by mudstone and carbonate silt deposition. This region received a larger input of terrigenous sediments than the areas to the north, as well as occasional storm layers of carbonate silt (pellets and fine skeletal debris), now represented by thin, persistent calcisiltite bands. Hence this facies is termed a "calcisiltite belt" (Fig. 15). Detrital carbonate was probably winnowed from carbonate shoal areas, including the bryozoan belt to the northwest, and transported downslope as suspension clouds or density currents (Fig. 12). Farther south, subsurface data indicate that calcisiltites also become scarce, the entire deposit consisting instead of calcareous mudstone (mudstone belt). The fine grain size and absence of sedimentary structures indicate deposition of terrigenous muds in relatively quiet, possibly deep water of the central Appalachian Basin, which occupied south-central New York, Pennsylvania, and southern Ontario. This low-energy, muddy environment was apparently favorable for a variety of brachiopods, notably the *Striispirifer* and *Amphistrophia* associations. However, many of the bryozoans and echinoderms which typify the lower Rochester Shale along the western escarpment were apparently excluded from that southern area.

Thus, at any given time, during deposition of the Lewiston Member, an array of subparallel east-west trending lithofacies existed; from north to south these were a) Wiarton crinoid bank-biohermal, b) argillaceous carbonate, c) bryozoan, d) calcisiltite, and e) mudstone belts. Corresponding biofacies include a) encrinite-fistuliporoid bioherm, b) trace fossil, c) *Atrypa*-bryozoan cluster, d) *Striispirifer*, and e) *Amphistrophia*-trilobite associations.

Fluctuation of these environmental-facies belts is indicated by detailed stratigraphic studies of the Lewiston Member (see above). The bryozoan belt facies appears to have been established with the onset of Rochester clastic deposition, as indicated by a transition from crinoid-brachiopod-rich limestone of the Irondequoit into interbedded shale and bryozoan-rich limestone of the lower Rochester at many localities in western New York. An apparent upward increase in the percentage of barren shale and calcisiltites in the lower half of the Lewiston Member (units A–C) suggests that the bryozoan belt shifted northward through time as a result of minor transgression or increased sedimentation rates. Reappearance of bryozoan-rich beds in the Lewiston Member above submember C indicates that the environment of the bryozoan belt again migrated southward toward the close of Lewiston deposition.

Sedimentologic and taphonomic evidence suggests that the lowest and highest portions of the Lewiston Member were deposited under shallower water than the intervening sediments. Hence, the Lewiston Member as a whole constitutes a single subsymmetrical transgressive-regressive cycle, with unit C representing maximum northward transgression. This interpretation is further supported by the southward (basinward) thickening of the barren shale and calcisiltite facies (unit C). Conversely, the upper bryozoan-rich beds (unit E) show a rapid southward rise (in concert with the thickening of unit C) and a thinning out to a single 5-cm band.

A probably analogous sequence in eastern New York State is represented by the Kirkland Hematite-lower Rochester-Rochester "lean iron ore" sequence (Gillette, 1942). Again, both the basal and middle portions of the Rochester Shale show evidence of deposition under shoaling conditions, conducive to the formation of oölithic hematites, whereas the intervening shales represent quieter conditions farther offshore.

Upper Rochester-Gasport Sequence

One of the most striking features of the Rochester Shale in western New York and Ontario is the break between the uppermost bryozoan-rich limestone of the Lewiston Member and the overlying barren shales or shaly dolostone of the Stoney Creek-Burleigh Hill Members. The lower part of the Burleigh Hill Member is nearly barren, well laminated, dark gray shale; the unit then shows an upward increase in burrowed calcisiltites and ultimately grades into dolomitic shale or argillaceous dolostone of the DeCew Formation. The base of this sequence strongly resembles the middle unit (submember C) of the Lewiston Member, both faunally and lithologically, and is interpreted as indicating a recurrence of deeper water depositional conditions than the underlying bryozoan beds (that is, mudstone and calcisiltite belts). On the other hand, sedimentary structures near the top of the Burleigh Hill and throughout most of the Stoney Creek Member suggest deposition in shallower water; these include dolomitic siltstone with medium-scale cross bedding and cross lamination, vertical and oblique burrows, abundant storm deposits, beds of oriented *Tentaculites* and crinoid columnals, drag marks, ripples and stringers of crinoidal sand, and some beds of dolomitic shale intraclasts. Well-preserved accumulations of fossil crinoids and some vertically embedded crinoid stems up to 6 cm long point to intermittent scouring and rapid deposition of silty sediments.

Furthermore, the upper Burleigh Hill and Stoney Creek units are clearly transitional into the overlying DeCew Dolostone, which has been interpreted by Crowley (1973) and Nairn (1973) as dolomitic carbonate silt accumulation in a restricted shallow water environment in front of the advancing Gasport (= Wiarton, in part) crinoid bar. Fine-grained calcareous sediments which comprise up to 60 percent of the upper Rochester Shale and DeCew Dolostone were probably derived from winnowing of the crinoid bank (Crowley, 1973). Indeed, some of the silty upper Rochester Shale contains minute crinoid ossicles.

Together, this evidence suggests a rapid transgressional phase followed by upward shoaling of the Rochester sea. The Burleigh Hill-Stoney Creek members are thus interpreted as an upward, regressional hemicycle. Unlike the lower Lewiston Member, which is subsymmetrical, there is apparently little record of the upper Rochester transgressive phase. Thus, the Burleigh Hill pattern is consistent with the PAC (Punctuated Aggradational Cycle) model of epeiric sea sedimentation proposed by Anderson et al. (1978), whereas the lower Rochester seemingly would imply that the model is not invariably applicable.

A rarity of bryozoans and a paucity of other fossils from the uppermost Rochester is problematical. Seemingly, during Burleigh Hill-Stoney Creek deposition, the argillaceous-carbonate belt largely displaced the bryozoan belt. This situation may have resulted from a variety of causes. First, as noted above, there is evidence for intermittent rapid sedimentation as well as agitation of the bottom, so as to resuspend fine calcareous silts and muds. Secondly, the strongly bioturbated character of the upper Rochester, which is particularly evident in the Hamilton area, suggests that this portion of the Rochester sea floor was inhabited chiefly by infaunal burrowers. The activity of such organisms may, in turn, have rendered the sea floor uninhabitable to most epifaunal organisms. Restricted circulation of the sea water may also have been a factor (Nairn, 1973), although the occurrence of scattered patches of brachiopods, trilobites, and crinoids throughout the interval argues against drastic changes in salinity or water chemistry in general.

In contrast to the completely gradational lower contact of the DeCew Dolostone with the upper Rochester, the upper DeCew is truncated abruptly by the overlying Gasport crinoidal limestones. This sharp upper contrast marks the migration of crinoid sand over these finer sediments. Migration of the crinoid bank may have proceeded in a stepwise manner, initiated by spreading of a blanket of skeletal sands by currents outward from the existing bank edge (Crowley, 1973). In many cases, initial deposition was preceded by a period of scouring of older deposits, so that clasts of DeCew Dolostone were ripped up and incorporated into the basal Gasport crinoidal sands. As skeletal sands became stabilized, they provided suitable areas for colonization by crinoids and other organisms. In turn, the debris of these organisms was eventually swept forward providing substrates for further colonization. In places, biohermal buildups, dominated by stromatoporoids and tabulate corals, developed on this platform of skeletal debris (Crowley, 1973; Crowley and Poore, 1974). Such patch reefs were further colonized by various pelmatozoan echinoderms, as indicated by in situ holdfasts on the reef surfaces and abundant, well-preserved calyx and stem remains in their flank sediments.

A shallow-water, high-energy environment for the Gasport is clearly indicated by the occurrence of biosparite, cross-bedding of crinoidal debris, DeCew intraclasts, overturned coral and stromatoporoid heads, as well as reef buildups. Crowley (1973) also provided evidence for shallow submergence or even subaerial exposure of reef tops at the close of Gasport deposition.

DISCUSSION

Dennison (1970) and Dennison and Head (1975) used a variety of stratigraphic, sedimentologic, and paleontologic criteria to infer eustatic or basinwide fluctuations in sea level within the Appalachian Basin during the Silurian and Devonian periods. They postulate two intervals of lowered sea level during the middle and upper Niagaran or Wenlockian Epoch. Based on the basinward extension of paralic sheet sands and oölitic hematite seams (Keefer Sandstone), Dennison (1970) postulated a major regressive-transgressive cycle. Dennison and Head (1975) suggested that the Irondequoit Limestone of western New York corresponds to this sea-level drop, and they speculated that the overlying Rochester Shale was deposited during subsequent transgression.

A shallowing of lesser magnitude than that associated with the Keefer-Irondequoit deposition probably occurred near the end of the Wenlockian. This is reflected by a redbed (Rabble Run Member) and sandstone tongue within the McKenzie Formation of Maryland and West Virginia (Travis, 1962). Dennison and Head (1975, p. 1098) correlate this event with erosion surfaces recognized by Crowley (1973) at the tops of bioherms in the Gasport Limestone. The lithologic and faunal similarity of the Gasport to the Irondequoit indicates that both were deposited under nearly identical depositional conditions in western New York, although the Irondequoit extends considerably farther southeastward into the Appalachian Basin than does the Gasport. This strongly suggests that the Gasport Formation itself resulted from a widespread regressive event similar to, but of lesser extent than, that which produced the Irondequoit. Erosional tops of Gasport bioherms may represent the final and most extensive phase of the late Wenlockian regressive episode.

As noted earlier (Fig. 1), the Irondequoit and Gasport appear in north-south cross sections as two basinward extensions of the Wiarton crinoid bank facies. It is evident that these tongues define a large-scale transgressive-regressive cycle comprising the Irondequoit-Rochester-DeCew-Gasport. Dennison and Head (1979) had suggested that the Rochester Shale was deposited during a single rise of sea level, but the Rochester subdivisions indicate that this is an overly simplistic view. Detailed stratigraphy of the Rochester reveals evidence for a minor regressive event, of lesser magnitude than that which produced the Irondequoit or Gasport limestones, during the middle of Rochester Shale deposition. This event is reflected by a crinoidal biosparite tongue at the base of the Stoney Creek Member in Ontario, the bryozoa beds of the Lewiston Member, a middle limestone in the Rochester Shale in Wayne County, and perhaps a "lean iron ore" near the center of the Rochester Shale in central New York (Gillette, 1940, 1947). These units locally separate the Rochester Shale into upper and lower members, each of which represents a smaller scale transgressive-regressive cycle. In western New York, the lower cycle, comprising the entire Lewiston Member, is by far the more complete and is nearly symmetrical. In contrast, the upper unit (Stoney Creek-Burleigh Hill) is highly asymmetrical and represents only an upwardly regressional hemicycle. Predictably, in outcrops toward the center of the basin, for example, in the Genesee River Gorge, these smaller cycles are less obvious, and the entire section takes on a more monotonous, homogeneous aspect.

CONCLUSIONS

1) Stratigraphic evidence strongly suggests that Rochester Shale facies occurred in elongate east-west trending belts subparallel to the present Niagara Escarpment. Layer-cake stratigraphy observed in Rochester Shale outcrops reflects parallelism of outcrop- and facies-belt orientations.

2) The Rochester Shale consists of bioturbated gray mudstone with abundant carbonate interbeds, including intrasparites, lenticular biosparites and biomicrites (= calcarenites), and laminated unfossiliferous pelmicrites (= calcisiltites). These units, together with "smothered bottom layers" (well-preserved fossil assemblages), provide evidence for episodic storm deposition. Carbonate sediments were concentrated and locally transported by storm-wave action on a gently sloping shelf. Intraclastic limestones and coarse calcarenite lenses formed as erosion-lag deposits in areas within storm-wave base, and thus characterize the shallowest water depositional settings; they typify the lower and upper parts of the Lewiston Member and, to a lesser extent, the upper Burleigh Hill Member. Finer debris was winnowed from shoal areas, forming suspension clouds which moved down a southward-facing

paleoslope, depositing storm-silt (calcisiltite) and mud layers, in slightly deeper water environments. Such deposits are typical of the middle Lewiston (submember C) and lower Burleigh Hill members.

3) The general depositional environment of the Rochester Shale in Ontario and western New York is envisaged as a shallow (less than 50 m), gently southeastwardly sloping muddy shelf. This region was bordered on the southeast by a sandy shoreline and on the northwest by carbonate shoals. A hypothetical northwest to southeast transect would include the following facies: A) *crinoidal bank-biohermal facies* (Wiarton), coinciding with the Algonquin axis; B) either an *argillaceous-carbonate facies* reflecting mixed terrigenous and detrital carbonate sedimentation (portions of Lewiston, Stoney Creek and upper Burleigh Hill Members), or a *bryozoan calcarenite facies* consisting of abundant patches of ramose bryozoans, and associated diverse brachiopods, echinoderms, and other fossils, formed during times of low-sedimentation rates (Lewiston B, D, and E); C) a *calcisiltite facies* comprising mudstone and interbedded barren, carbonate, storm-silt layers (Lewiston C, lower Burleigh Hill); D) a sparsely fossiliferous *mudstone facies* (undifferentiated lower Rochester Shale, lower Burleigh Hill in part).

4) Vertical facies changes in the Rochester Shale at a given section are attributed to lateral (north or south) shifts of environmental (facies) belts due to migration of a northern paleoshoreline. The Irondequoit to Gasport sequence constitutes a major transgressive-regressive cycle with two superimposed subcycles in the Rochester Shale. The Lewiston Member records a subsymmetrical cycle of a deepening (units submembers A–C) and shallowing (submembers C–E). In contrast, the upper unit (Burleigh Hill or Stoney Creek member) reflects aspects of an asymmetrical shallowing-upward hemicycle. The transgressive portion of this sequence is poorly preserved or absent and is usually represented by a slight disconformity: the contact between calcarenites of Lewiston E submember and upper (Burleigh Hill) barren shales. Greatly increased allodapic carbonate sedimentation during deposition of the upper Burleigh Hill-DeCew interval inhibited the growth of bryozoans in shallow water and so prevented the development of bryozoan facies analogous to those observed in the Lewiston Member.

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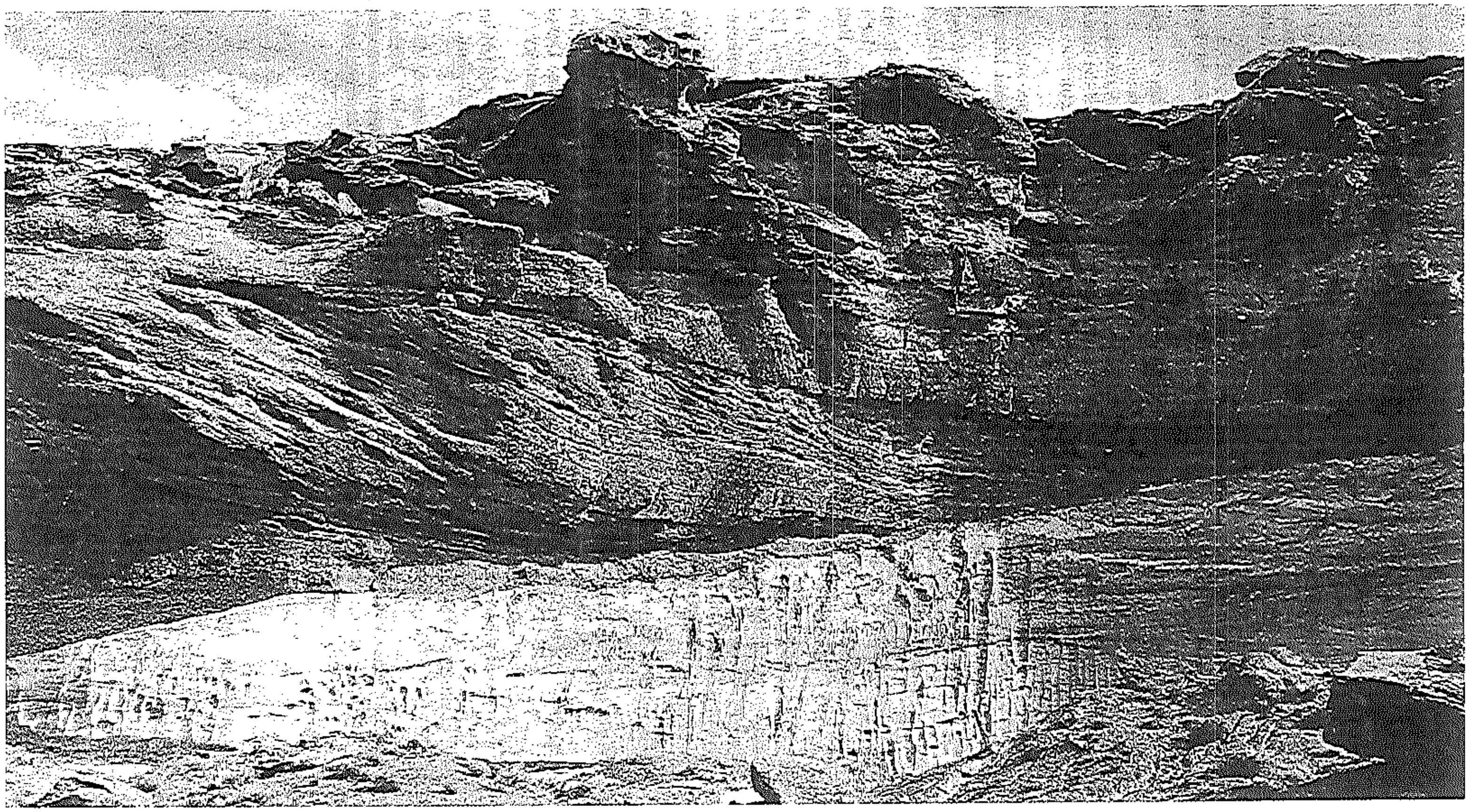
SEDIMENTOLOGY PHOTO BY BARBARA A. AM ENDE



Lateral accretion surfaces in conglomerate of the Cretaceous Dakota Formation near Glen Canyon City, Utah. Photo shows a portion of the east flank of a broad, 10-m-deep channel. Flow was nearly perpendicular to the observer (NNE). The channel is cut into the eolian Entrada Sandstone (Jurassic). After partial channel filling (not shown in photo), lateral accretion bars developed. Their thickness suggests that the paleochannel was about 5 m deep. Photo by Barbara A. am Ende, Department of Geology, Northern Arizona University, Flagstaff, Arizona 86011.