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Nigel C. Hughes
Cincinnati Museum Center
1720 Gilbert Avenue
Cincinnati, Ohio 45202

Stephen P. Hesselbo
Department of Earth Sciences
University of Oxford
Parks Road
Oxford OX1 3PR, United Kingdom

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ABSTRACT

New collections of fossils and description of stratigraphic sections through the St. Lawrence Formation in the Upper Cambrian of the northern Mississippi Valley provide the basis for reassessment of the stratigraphy and sedimentology of this unit. The Formation contains three lithofacies groups: 1) heterolithic dolomicrite, siltstone and sandstone; 2) flat-pebble conglomerate and laminated sandstone, and 3) stromatolitic dolomite. Deposition occurred in marine conditions on a shallow shelf; evidence for periodic exposure within the heterolithic facies is equivocal. The biozonation of the Formation is described, and correlation with other areas of North American clarified. In the northern Mississippi Valley area the *Saukia* Zone comprises three subzones, in ascending order: *Illaenurus priscus*, *Osceolia osceola* and *Saukia*, with a possibly distinct *Plethopeltis* fauna at the top. Consideration of biostratigraphic, lithostratigraphic, and sedimentologic data suggests that the boundary between the St. Lawrence Formation and the overlying Jordan Formation is diachronous, being older in the north than the south. Sediments accumulated during a relative sea-level rise represented in the lower *Saukia* Zone (*I. priscus* to *O. osceola* subzones) and was terminated by a regressive phase represented in the middle to upper *Saukia* Zone (*O. osceola* and *Saukia* subzones through the *Plethopeltis* fauna). Hence, strata comprising the lower part of the Formation (commonly glauconitic flat-pebble conglomerates and fine sandstones), probably represent the offshore toe-sets of retrograding and aggrading shoreface sediments. The predominantly heterolithic upper part of the St. Lawrence Formation in the southern area probably represents the offshore toe-sets of rapidly prograding shoreface sediments.

INTRODUCTION

The 'Croixan' succession of the northern Mississippi Valley constitutes a thin widespread deposit, spread across a stable intra-cratonic area (Bell and others, 1956; Byers and Dott, 1978). The succession was used in the first half of the century to attempt a biostratigraphy for the North American Upper Cambrian. However, modern work, in the thicker and more fossiliferous deposits of western and southern North America, have shown that the northern Mississippi Valley succession is inadequate as a stratotype because it is highly incomplete. This inherent stratigraphic incompleteness was the basis for subdivision of the succession into large-scale 'sequences' or unconformity-bounded stratigraphic units by Sloss (1963, 1988).

In this paper we present detailed measured sections through the St. Lawrence Formation; mixed carbonate and siliciclastic deposits of Sunwaptan (Late Cambrian) age (Figs. 1, 2 and Appendix); these rocks constitute part of Sloss's (1963) 'Sauk Sequence'. The St. Lawrence Formation occupies a pivotal position in the uppermost Upper Cambrian succession, representing the thickest and most widespread development of carbonate facies within the outcrop belt, in an interval dominated by siliciclastic sediments. It was for this reason that Ostrom (1978) placed the top of one of his large-scale siliciclastic-carbonate cycles at the top of the St. Lawrence Formation. However, the paleoenvironment of the St. Lawrence Formation has proved particularly difficult to interpret in the past and it has been assigned to various depositional environments ranging from offshore marine (*e.g.* Runkel 1994a) to inter- or supratidal (*e.g.* Byers, 1978). Environmental analysis of the northern Mississippi

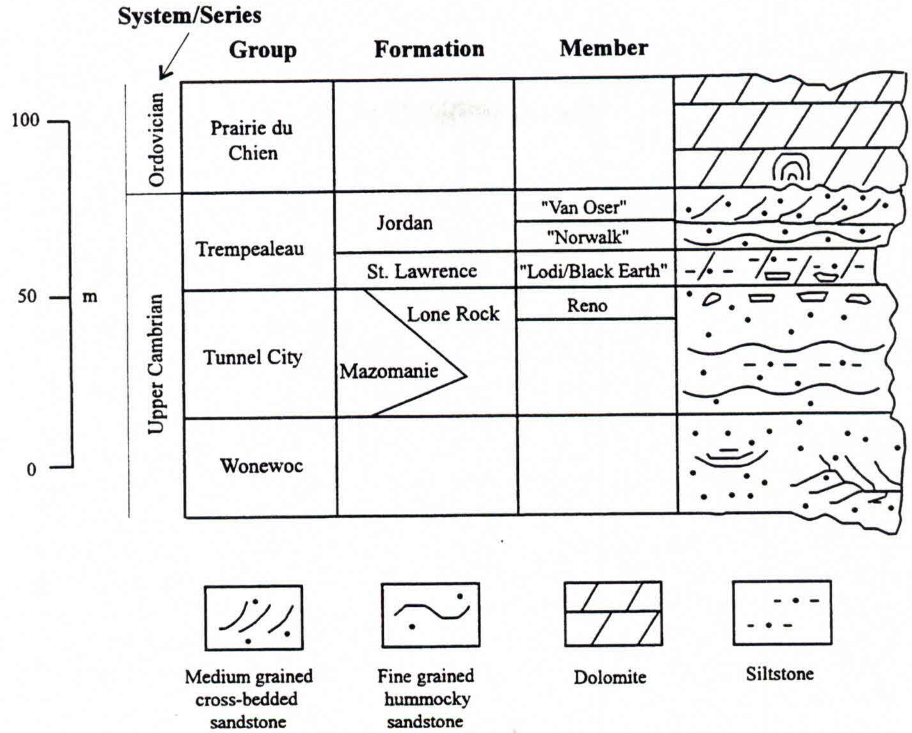

Fig. 1. Lithostratigraphy of the St. Lawrence Formation and adjacent units, modified from Byers and Dott (1995). Quotation marks around Member names indicate that these terms are of questionable stratigraphic value.

Valley Upper Cambrian is hampered by a lack of modern analogs for many of the sedimentary facies (Dott and others, 1986).

A discordance between zonal and lithofacies boundaries in the Upper Cambrian succession has been described by Berg (1954), Nelson (1956), Bell and others (1956) and McGannon (1960), but few detailed accounts of the best sections have ever been published. One aim of this paper is to document the faunal and lithologic succession of some of the best exposed St. Lawrence Formation sections (see Appendix). Recent morphometric analyses of the trilobite genus *Dikelocephalus*, abundant in these strata, has shown that fine biostratigraphic subdivision based on the species of this genus are invalid (Hughes 1994; Labandeira and Hughes 1994); species-level taxonomy of all Late Cambrian trilobites from this area is in need of substantial revision, and we consider it timely to consider the detailed stratigraphy of the St. Lawrence Formation in the light of these taxonomic changes and uncertainties. Locality information regarding the sections presented here, and others in the St. Lawrence Formation, are given in Hughes (1993).

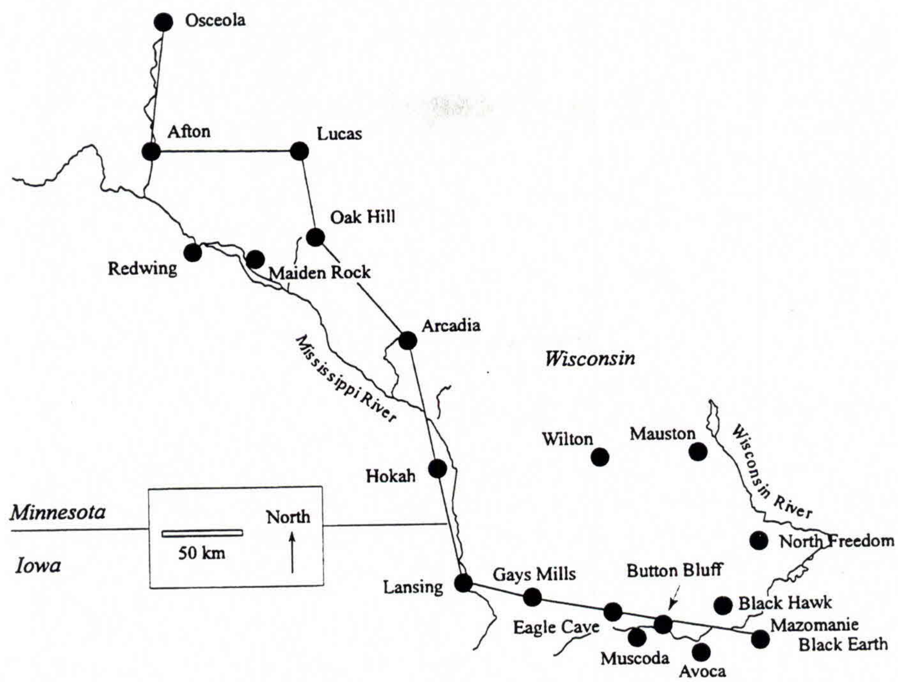

Fig. 2. Localities exposing the St. Lawrence Formation considered herein. Locality details are provided in Hughes (1993).

LITHOSTRATIGRAPHY

The St. Lawrence Formation (Fig. 1) has previously been divided into two members: a predominantly dolomitic Black Earth Member, generally overlain by the heterolithic Lodi Member (Nelson, 1956). The Black Earth Member is a heterogeneous grouping of stromatolitic dolomites, flat-pebble conglomerates and dissolution-affected sandy dolomites. The Lodi Member comprises finely interlayered dolomites ('siltstones') and very-fine sand. We have not found this member-level subdivision of the St. Lawrence Formation useful, partly because of their imprecise definition, and partly because the members do not represent contiguous rock units, nor even distinct environments of deposition. Instead we advocate recognition of lithofacies within the St. Lawrence Formation, an approach similar to that used by Runkel (1994a,b) for the overlying Jordan Formation.

Underlying the St. Lawrence Formation is the Tunnel City Group (Fig. 1); this can be subdivided into a relatively coarse-grained arenaceous facies, the Mazomanie Formation, and a fine-grained arenaceous facies, the Lone Rock Formation (Ostrom, 1967; Odom, 1978a). The junction between the Tunnel City Group and the St. Lawrence Formation frequently comprises a thin series of flat-pebble conglomerates (Owens, 1985; Sutherland, 1986). These beds have previously been classified with either the St. Lawrence Formation (Twenhofel and others, 1935) or the Tunnel City Group (Nelson, 1956).

Overlying the St. Lawrence is the Jordan Formation (Fig. 1), a sandstone unit divisible into two major facies; a very fine-grained feldspathic sand facies which occurs predominantly at the base of the Formation, and a fine to coarse grained quartzose sand facies which occurs mainly at the top (Runkel 1994b). A similar but threefold facies subdivision was used by Byers and Dott (1995) who, unlike Runkel (1994b), have retained the established lithostratigraphic scheme referring to the lower fine-grained facies as the Norwalk Member, and the upper coarser grained facies as the Van Oser Member (Odom and Ostrom, 1978). Locally the quartzose facies is reported to rest with a marked erosional contact on the feldspathic facies, or even on the St. Lawrence Formation (Ostrom, 1978; Odom and Ostrom, 1978), although we have not observed this in outcrop.

BIOSTRATIGRAPHY

St. Lawrence Formation biostratigraphy

The St. Lawrence Formation was deposited during Raasch's (1951) *Saukia* Zone of the northern Mississippi Valley, within the Upper Sunwaptan Stage (Ludvigsen and Westrop, 1985) (correlative with the Trempealeauan Stage of other workers) of Late Cambrian time. The base of the *Saukia* Zone lies within deposits of the Tunnel City Group. Its top is poorly defined, but may occur directly below the base of the Coon Valley Member of the Prairie du Chien Group (Runkel, 1994a). A comprehensive subdivision of the Sunwaptan Stage in the northern Mississippi Valley must rely on species-level taxonomy, and work on the dikelocephalid trilobites shows that the validity of many trilobite species from this interval is questionable (Hughes, 1994; Labandeira and Hughes, 1994; Hughes and Labandeira, 1995). Nevertheless we believe that the faunal succession can be usefully employed to subdivide the succession (see Fig. 3). In view of current taxonomic uncertainties this zonation is largely based at the generic level; exceptions include distinctive species of both *Illaenurus* and of the Dikelocephalidae.

The base of the Upper Sunwaptan Stage in the northern Mississippi Valley is marked by the appearance of dikelocephalid and advanced saukiid trilobites (*e.g. Dikelocephalus minnesotensis*, *Saukiella*, and *Calvinella*). Primitive libristomates that first occur in this interval within the northern Mississippi Valley include *Illaenurus*, *Macronoda* and *Euptychaspis*. *Illaenurus priscus* characterizes this unit (Nelson, 1951)(Fig. 4) and its first occurrence is used here to define the base of the *I. priscus* subzone (Fig. 3).

The interval immediately above the *I. priscus* subzone is defined by the first appearance of the dikelocephalid *Osceolia osceola*. Other trilobites that first appear in the northern Mississippi Valley along with *O. osceola* include *Illaenurus quadratus* and the genera *Plethometopus*, *Stenopilus*, *Tellerina*, *Eurekia*, *Corbinia* and *Bowmania*. *Osceolia* and *Rasettia* have not been found to co-occur within the area, but the possibility that *Osceolia* and *Rasettia* (then known as *Platycolpus*) were time-equivalent genera was raised by Nelson (1956). This assertion receives support from the stratigraphic position of *Rasettia* in the northern Mississippi Valley and in other areas of Laurentia, and the distinct preference of this trilobite for stromatolitic facies (Stitt, 1977, p. 17), to which it is restricted within the northern Mississippi Valley.

The succeeding subzone is characterized by the first occurrence of the genus *Saukia*. Other trilobites commonly associated with *Saukia* include *Dikelocephalus minnesotensis*,

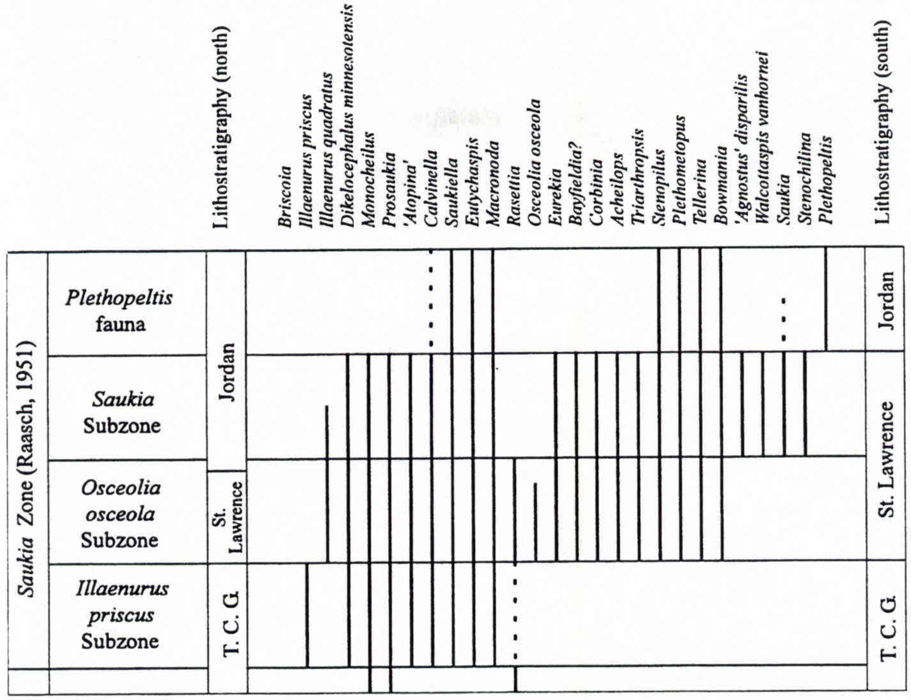

Fig. 3. Relative temporal distributions of trilobite genera in the Upper Cambrian of the northern Mississippi Valley. '*Saukia* Zone' is used in the sense of Raasch (1951). Due to uncertainties in the ranges of individual taxa and the degree of biostratigraphic resolution, taxa are generally shown to occupy the entire ranges of the zones in which they occur. Dashed lines indicate inferred or disputed occurrence. Data sources: Raasch (1935, 1939, 1951); Twenhofel, Raasch and Thwaites (1935); Stauffer (1940); Howell and others (1944); Nelson (1951, 1956); Berg, Nelson and Bell (1956), Raasch's unpublished fieldnotes and faunal lists held in the Milwaukee Public Museum and Geology Museum, University of Wisconsin, Madison, and our own fieldwork. T.C.G. = Tunnel City Group.

Illaenurus quadratus, *Eurekia*, *Tellerina*, *Calvinella*, and *Macronoda* (Fig. 3). This unit may be approximately equivalent to the Upper *Dikelocephalus* and *Saukiella-Calvinella* subzones of Bell and others (1956). We choose not to apply their nomenclature because the genera *Saukiella* and *Calvinella*, and the species *Dikelocephalus minnesotensis*, all range from the upper Reno Member through the lower Jordan Formation (Figs. 3, 4, Appendix). Hence we do not believe that these terms define temporally distinct faunal units. McGannon (1960) suggested the occurrence of *Osceolia* was tightly controlled by lithofacies, and that this genus should not be used for biostratigraphic zonation. We have found no obvious relationship between lithofacies and occurrence of either *Osceolia* or *Saukia* in the St. Lawrence Formation (Appendix). Neither is their distribution likely to be under the control

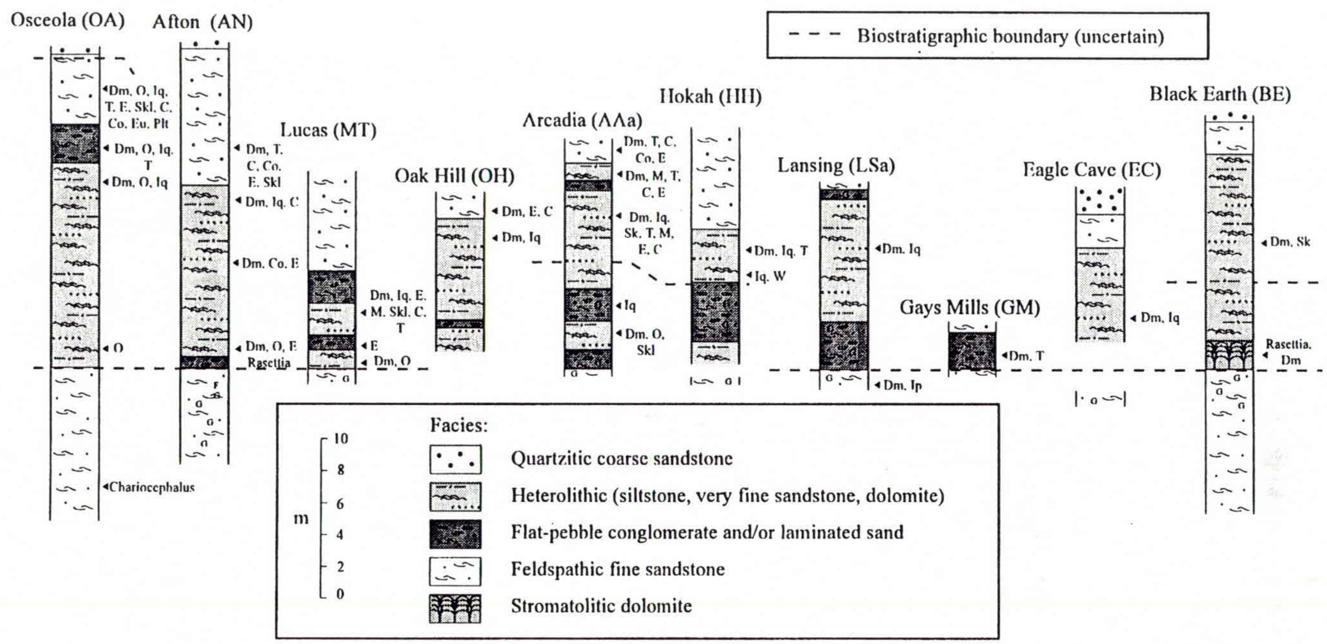

Fig. 4. Stratigraphic sections through the St. Lawrence Formation, with trilobite occurrences marked. Occurrence data is based on our field collections, and on reported occurrences at these sections in data sources listed in caption to Figure 3. Localities shown in Fig. 1. Detailed sections showing only those taxa we collected are given in the Appendix. Dm = *Dikelocephalus minnesotensis*, O = *Osceolia*, W = *Walcottaspis*, Ip = *Illaenurus priscus*, Iq = *Illaenurus quadratus*, Sk = *Saukia*, T = *Tellerina*, C = *Calvinella*, Skl = *Saukiella*, E = *Eurekia*, Co = *Corbinia*, M = *Macronoda*, Eu = *Euptychaspis*, Plt = *Plethometopus*.

of a latitudinal climatic gradient as the dividing line between occurrence and non-occurrence of *Osceolia* and *Saukia* is essentially north-south (ancient orientation). Therefore we recognize separate *O. osceola* and *Saukia* subzones in Figs. 3 and 5.

An uppermost division of the northern Mississippi Valley Sunwaptan based on the first occurrence of *Plethopeltis* may eventually be found to be valid (cf. Stitt, 1977), though the diversity in this interval is much reduced (Fig. 3). *Plethopeltis* is a relatively long-lived genus, occurring in both Sunwaptan (Upper Cambrian) and Ibexian (Lower Ordovician) rocks (*e.g.* Longacre, 1970; Stitt 1977; Westrop, 1986). The co-occurrence of *Plethopeltis* with typically Cambrian trilobites including *Tellerina*, *Saukiella*, *Calvinella*, *Entomaspis*, *Plethometopus*, and possibly *Dikelocephalus* (Stauffer, 1940; Raasch, 1951) confirms a Cambrian age for at least some of the strata bearing *Plethopeltis*, but the biostratigraphic definition of the uppermost Cambrian in the northern Mississippi Valley is very poorly resolved (Runkel, 1994a; Byers and Dott, 1995). We designate the last portion of the *Saukia* Zone in the northern Mississippi Valley as the *Plethopeltis* "fauna" in view of these uncertainties, and leave its upper boundary as an open question.

Post-molt or post-mortem transportation of sclerites is unlikely to have significantly affected trilobite distributions in the St. Lawrence Formation. Although some degree of redistribution is probable (Hesselbo, 1987), sorting generally has not discriminated between large and small genera and taphonomic factors can be ignored when considering biostratigraphic zonation of the Formation (Hughes 1993).

Our studies re-affirm the discordance between the biostratigraphic and lithostratigraphic succession in the St. Lawrence Formation and the basal part of the Jordan Formation, which suggests that the boundary between the two Formations youngs southwards (Bell and others, 1956; Nelson, 1956)(Fig. 4). Some diachroneity was similarly suggested, to a lesser degree, internally within the Tunnel City Group (Bell and others, 1956, Fig. 5) although this may be due to differential compaction. There does not appear to be any marked diachroneity between the Tunnel City Group and the St. Lawrence Formation in the northern Mississippi Valley area.

Correlation with other areas

The 'Croixan' biozonation for the northern Mississippi Valley was used as a standard for the North American Upper Cambrian (Howell and others, 1944). Further attempts to refine that biostratigraphy (Raasch, 1951; Nelson, 1956; this paper) constitute minor variations on that scheme. Because northern Mississippi Valley Sunwaptan deposits are not easily correlated with other areas (Winston and Nichols, 1967), Longacre (1970) suggested that the zonation based on the northern Mississippi Valley should be abandoned and proposed an alternative zonation based in central Texas (Fig. 5). This scheme has proved much more widely applicable among shelfal deposits from the carbonate belt. More recently Ludvigsen and Westrop (1985) proposed new stratotypes for new Upper Cambrian stages in Utah, Nevada and Alberta, based on the more complete successions in those areas. Progress has also been made in the biostratigraphy of deeper-water trilobite faunas of similar age (Ludvigsen and others, 1989; Westrop, 1995), and towards understanding of trilobite biofacies relationships among different Laurentian areas (*e.g.* Ludvigsen and Westrop, 1983). Biofacies differentiation during the Late Cambrian presents difficulties for biostra-

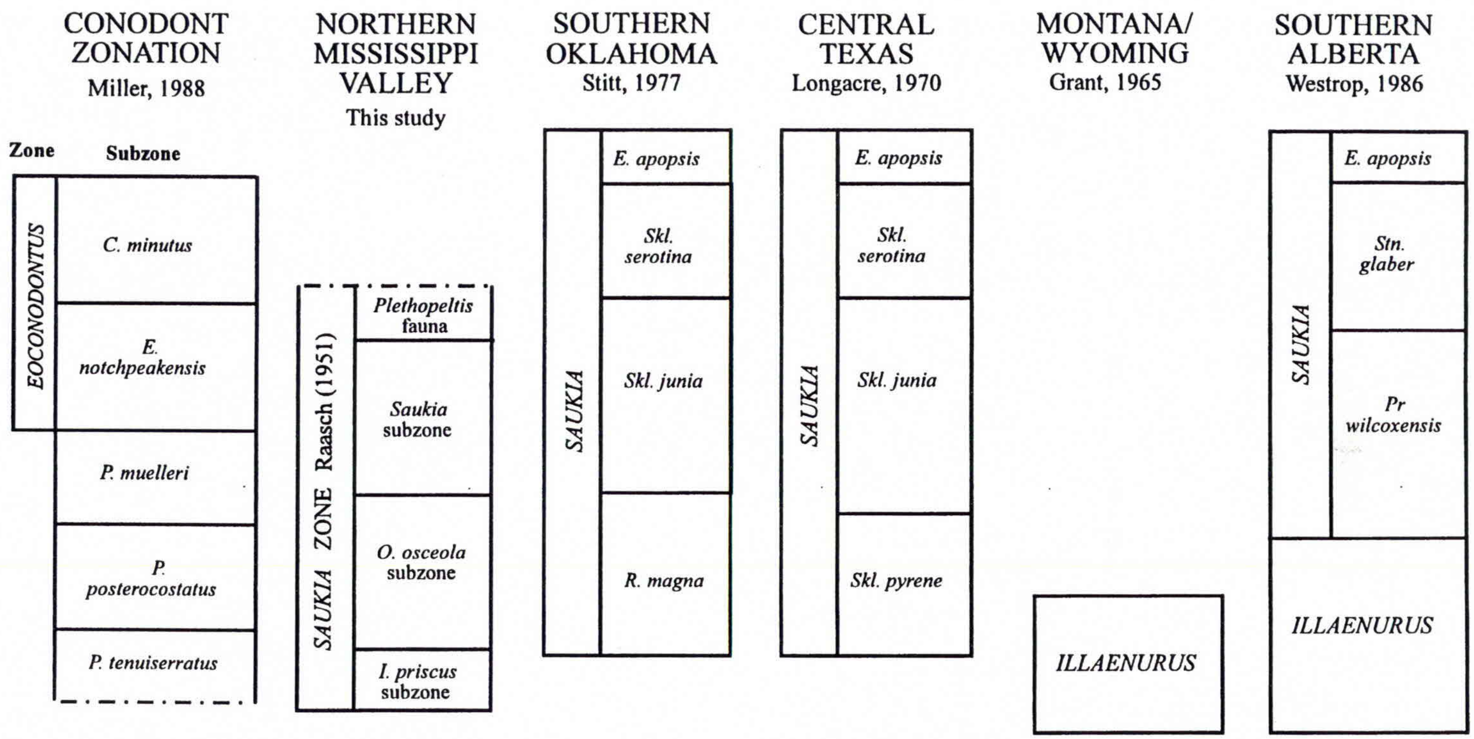

Fig. 5. Biostratigraphy of the uppermost Cambrian of the northern Mississippi Valley compared to other areas of North America. Dashed lines indicate a high level of uncertainty in the relative positions of the boundaries. Taxon names in capital letters indicate Zones, lowercase names indicate subzones.

tigraphic correlations of northern Mississippi Valley Sunwaptan deposits with those of other areas because its faunas are distinct. Uncertainties in error estimates associated with stratigraphic ranges of individual taxa, poorly resolved taxonomy, and relatively low generic diversity within individual northern Mississippi Valley collections (Hughes, 1993), all limit confidence in biostratigraphic correlations between this and other areas.

The *Saukia* Zone has several different definitions within Laurentia (Fig. 5). The base of the *Saukia* Zone in the northern Mississippi Valley occurs slightly above the base of the *Illaenurus* Zone in southern Alberta (Westrop, 1986) and in Montana/Wyoming (Grant, 1965) (Fig. 5). This is because *I. priscus* first occurs above the base of the *Illaenurus* Zone in the western areas, whereas it defines the base of the Saukia Zone in the northern Mississippi Valley. The *Saukia* Zone in southern Alberta (Westrop, 1986) occurs immediately above the *Illaenurus* Zone, and hence the *Saukia* Zones in southern Alberta and in the northern Mississippi Valley are not time-equivalent. The base of the *Saukia* Zone in Oklahoma (Stitt, 1971, 1977) and central Texas (Longacre, 1970) also occurs well above the base of the *Saukia* Zone in the northern Mississippi Valley (Raasch, 1951) because in central Texas and in the Arbuckle mountains of Oklahoma the first occurrence of *Illaenurus quadratus* is used to define the base of this Zone (Longacre, 1970; Stitt, 1971) (but also see Stitt and Metcalf, 1995). Hence the base of the *Saukia* Zone in these areas can be correlated with the base of the *Osceolia osceola* subzone of the northern Mississippi Valley.

The base of the *Saukia* subzone in the northern Mississippi Valley may correlate with the base of the *Saukiella junia* subzone in Oklahoma (Stitt, 1971, 1977) as both are based on the first appearance of *Saukia*. In Texas the first occurrence of *Saukia* occurs above the base of the *Saukiella junia* subzone (Longacre, 1970, Text-Fig. 3), so the base of the *Saukia* Zone is slightly lower in that region (Fig. 5). A similar situation occurs in southern Alberta where the base of the *Saukia* Zone is defined by the appearance of *Proricephalus wilcoxensis*. In this case *Saukia* does not appear until the middle part of the *P. wilcoxensis* Fauna (Westrop, 1986). Saukia does not occur in Montana/Wyoming, and so the correlation with the northern Mississippi Valley relies on indirect correlations through the southern areas. *I. quadratus* and *Saukia* commonly co-occur in the St. Lawrence Formation; this is noteworthy because *Illaenurus* and *Saukia* have not been recorded together in Sunwaptan strata from any other region.

Correlation of the top of the *Saukia* subzone and Zone with other areas is impossible at present, largely because the fauna of the Jordan Formation is rare, of low diversity, and is poorly preserved. However, limited evidence suggests that the Jordan Formation on the Wisconsin Arch was deposited prior to the time represented by the *Eurekia apopsis* subzone of other areas (Byers and Dott, 1995)(Fig. 5). The majority of the St. Lawrence Formation was deposited during the time represented by the *Saukiella pyrene* and *Saukiella junia* subzones of central Texas. This conclusion is supported by the preliminary conodont studies of Miller and Melby (1971) who recovered *Proconodontus muelleri muelleri* and *Eoconodontus notchpeakensis* in heterolithic beds from Lucas (MT), suggesting an age older than the *Saukiella serotina* subzone (Fig. 5).

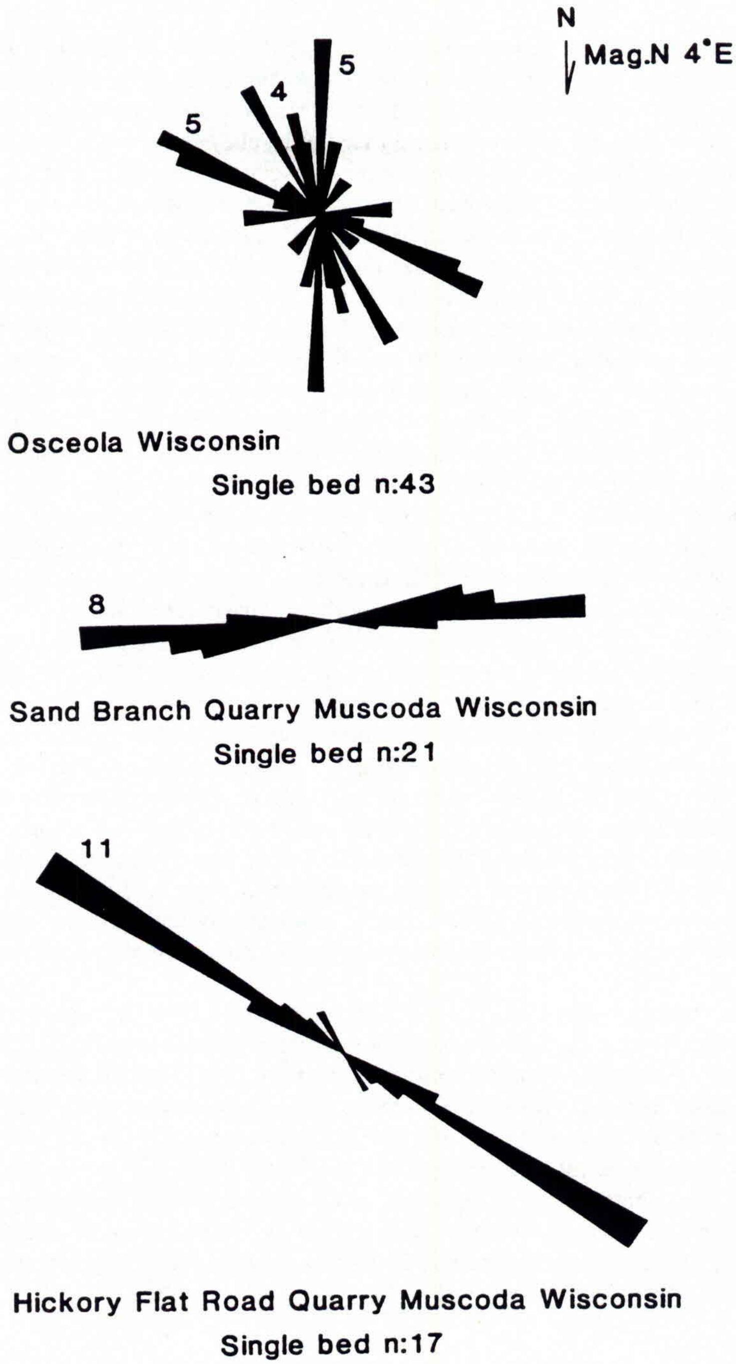

Fig. 6. Orientations of parting lineation and tool marks from three localities in the St. Lawrence Formation.

LITHOFACIES AND SUCCESSIONS THROUGH THE ST. LAWRENCE FORMATION

Heterolithic Dolomicrite, Siltstone and Sandstone facies

The heterolithic facies is the most important volumetrically, comprising coarsely and finely interlayered dolomite, clay and very fine sand. The sandy layers are composed of coarse silt and very fine sand-grain sized feldspar with subsidiary quartz and muscovite. Graded bedding is rare or absent. Dolomite is fine-grained with a planar texture (Sibley and Gregg, 1987) of slightly interpenetrating rhombs set in a matrix of amorphous interstitial brown material, composed of illite and probable iron oxy-hydroxides (Hughes, 1993, pl. 1, fig. 6).

The heterolithic facies is represented at most localities by beds of interlayered calcareous claystone or dolomitic siltstone and white sandstone. The sand and clay/dolomite layers vary from very-thin to very-thick laminae or from very-thin to thick beds (as defined in Collinson and Thompson, 1988, p. 8). The grade of sand is generally very fine with rare coarse sand sometimes concentrated in burrows. No internal sedimentary structures can be seen within the claystone but the sand is parallel laminated or very low-angle cross-stratified and thicknesses may pinch and swell. Small-scale hummocks (amplitudes <5 cm) are also present. Internal lamination in the sands is often truncated, commonly at angles of <20 degrees.

Sand layers occasionally have a strong parting lineation. Current orientation varied areally and temporally, but every locality shows a general WNW-ESE trend (Fig. 6), in contrast to the SW trend of the underlying Tunnel City Group (Mickelson and Dott, 1973), but similar to that in the lower facies in the overlying Jordan Formation (Runkel, 1994a).

Unequivocal ripples are generally rare. Asymmetrical ripples are the most common, but symmetrical, starved, interference and flat-topped varieties all occur locally (Figs. 7 and 8). At Osceola, a bedding surface has abundant flat-topped ripples in straight-crested or interference form. The truncation surfaces bear well-preserved wrinkle marks, which form low, sinuous ridges composed of very-find grained sand which parallel the ripple crests and are more closely spaced in the interior of the truncation surface (Fig. 7C). Other wrinkle marks, less regular in size and shape, occur in this facies in silt-grade sediment preserved in the troughs of ladder-back ripples, and occur together with parting lineation.

Groove and bounce marks are common and gutter casts less abundant. Tool marks present on the bases of sandy layers show a consistent alignment with the parting lineation throughout the rocks (Fig. 6).

Shrinkage cracks are common in the clay-rich parts of the heterolithic facies (Fig. 9). They typically show an irregular polygonal configuration. Some examples display considerable disturbance of the sand laminae above the crack with a concomitant thinning of the overlying layer (Fig. 9B). At Osceola, shrinkage cracks are common and are present in centimeter-thick homogeneous fine-grained dolomitic clay layers. In these cases, the sand fills do not invariably make contact with the underlying or overlying sandstone layers where seen in section; they tend to be widest at the center of the clay layers, producing a

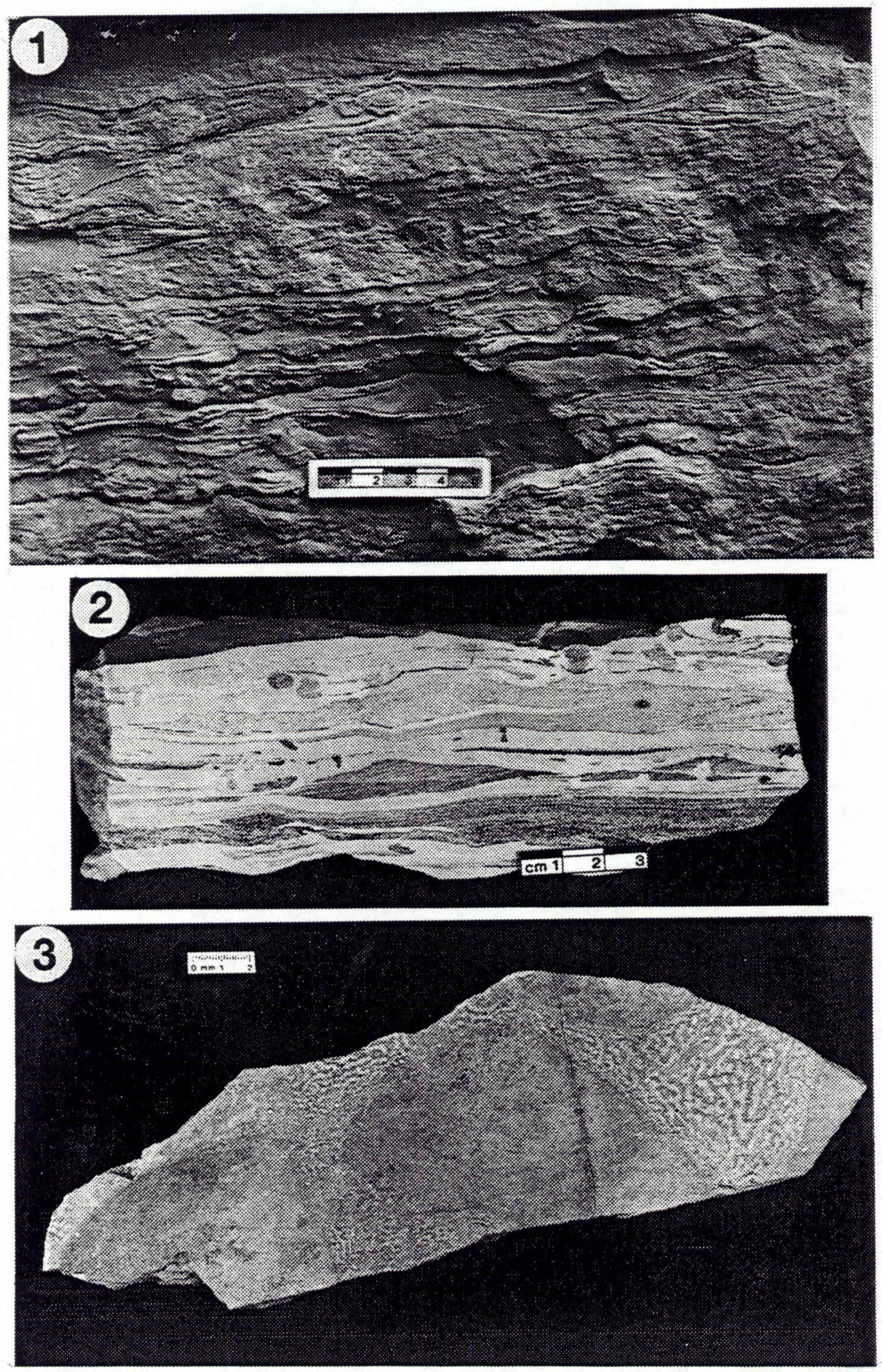
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Fig. 7. St. Lawrence Formation: heterolithic facies. Distances in meters refer to height above the base of measured sections. 1. Heterolithic bedding, St. Lawrence Formation, heterolithic facies, Maiden Rock (MR), Pepin County, Wisconsin. 2. Heterolithic bedding showing ripple lamination and horizontal burrows in glauconitic sandstones, Cut and oil-spayed. 13.25 meters, Osceola section (OA), Polk County, Wisconsin. 3. Plan view of flat-topped ripples with wrinkle marks on flattened crests, 22.25 meters, Osceola section (OA), Polk County, Wisconsin.

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spindle-shaped vertical cross section (Fig. 9A). The horizontal section at the top of each clay layer is also spindle-shaped and each crack is commonly isolated (Fig. 9C). Thus, the maximum shrinkage appears to have occurred in the middle of the fine-grained dolomite layers. We have not observed these cracks cutting across more than one fine-grained layer.

Trace fossil assemblages are dominated by horizontal burrows, but also include a number of unusual forms including *Raaschichnus* - traces made by aglaspidid arthropods (Hesselbo, 1988), and circular trace fossils (Fig. 8D). Complete homogenization through bioturbation occurs in some beds, but this is not predominantly the case (Raasch, 1939). At Hokah (see appendix for detailed log) ichnofabric indices (Droser and Bottjer 1986) range from 1 to 4, and this range appears typical of other sections. Heterolithic beds containing abundant fossils typically have ichnofabric index 2 or lower, suggesting that they have not been extensively bioturbated.

The body-fossil fauna, which is not obviously different in the clay- or dolomite-dominated lithotypes, includes the *Osceolia* and *Saukia* subzone trilobites referred to above except for *Rasettia*. In addition to the trilobites (Ulrich and Resser, 1930; 1933; Raasch, 1951; Hughes, 1993, 1994), there is a rich fauna of well preserved aglaspidid arthropods (Raasch, 1939; Hesselbo 1992), inarticulate brachiopods, gastropods, dendroid graptolites (Ruedemann, 1933), phyllocarids, rare hyolithids, 'serpulids', possible primitive conulariids (Raasch, 1939) and echinoderm columnals. The fauna is locally abundant. Trilobite generic diversity is comparable to that of similar aged deposits in other parts of Laurentia (Hughes 1993). Taphonomic studies of the trilobite fauna (Hughes, 1993) show that the vast majority of sclerites are disarticulated, and suggest limited post-disarticulation sclerite sorting, took place mainly on the basis of shape differences.

Interpretation

This facies appears to represent a marine environment and was subject to episodically changing energy conditions. Unidirectional currents were the predominant agents of sediment transport. Given the unanimity of view that the overlying Jordan Formation represents a prograding shoreface succession (Runkel, 1994a; Byers and Dott, 1995) an offshore setting below fair-weather wave-base would seem to be most likely. In that case the sedimentary structures suggestive of exposure or shallow water (interference and flat-topped ripples, wrinkle marks and mudcracks) stand out as highly anomalous and require further discussion. Flat-topped ripples are known to form in very shallow water 'less than 5 cm deep' (Tanner, 1958); they are often interpreted (*e.g.* Klein, 1977) to result from the reworking of ripple-tops

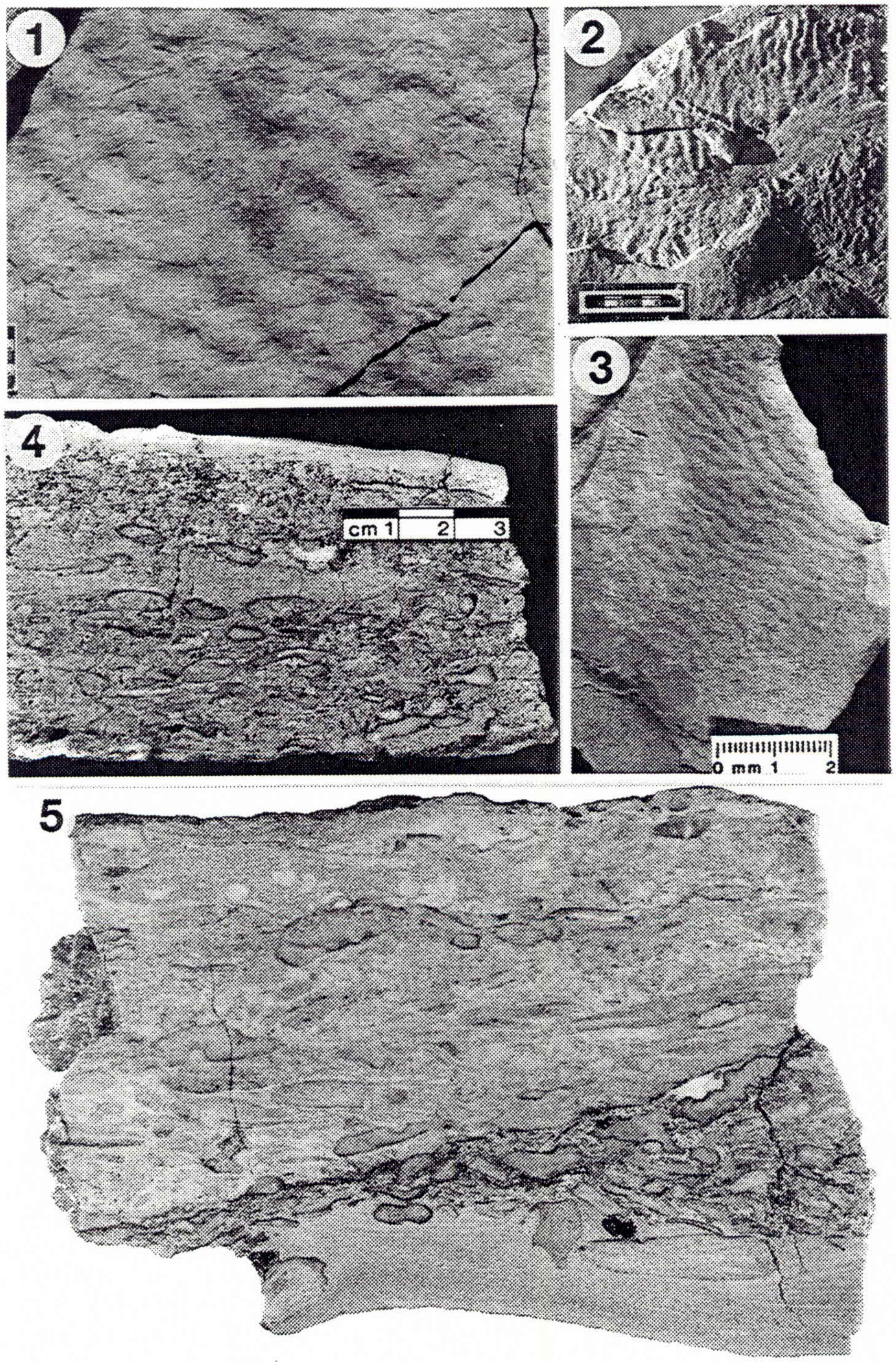
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Fig. 8. St. Lawrence Formation. Distances in meters refer to height above the base of measured sections. 1 to 3. Plan views of heterolithic facies. 1. interference ripples, 5.2 meters, Arcadia (AAa), Trempealeau County, Wisconsin. 2. Wrinkled surface, 3.0 meters, Arcadia (AAa), Trempealeau County, Wisconsin 3. Wrinkled surface, loose slab probably from 6.5 meters, Lansing (LSa), Allamakee County, Iowa. 4 and 5. Flat-pebble conglomerate and laminated sand facies. 4. Flat-pebble conglomerate clasts with glauconitic rinds, 10.3 meters, Afton (AN), Washington County, Minnesota. 5. Pebble-supported flat-pebble conglomerate, pebbles showing glauconitic rims and possible borings, with pressure dissolution seam. Maiden Rock (MR), Pepin County, Wisconsin.

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as the water level falls to a few centimeters or to exposure. However, flat-topped ripples can also be formed subtidally, where they have been observed to form in 3.5 to 4.5 meters of water in a subtidal inlet ebb channel (Reddering, 1987).

Wrinkle marks, also known as Kinneyian marks, have been observed to form naturally by the decay of stranded foam patches (Allen, 1982) or through the re-working of rain-drop marks by wave swash (Klein, 1977). Wrinkle marks have been produced experimentally in damp windblown sand (Kocurek and Fielder, 1982) or subaqueously (Dzurlynski and Simpson, 1966) where dense sediment suspensions flow over cohesive mud. We are unaware of reports of wrinkle marks in association with flat-topped ripples in any modern setting. It is possible that wrinkles on flat-topped ripples are due to wind-stress acting on an exposed surface (Reineck and Singh, 1980, p. 65; Kopaska-Merkel and Grannis, 1990). The wrinkle marks we observe associated with flat-topped ripples are confined to the flat surfaces and do not form in the troughs, where they occurred in subaqueous experimental simulations. The wrinkles are formed of fine sand, but are not underlain by clay. This contrasts with the experimental conditions in which high density suspension flow over cohesive muds were needed to produce subaqueous wrinkles (Dzurlynski and Simpson, 1966). Seilacher (1982, p.340) illustrated flat-topped ripples with wrinkle marks, similar to those observed in the St. Lawrence Formation, and suggested an early substratal origin, in connection with storms. Martinsson (1965) and Goldring (1971, p. 10) also favored a subaqueous origin for similar features, although a specific mechanism for their subaqueous formation has not been proposed. In summary, despite their distinctive appearance the origin of wrinkle marks in the St. Lawrence Formation remains obscure.

The abundant shrinkage cracks might also be used to argue for common exposure (*e.g.* Allen, 1984; Astin and Rogers, 1991) and some of the St. Lawrence Formation shrinkage cracks do conform to types commonly associated with desiccation. However, we argue that at least some of the examples of mudcracks owe their origin to substratal sediment transposition and closely resemble mechanically formed diastasis cracks (Cowan and James, 1992). The strongest evidence for this interpretation is thinning of sand layers overlying cracks, and the fact that cracks are often widest in the middle of the fine-grained layers. Other authors (*e.g.* Plummer and Gostin, 1981; Haddox and Dott, 1990) have suggested a subaqueous origin for some shrinkage cracks, and these features cannot be considered unequivocal indicators of exposure in the St. Lawrence Formation.

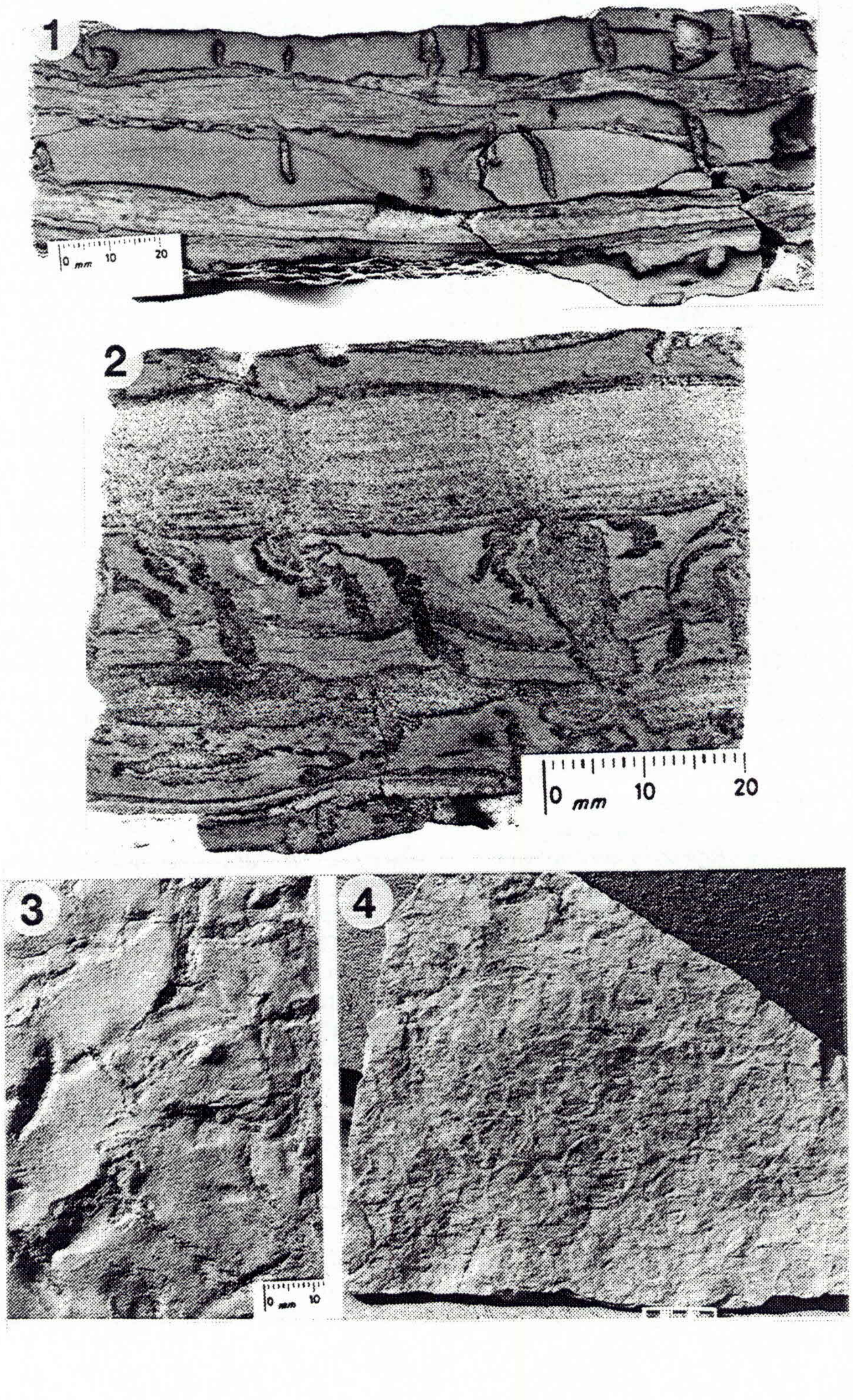
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Fig. 9. St. Lawrence Formation: heterolithic facies. Distances in meters refer to height above the base of measured sections. 1. Shrinkage cracks showing sand-in-filling of shrinkage cracks in clay-rich layers from beds within 10 - 17 meter interval, Osceola section (OA), Polk County, Wisconsin. Most cracks are isolated and spindle-shaped, and widest at the centers of the fine-grained layers. Cut and oil-sprayed. Collected by R.A. Byers. 2 and 3. Shrinkage cracks from Tubb's Farm, Avoca (AT), Iowa County, Wisconsin. 2. Cracks showing disturbance and thinning of overlying sandstone layer, suggesting substratal development. Cut and oil-sprayed. 3. Plan view. 4. Plan view of upper surface of heterolithic unit, showing circular trace fossils. UW-1463.5, 3.6 meters, Hickory Flat Road section (MCa), Muscoda, Grant County, Wisconsin.

The varied skeletal and ichnofauna, along with inchofabric index values typical for strata of this age (Droser and Bottjer, 1988), suggest that normal marine conditions prevailed.

Flat-Pebble Conglomerate and Laminated Sand facies

Flat-pebble conglomerates form the second most abundant facies in the St. Lawrence Formation. The composition of the matrix and pebbles is highly variable.

Pebbles are composed of fine to very fine-grained sand, glauconitic sand or dolomitic siltstone. They appear to be intra-formational in origin. The matrix is of dolomitic sand, glauconitic sand of very fine to medium grade or fine-grained dolomite and dolomitic siltstone. Within individual beds the composition of matrix and pebbles is usually different. Pebbles are mostly discoid and range in diameter from a few millimeters to over 24 cm. Many show parallel lamination internally. Bases of beds are commonly planar but may be bulbous and apparently load-casted.

Two types of flat-pebble conglomerate are distinguished by their textures and relationships to the overlying beds (Figs. 10 and 11). Matrix-supported flat-pebble conglomerates are composed of poorly-sorted angular pebbles, oriented parallel or subparallel to bedding, as at Lucas (Fig. 10). Glauconite is absent from both pebbles and matrix. Individual conglomeratic layers are overlain by parallel/low angle cross-stratified sandstones several decimeters thick, the tops of which contain the trace fossil *Skolithos*. Planar lamination, low angle cross-stratification and possible hummocky cross-stratification are all present in decimeter-thick fine-grained sandstone beds that occur in association with matrix-supported flat-pebble conglomerates. These sandstones are most common in the northeastern parts of the exposure area (Nelson, 1956) and in the higher parts of the Formation.

The majority of flat-pebble conglomerates are, however, pebble-supported and are overlain sharply by heterolithic beds or further flat-pebble conglomerates; most pebbles lie parallel or sub-parallel to bedding. Imbrication is observed locally but is impersistent and variable in orientation. Hemispherical, fan-shaped accumulations of flat pebbles (25 cm diameter) have been observed at Lucas, Redwing and Maiden Rock and more extensive edgewise stacks have also been reported (Twenhofel and Thwaites, 1919). Both normal and reverse grading may be present within individual beds, but most beds show an ungraded

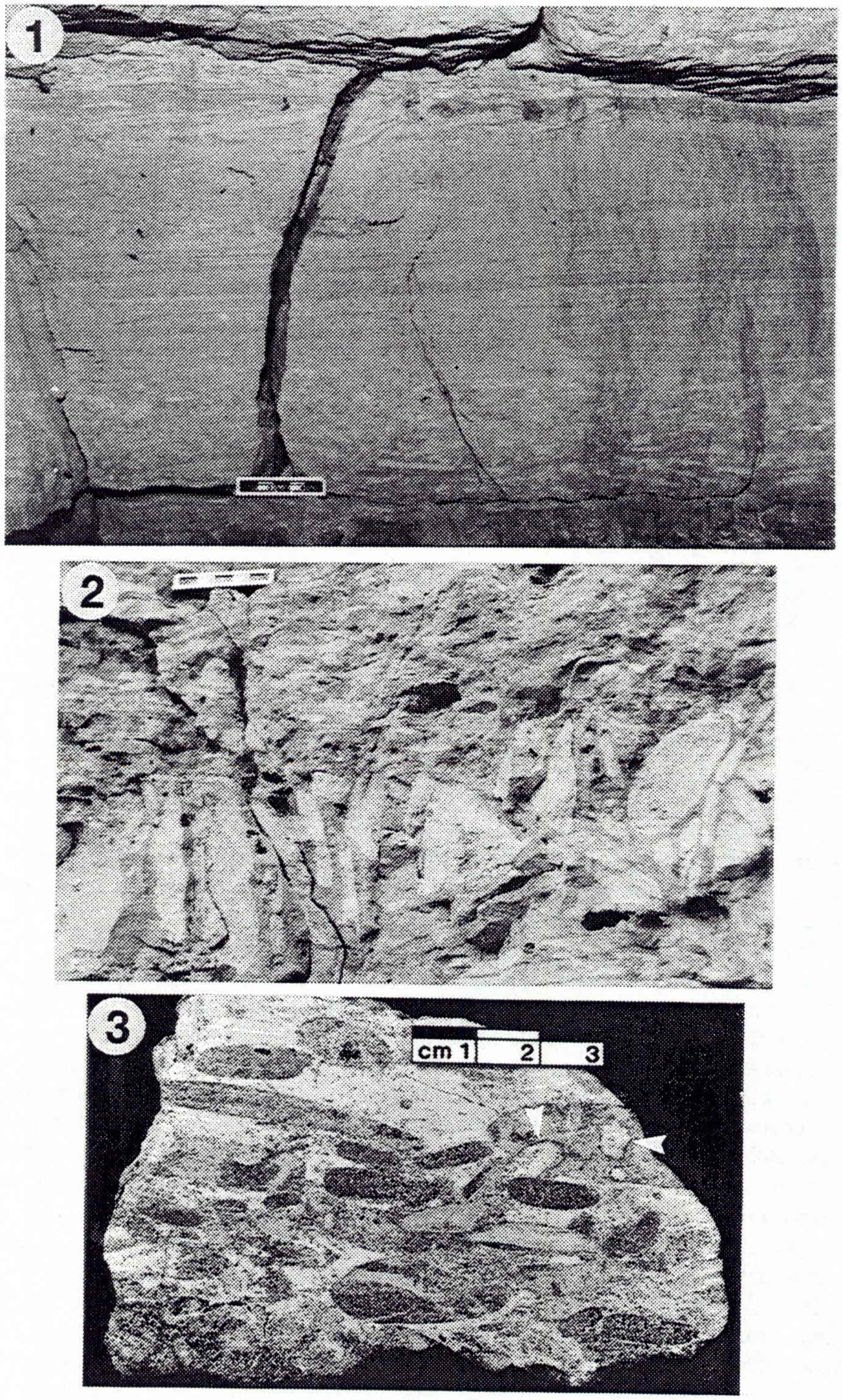
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Fig. 10. St. Lawrence Formation: flat-pebble conglomerate and laminated sandstone facies. Distances in meters refer to height above the base of measured sections. 1 and 2. Lucas section (MT), Dunn County, Wisconsin. 1. Matrix-supported flat-pebble conglomerate bed overlain by low angle cross laminated sandstone, and subsequent clast-supported flat-pebble conglomerate. Bases of flat-pebble conglomerates are planar. 5.1 to 6.0 meters. 2. Edgewise stack of conglomerate clasts, 6 meters. 3. Flat-pebble conglomerate showing bored sandstone clasts. 6.4 meters, Afton (AN), Washington County, Minnesota.

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fabric. Pebbles are rounded, and are commonly penetrated by cylindrical borings which may pass through the pebble but do not extend into the surrounding matrix (Fig. 10C) (cf. Brett and others, 1983). The rims of the pebbles and the borings have glauconitized rims. The matrix also contains abundant glauconite. Body fossils are very uncommon but at Oak Hill, for example, the fauna is similar to that found in the heterolithic facies. Decimeter-thick beds are generally laterally persistent on an outcrop scale (up to 100 meters), but are not sufficiently distinctive to act as marker horizons between outcrops.

The flat-pebble conglomerate facies and laminated sand facies occur interbedded with the heterolithic facies in southern (basinal) localities, but laminated sandstones predominate at the northern (proximal) Mauston and Wilton localities, which lie on the flanks of the Wisconsin arch. In SW Wisconsin and NE Iowa (Figs 2 and 5) the base of the St. Lawrence Formation is characterized by a sequence of amalgamated, channeled and pebble-supported flat-pebble conglomerates up to 1 m thick.

Interpretation

Most flat-pebble conglomerates are thought to form during high-energy events (generally taken to be storms) when semi-lithified sea-floor is ripped-up and re-deposited, and they are a common feature of other Lower Paleozoic cratonic deposits, particularly marine, mixed shale/carbonate/sand successions (Lindholm, 1980; Markello and Read, 1981; Sepkoski, 1982; Brett and others, 1983; Mount and Kidder 1993). Although the matrix-supported flat-pebble conglomerates evince rapid deposition from highly sediment-laden flows, edgewise sacks and fan-shaped arrays of clasts closely resemble those interpreted to form during intense, storm-generated, combined flows (*e.g.* Mount and Kidder 1993). Many pebble-supported conglomerates also show evidence of prolonged periods of reworking under high-energy conditions at the sediment-water interface during which time they were rounded, bored and developed glauconite rims. The occurrence of marine fossils and abundant glauconite in the St. Lawrence Formation flat-pebble conglomerates indicates a subaqueous and marine environment of deposition, although the data provided by some authors (Kazmierczak and Goldring, 1978; Aigner, 1985; Whisonant, 1987) indicate that some flat-pebble conglomerates may also be generated in inter-tidal environments. Glauconitic rims would not be expected under such conditions.

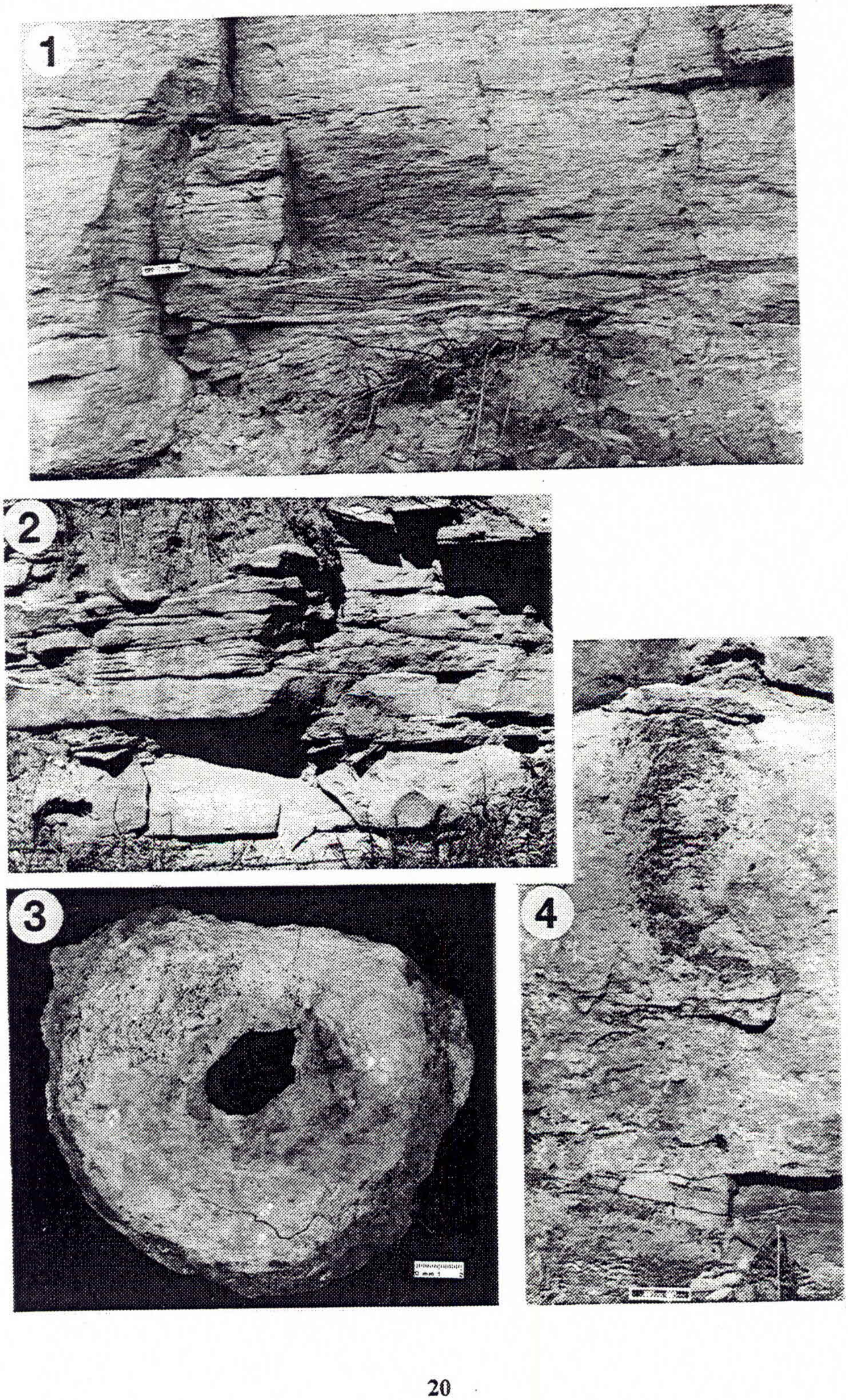
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Fig. 11. St. Lawrence Formation. Distances in meters refer to height above the base of measured sections. 1 and 2. Flat-pebble conglomerate and laminated sandstone facies. 1. Laminated sandstones showing trough and hummocky cross bedding. 4 meters, Arcadia north section (AAa), Trempealeau County, Wisconsin. 2. Laminated sandstones, 6.6 meters, Mauston section (MN), roadcut on north side of County Trunk O, 8 km east of Elroy, Juneau County, Wisconsin. 3 and 4. Stromatolitic dolomite facies, 9.7 meters, Black Earth (BE), Dane County, Wisconsin. 3. Plan view of top of stromatolite column showing microatoll structure. 4. Lateral view of vertically-stacked hemispheroidal stromatolite.

Stromatolitic Dolomite

Vertically-stacked hemispheroidal stromatolites are found at the base of the St. Lawrence Formation in the Madison area (Black Earth, Lake Mendota and near Baraboo).

At Black Earth individual stromatolites in growth position are parallel-sided columns up to 30 cm high and 20 cm wide with a circular-cross-section (Fig. 11). Their tops are generally domed, but a few have a central depression similar to the 'microatoll' structure of Dill and others (1986). Stromatolites occur in clusters, separated by structureless interstitial dolomite. Convex-up laminae can be seen in the upper parts of most stromatolites, but dolomitization has destroyed the primary fabric at their bases. The trilobite *Rasettia*, articulate brachiopods and gastropods occur in the interstitial dolomite.

Clusters of stromatolites occur as discrete clumps up to 3.5 meters wide, separated by wide, shallow channels containing trough cross-stratified glauconitic sands with small, tabular disc-shaped dolomite pebbles, concentrated at the bases of cross-sets. The stromatolites are overlain by a thin discontinuous layer of glauconitic sandstone with dolomite pebbles filling the interstices between stromatolite heads, which show no sign of abrasion.

At Wood's Quarry, near Baraboo, large, discrete stromatolite columns have been recorded (C.W. Byers, 1978; R.A. Byers, 1979). Columns are up to 1.3 m in height and are either parallel-sided or upwardly-divergent. Mat-like, space-linked hemispheroids occur above the pillar-stromatolite horizon.

Interpretation

Algal stromatolites indicate well-illuminated conditions. Columnar algal stromatolites grow both inter-tidally (Logan, 1961) and sub-tidally (Dill and others, 1986) in very clear water at shallow depths. The presence of channels between stromatolite clumps confirms high-energy conditions. There are no exposure features associated with the stromatolites, and hence these features do not necessarily represent emergent conditions, although water depths must have been sufficiently shallow to permit

1

2

Fig. 12. St. Lawrence Formation: heterolithic facies. Diagenesis at Mazomanie (MMa), Dane County, Wisconsin. 1. Appearance of bed at outcrop, showing episodic nature of deposition and alternate bioturbated/unbioturbated layers, x 1. 2. Nodular and seamy layer (center) interbedded with diagenetically unaffected layers, x 1. Cut and oil-spayed.

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photosynthesis. This condition places a maximum water depth at no more than a few tens of meters.

DIAGENESIS

The predominant macroscopic diagenetic fabric, which principally affects beds in the heterolithic and flat-pebble conglomerate facies, comprises (Fig. 12) dolomite nodules and clay seams ('stylonodular' fabric of Logan and Semeniuk, 1976). Considerable variation occurs in the thickness of affected beds, the relative importance of dolomite nodules to clay seams, and relationships with pre-existing sedimentary structures.

That undulatory clay seams and associated dolomite nodules, such as those from the St. Lawrence Formation, are the products of pressure dissolution is now widely accepted (Logan and Semeniuk, 1976; Wanless, 1979; Bathurst, 1987 and references therein). In general, it is the bioturbated beds in the St. Lawrence Formation of the south Wisconsin area that were preferentially diagenetically altered

Because of the hard and massive nature of the diagenetically-altered beds, they fall within the definition of the Black Earth Member (Nelson, 1956). Published examples of nodular and clay-seam beds characterized as Black Earth Member (or its nomenclatural equivalent) are in Odom (1978b (after Thwaites) at Mazomanie, and Raasch (1939, p.98) at Button Bluff, near Lone Rock. In the SE of the study area, in the Wisconsin River Valley region (Fig. 2) many beds identified as Black Earth Member may be diagenetically altered lithologies which would otherwise have been classified with the Lodi Member: they probably do not represent distinctly different sedimentary environments.

STRATIGRAPHIC EVOLUTION OF THE ST. LAWRENCE FORMATION

Although there remains some considerable ambiguity regarding the bathymetric significance of sedimentary structures within the St. Lawrence Formation, the stratigraphic relationships to the conformably overlying and underlying Formations leave little scope for any interpretation other than deepening from the Tunnel City Group into the St. Lawrence Formation, and shallowing from the St. Lawrence Formation into the Jordan Formation (scenario A of Fig. 13). The suggestion of Nelson (1956) and Berg and others (1956) that the lower Jordan Formation in the north of the study area is older than that in the south is (supported in this study) signifies that any interpretation of the St. Lawrence Formation stratigraphy must be compatible with interpretations of the Jordan Formation.

Recent authors are agreed that the Jordan represents a southwestward-prograding shoreface succession (Runkel, 1994a; Byers and Dott, 1995), but their views diverge concerning the number of progradational phases involved. Runkel (1994a) interpreted the

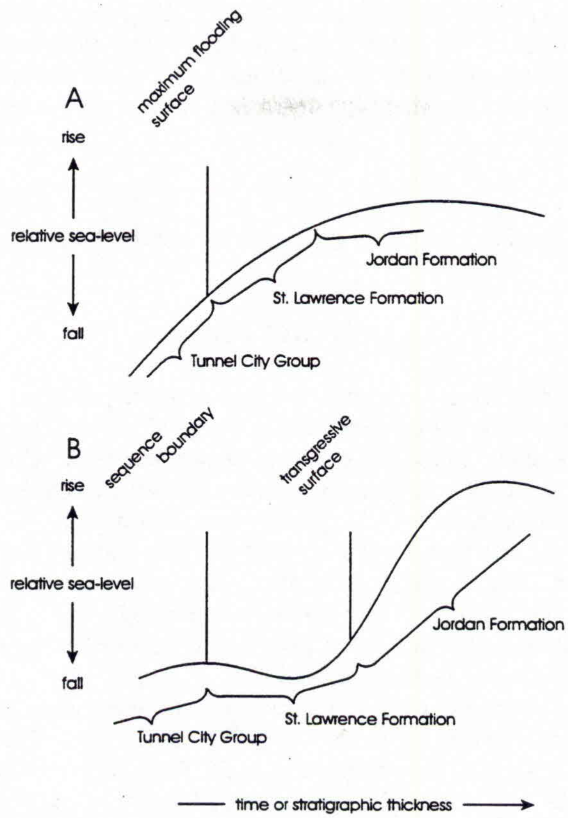

Fig. 13. Alternative hypotheses for the relationship between relative sea-level change and *Saukia*-zone stratigraphy in the northern Mississippi Valley. Interpretation A is favored: see text for details.

localized occurrence of tongues of fine-grained hummocky cross-stratified feldspathic sandstones within the overlying coarser quartzose facies, as being caused by an unspecified number of interruptions to progradation caused by sea-level rise. In contrast, Byers and Dott (1995) interpret same pattern of sedimentation as representing two cycles of progradation, with the upper cycle being locally removed by erosion below the Prairie du Chien Group.

Detectable diachrony within the St. Lawrence Formation, and between the St. Lawrence Formation and the Jordan Formation, appears most marked at the sections at Osceola and Afton in Minnesota (Figs. 2 and 5) but at present we have no way of telling whether this is simply an artifact of biostratigraphic resolution or whether it reflects enhanced rates of progradation 'post'-*Osceolia* subzone. Nevertheless, this pattern is in harmony with the notion of a Jordan Formation shoreface prograding southwards into a St. Lawrence Formation offshore setting. We use the term "southwards" in a general sense because the

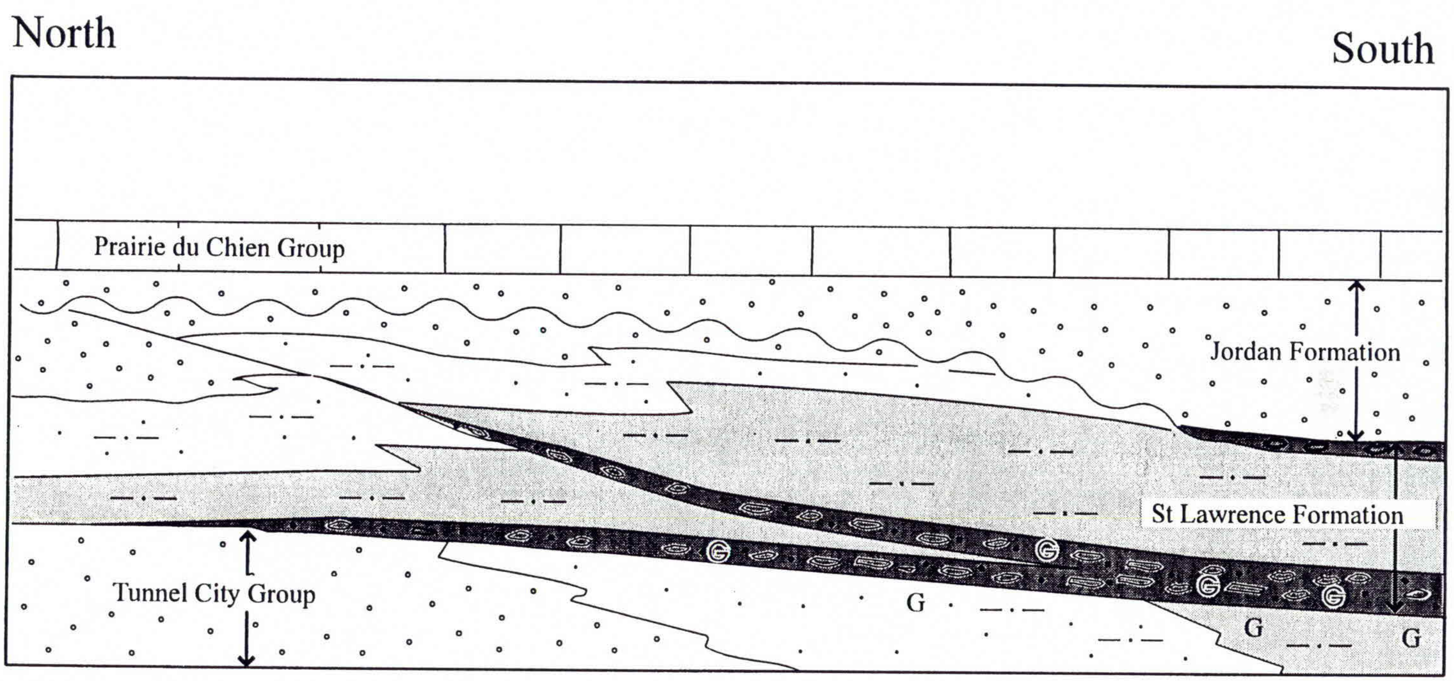

Fig. 14. Cartoon illustrating hypothetical stratigraphic relations of the St. Lawrence Formation to the underlying Tunnel City Group and the overlying Jordan Formation assuming that the lower St. Lawrence Formation represents the transgressive maximum (see Fig. 13A).

St. Lawrence Formation outcrop belt (Fig. 2) parallels the paleoshoreline and does not permit detailed evaluation of any east-west component to this trend.

The abundance of flat-pebble conglomerates within the St. Lawrence Formation suggests to us a scenario which builds particularly on the interpretation of Runkel (1994a), shown in Fig. 14. Following a relative sea-level rise and deepening represented by the top of the Tunnel City Group, deposition occurred predominantly in the northern area, and the southern area became starved of siliciclastic sediment. Hence, while heterolithic offshore facies and an feldspathic lower shoreface facies were being deposited in the neighborhood of Osceola, a relatively condensed succession of glauconitic flat pebble conglomerates accumulated in the south (*e.g.* Lansing). (Only locally at this time were conditions such that algal bioherms could develop, *e.g.* at Black Earth.) As the rate of relative sea-level rise slowed, so shoreface progradation became more rapid and eventually smothered the whole area.

The development of flat-pebble conglomerates in the middle parts of the St. Lawrence Formation may be related to the interruptions in progration suggested by Runkel (1994a). Runkel's fine-grained feldspathic tongues have flat-pebble conglomerates ("intraclast lags") at their bases which he attributed to erosion during short-lived phases of shoreface retreat, and the erosion products of this process, including both lithified and unlithified sand, would undoubtedly be transported out into the offshore environments represented by the St. Lawrence Formation. Both Runkel (1994a) and Byers and Dott (1995) infer that relative-level must have fallen to generate the facies juxtapositions that they describe within the Jordan Formation. Hence, it is also possible that flat-pebble conglomerates (particularly the matrix-supported varieties associated with laminated sand) were generated during phases of relative sea-level fall, when storm-wave-base impinged frequently upon the sea-floor, but in well before the advancing shoreface reached the area (cf. Plint, 1988; Hadley and Elliott, 1993); this situation is also illustrated schematically in Fig. 14.

CONCLUSIONS

Reinvestigation of the biostratigraphy and sedimentology of the St. Lawrence Formation in the northern Mississippi Valley reaffirms the previously reported discordance between lithologic and biostratigraphic units. Extensive taxonomic revision will be necessary before the faunal sequence can be tightly constrained, but nevertheless a revised four-fold subdivision of the *Saukia* Zone presently has utility. Detailed field descriptions reveal the presence of three main lithofacies: 1) a heterolithic dolomite-sandstone facies; 2) a flat-pebble conglomerate and laminated sandstone facies and 3) a stromatolitic dolomite facies. Bathymetric indicators within these facies are ambiguous.

Regional stratigraphic relationships suggest that over all but the most northern part of the study area the base of the St. Lawrence Formation was deposited as the toe-set of a northward retreating shoreface in response to regional relative sea-level rise. This interval is represented mainly by glauconitic flat-pebble conglomerates and laminated sandstones of the lower *Saukia* Zone which may locally be strongly condensed. The top of the St. Lawrence Formation, a mixture of heterolithic facies and flat-pebble conglomerate/laminated sandstone facies of the middle to upper *Saukia* Zone, is best interpreted as having been deposited as the toe-set of a southward prograding shoreface in response to regional relative sea-level highstand and fall.

The presence of flat-topped ripples, runzlemarks and mudcracks, often taken as good evidence of subaerial exposure, is seemingly in conflict with the faunal content and larger-scale stratigraphic relationships of the Formation which indicate open-marine conditions.

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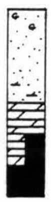
APPENDIX

Detailed stratigraphic sections of St. Lawrence Formation and adjacent units. Locality details for sections are given in Hughes (1993), except for the following localities: Hokah, HH, disused quarry on west side of Hwy 16, 6.5 km west of Hokah, Houston County, Minnesota; Tubb's Farm, Avoca, AT, old quarry, west side of Bremmer Road, 1.5 km south of junction with Hwy 133, Iowa County, Wisconsin; Mauston, MN, roadcut on north side of County Trunk O, 8 km east of Elroy, Juneau County, Wisconsin. The locality abbreviation LSa refers only to the section north of Lansing, Iowa (*contra* Hughes, 1993, p. 25). Division of the Jordan Formation into facies follows Runkel (1994a,b).

KEY TO STRATIGRAPHIC SECTIONS

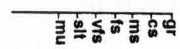
STRATIGRAPHIC ABBREVIATIONS:

FMN	Formation
MBR	Member
fs	facies
f/sd	flat pebble conglomerate/laminated sandstone
het.	heterolithic
strom. dol.	stromatolithic dolomite
feld	feldspathic
qtz	quartzose
——	Formation boundary
----	facies boundary



glauconitic sandstone
sandstone
dolomitic sandstone
dolomitic siltstone
dolomitic mudstone
mudstone

sediment grain size



mu	mud
slt	silt
vfs	very fine sandstone
fs	fine sandstone
ms	medium sandstone
cs	coarse sandstone
gr	gravel/pebble

220° n=2 ∂n=2° - paleocurrent - mean direction, number of measurements, standard deviation of direction

TRACE FOSSILS

- vertical burrow
- horizontal burrow
- *Rusophycus/Raaschichnus*
- *Arenicolites*
- circular trace
- spindle-shaped trace

- wrinkle mark
- ripple mark
- interference ripple
- flat-topped ripples
- shrinkage crack
- shell bed
- stylonodular texture

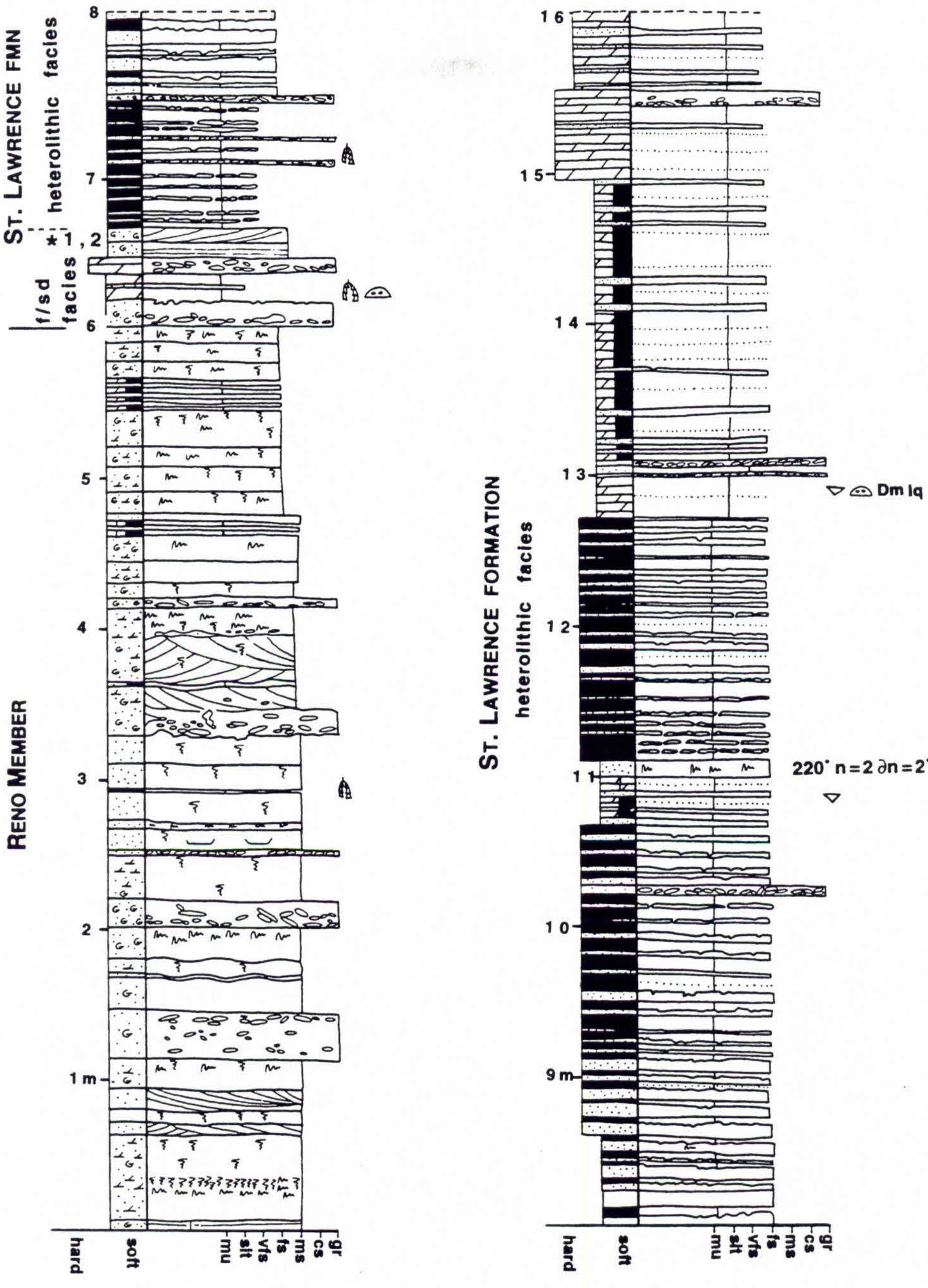
TRILOBITES

Dm	*Dikelocephalus minnesotensis*
O	*Osceolia*
W	*Walcottaspis*
Ip	*Illaenurus priscus*
Iq	*Illaenurus quadratus*
Sk	*Saukia*
T	*Tellerina*
C	*Calvinella*
Skl	*Saukiella*
E	*Eurekia*
M	*Macronoda*
R	*Rasettia*

OTHER BODY FOSSILS

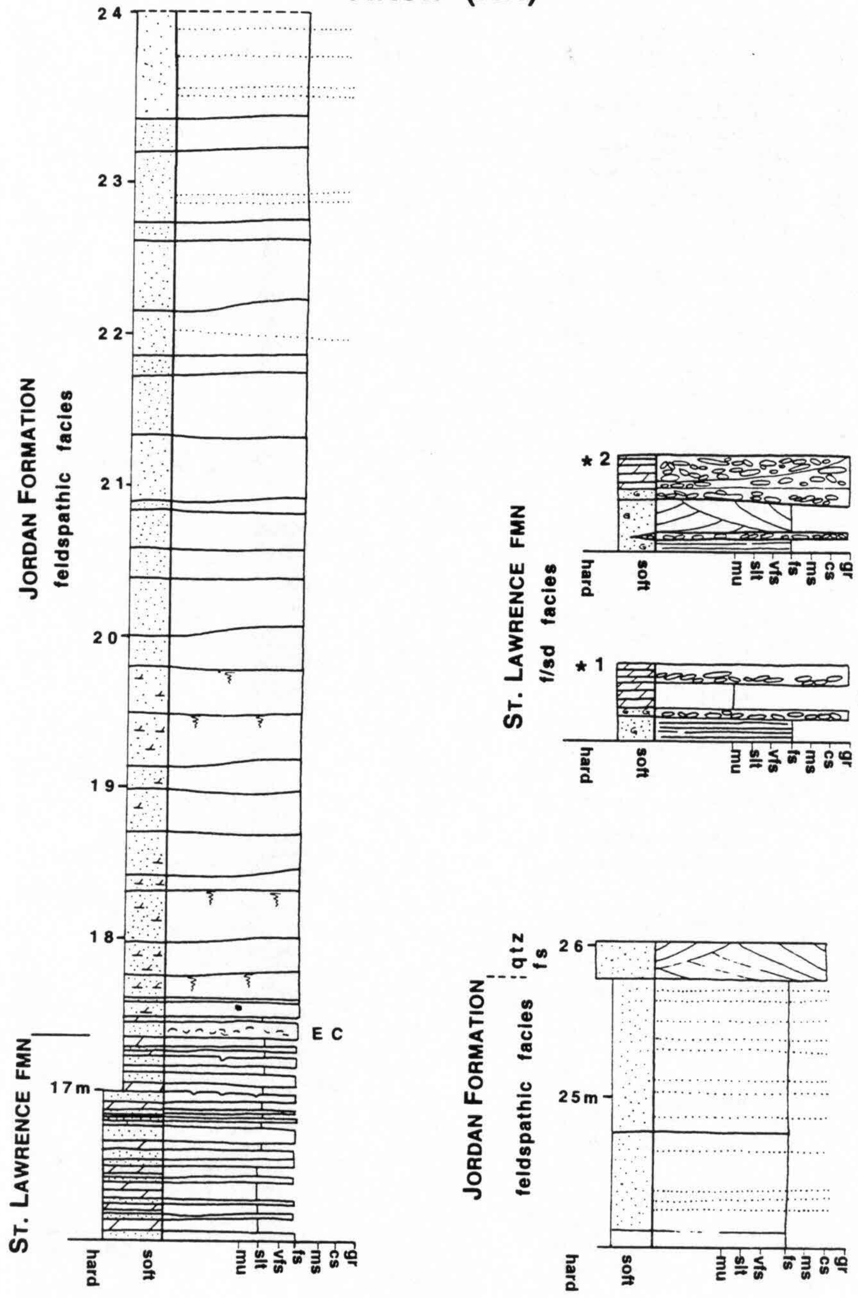
- inarticulate brachiopods
- articulate brachiopods
- aglaspidids
- dendroid graptolites
- gastropods
- serpulids
- echinoderm columnals
- hyolithids
- phyllocarids
- stromatolite

Afton (AN)



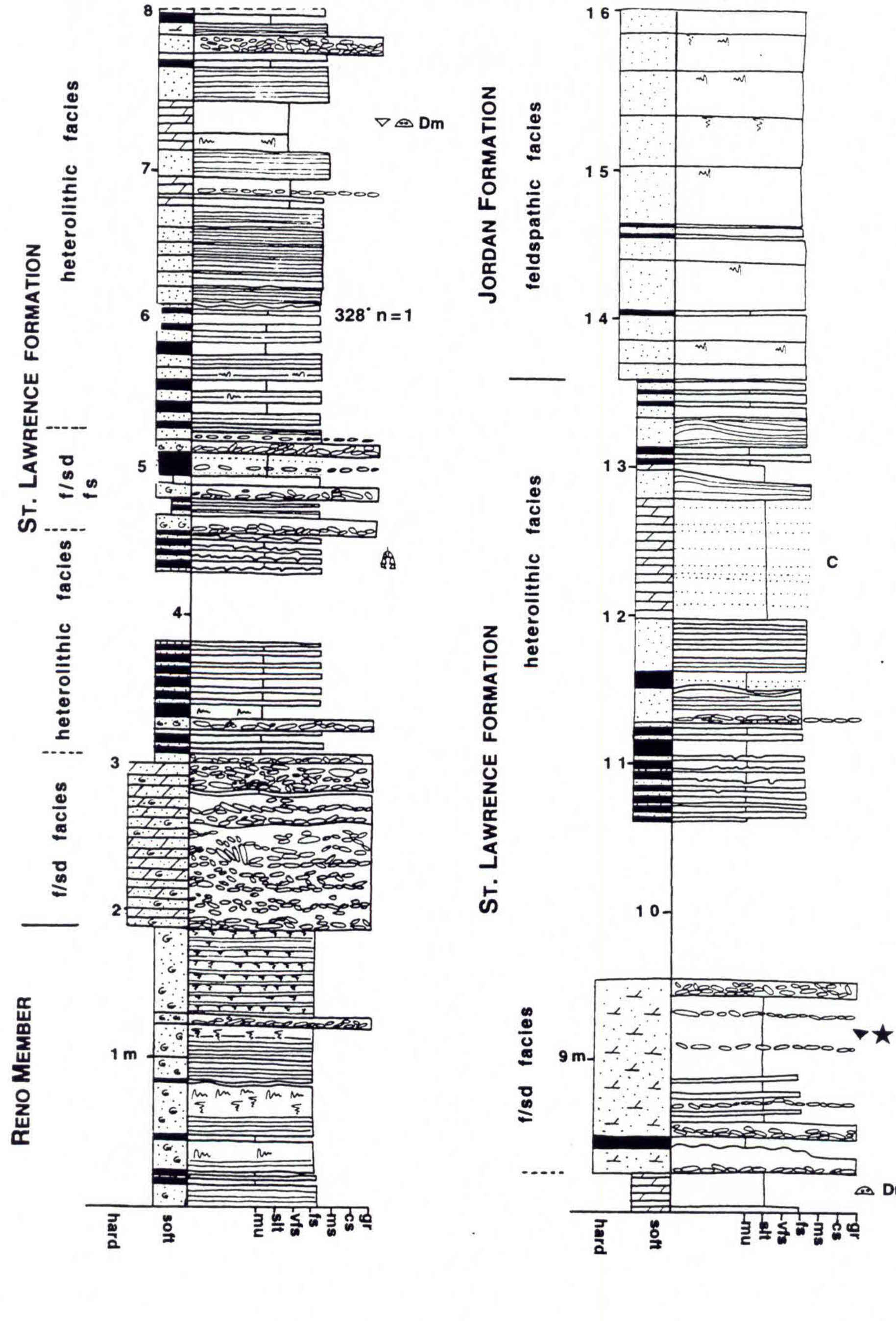
ST. LAWRENCE FMN
heterolithic facies
*1, 2
f/sd facies
RENO MEMBER
ST. LAWRENCE FORMATION
heterolithic facies
Dm lq
220° n=2 ∂n=2°
1 m
9 m
hard
soft
mu
slt
vfs
fs
ms
cs
gr

Afton (AN)

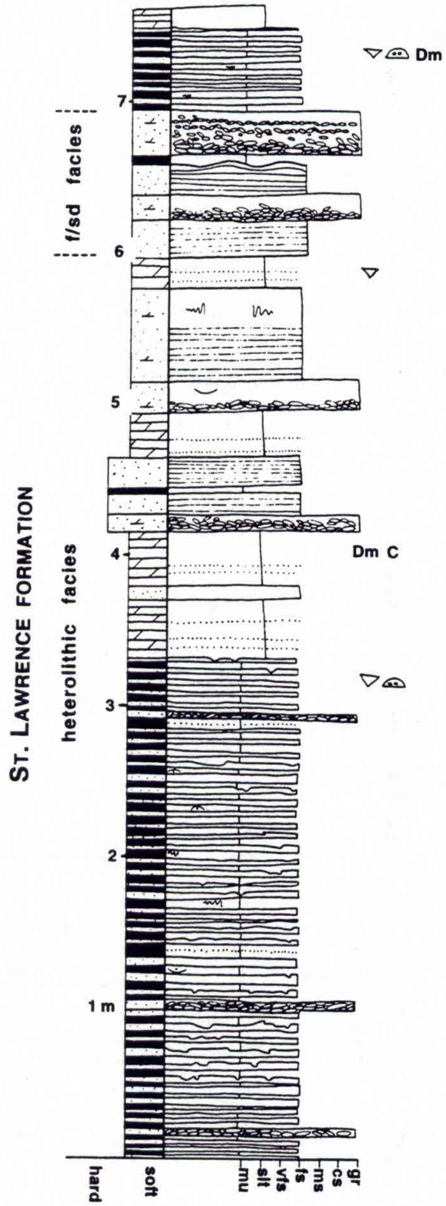


JORDAN FORMATION
feldspathic facies
ST. LAWRENCE FMN
17m
18
19
20
21
22
23
24
EC
hard
soft
mu
slt
vfs
fs
ms
cs
gr
ST. LAWRENCE FMN
f/sd facies
*1
*2
JORDAN FORMATION
feldspathic facies
qtz
fs
25m
26

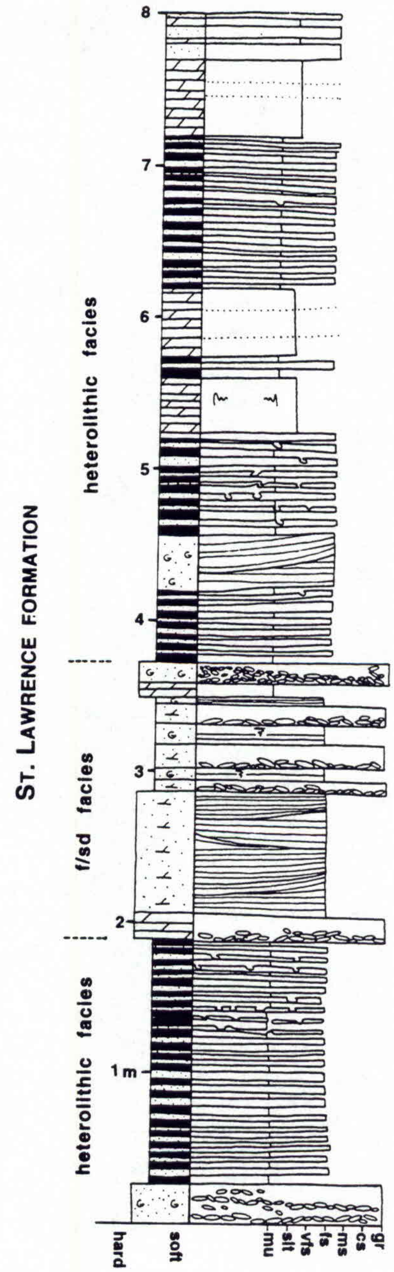
Arcadia, Co. J 13.5 km (AAb)



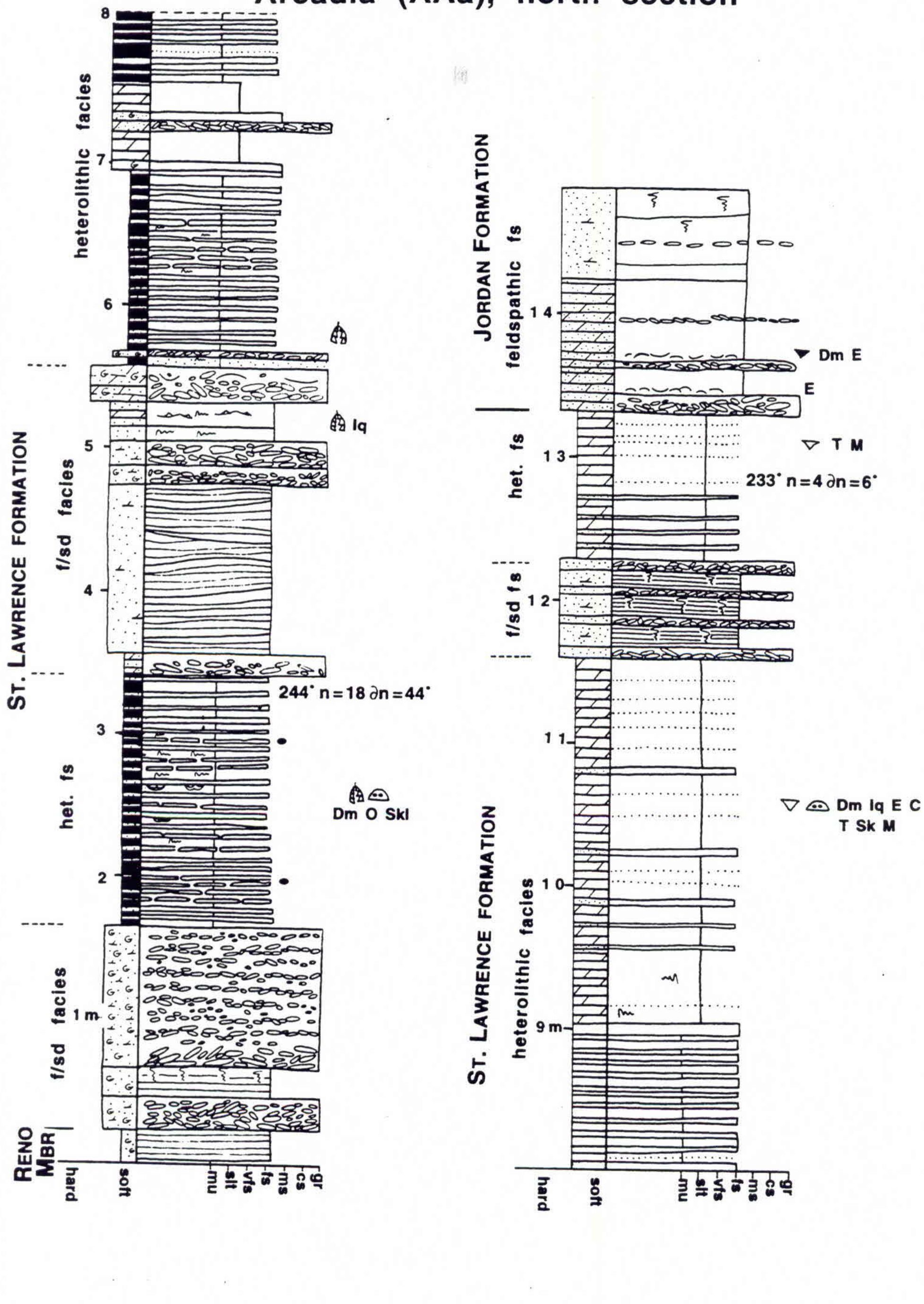
Arcadia,
Co. J 11 km (AAb)



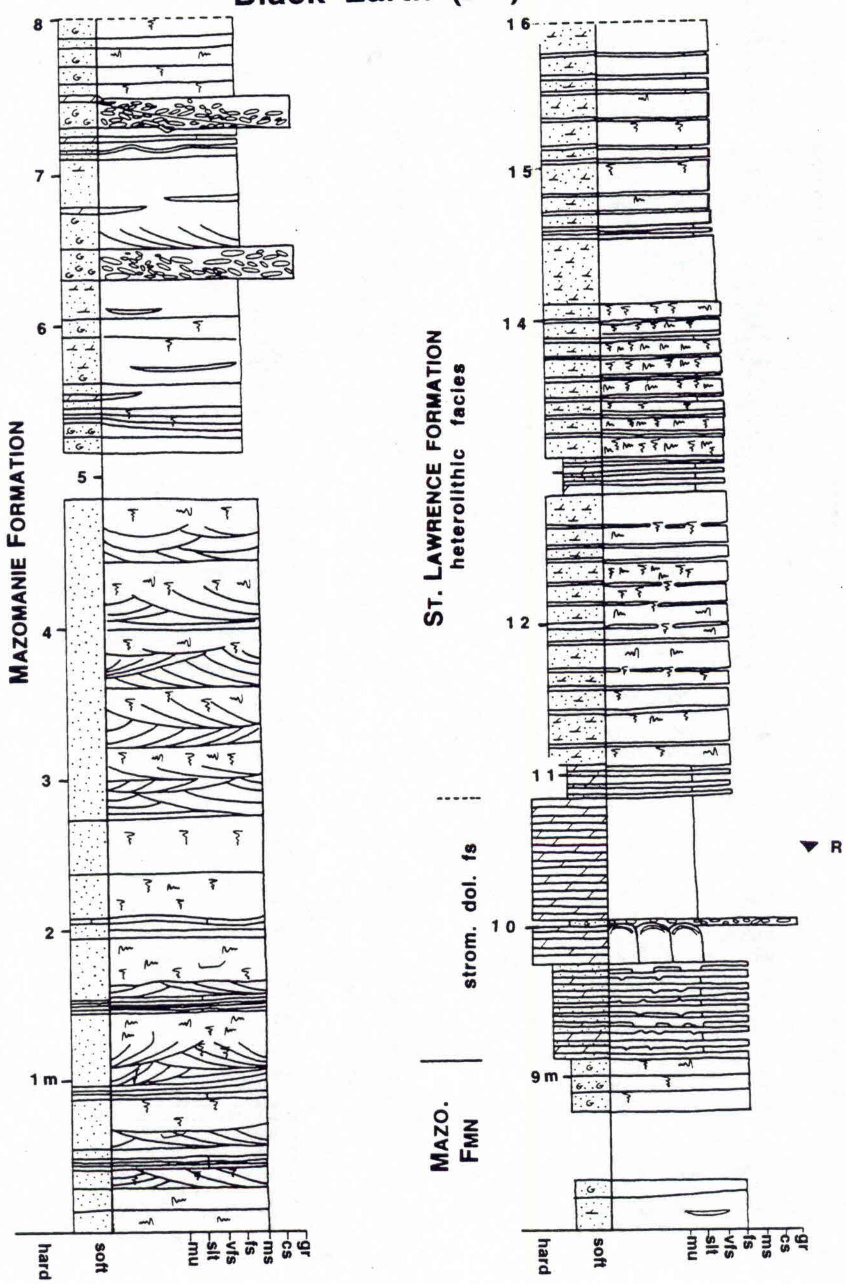
Arcadia (AAa),
south section

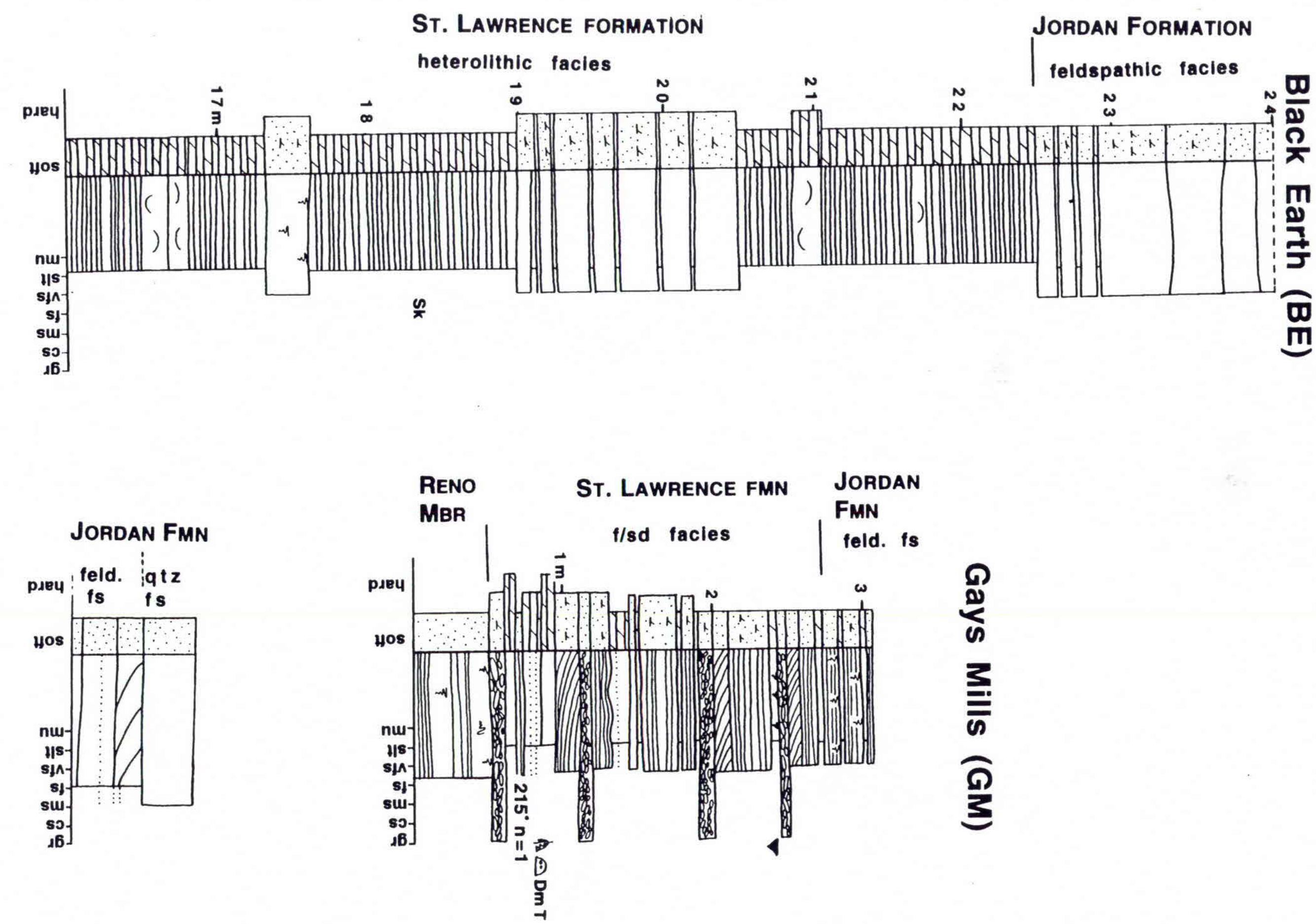


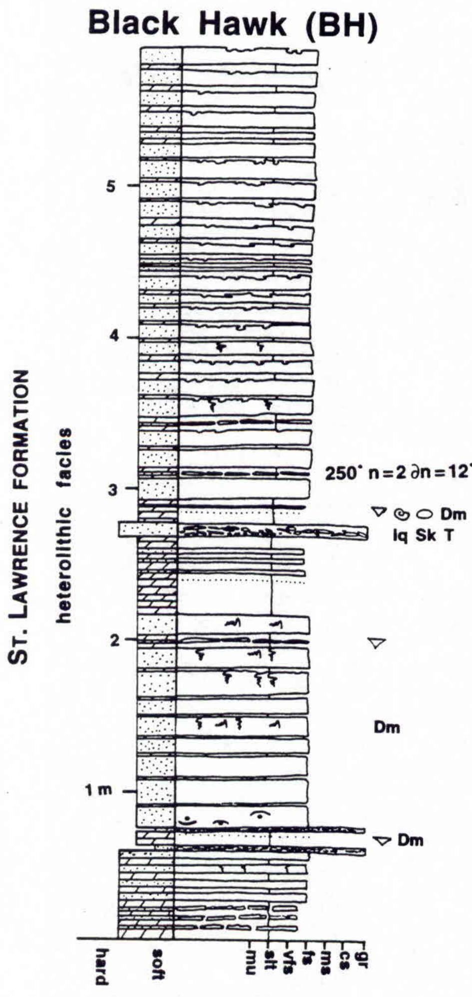
Arcadia (AAa), north section



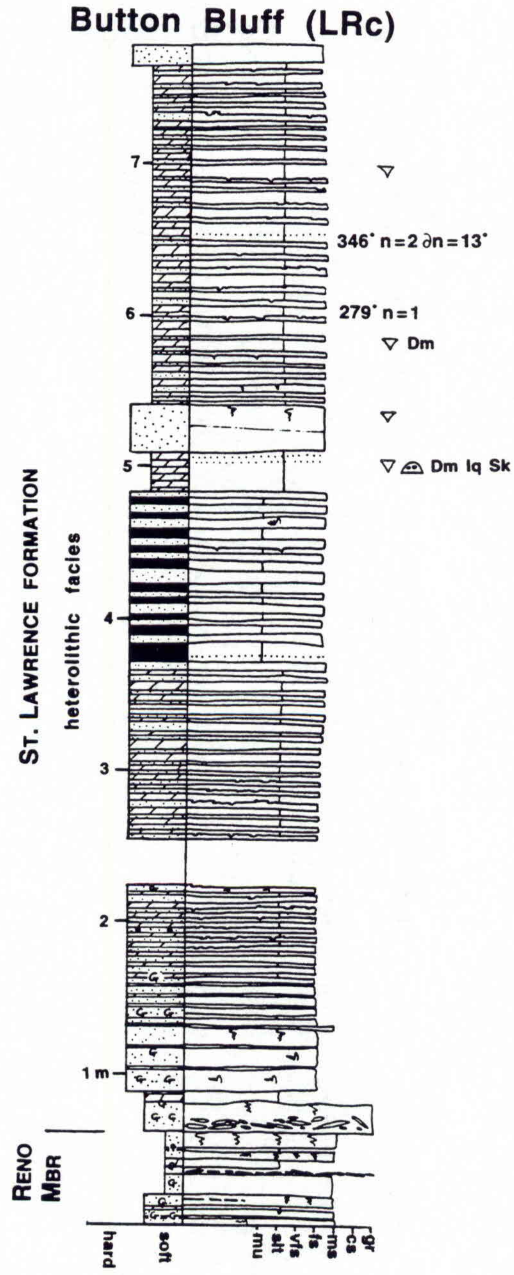
Black Earth (BE)




ST. LAWRENCE FORMATION
heterolithic facies
JORDAN FORMATION
feldspathic facies
Black Earth (BE)
17 m
18
19
20
21
22
23
24
hard
soft
mu
slt
vfs
fs
ms
cs
gr
sk
JORDAN FMN
feld. fs
qtz fs
RENO MBR
ST. LAWRENCE FMN
f/sd facies
JORDAN FMN
feld. fs
1 m
2
3
215° n=1
Dm T
Gays Mills (GM)

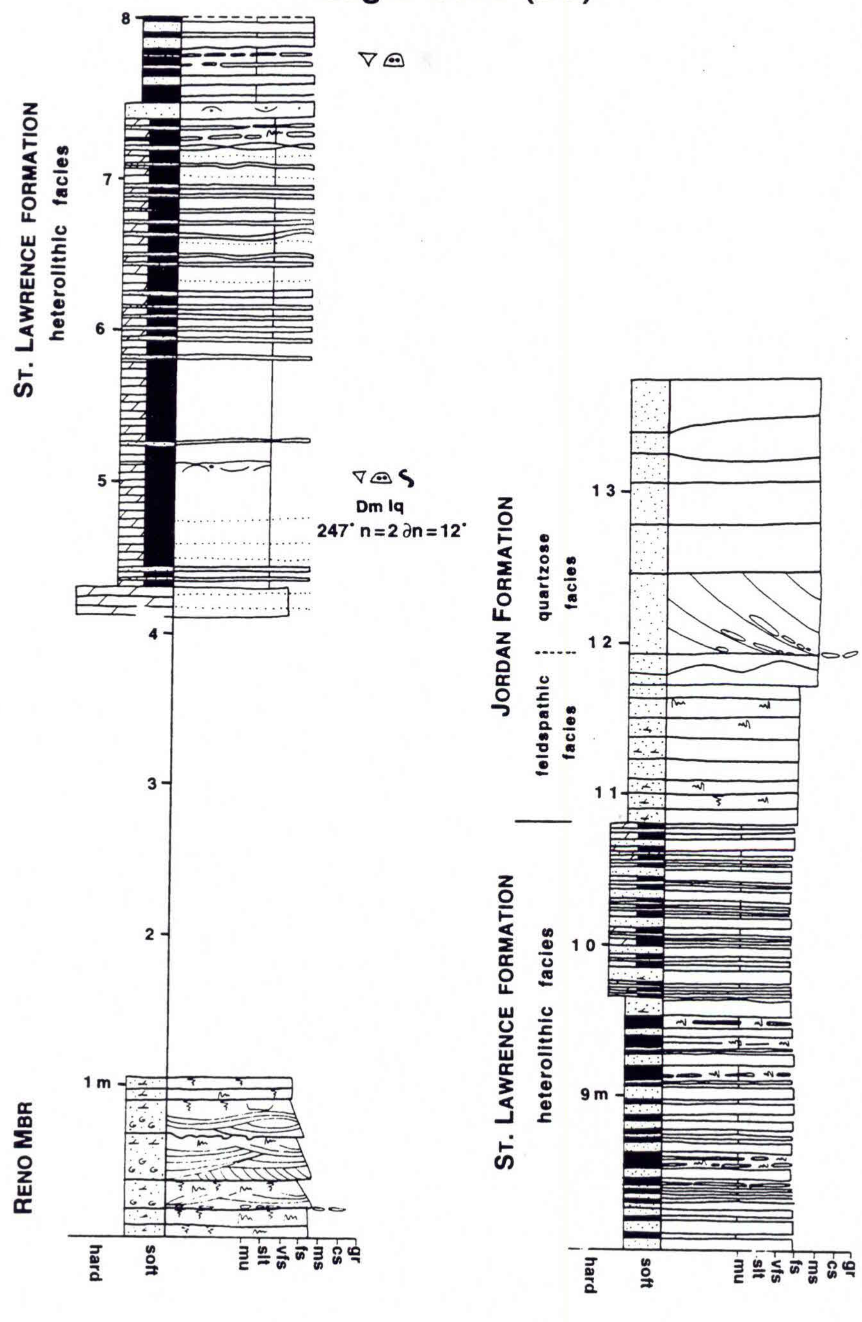


Black Hawk (BH)
St. Lawrence Formation
heterolithic facies
5
4
3
2
1 m
250° n=2 ∂n=12°
▽ Dm
Iq Sk T
▽
Dm
▽ Dm
hard
soft
mu
slt
vfs
fs
ms
cs
gr

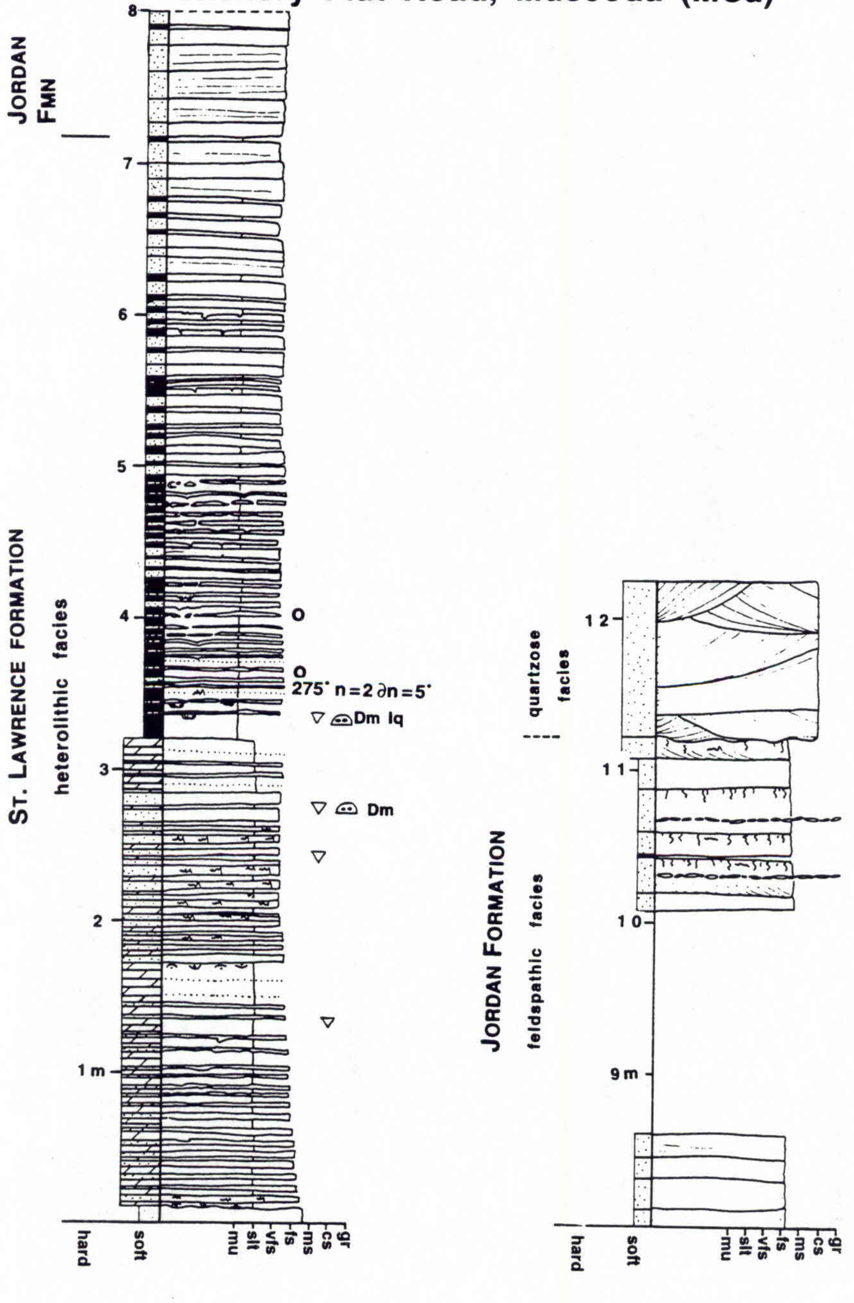


Button Bluff (LRc)
St. Lawrence Formation
heterolithic facies
Reno Mbr
7
6
5
4
3
2
1 m
▽
346° n=2 ∂n=13°
279° n=1
▽ Dm
▽
▽ Dm Iq Sk
hard
soft
mu
slt
vfs
fs
ms
cs
gr

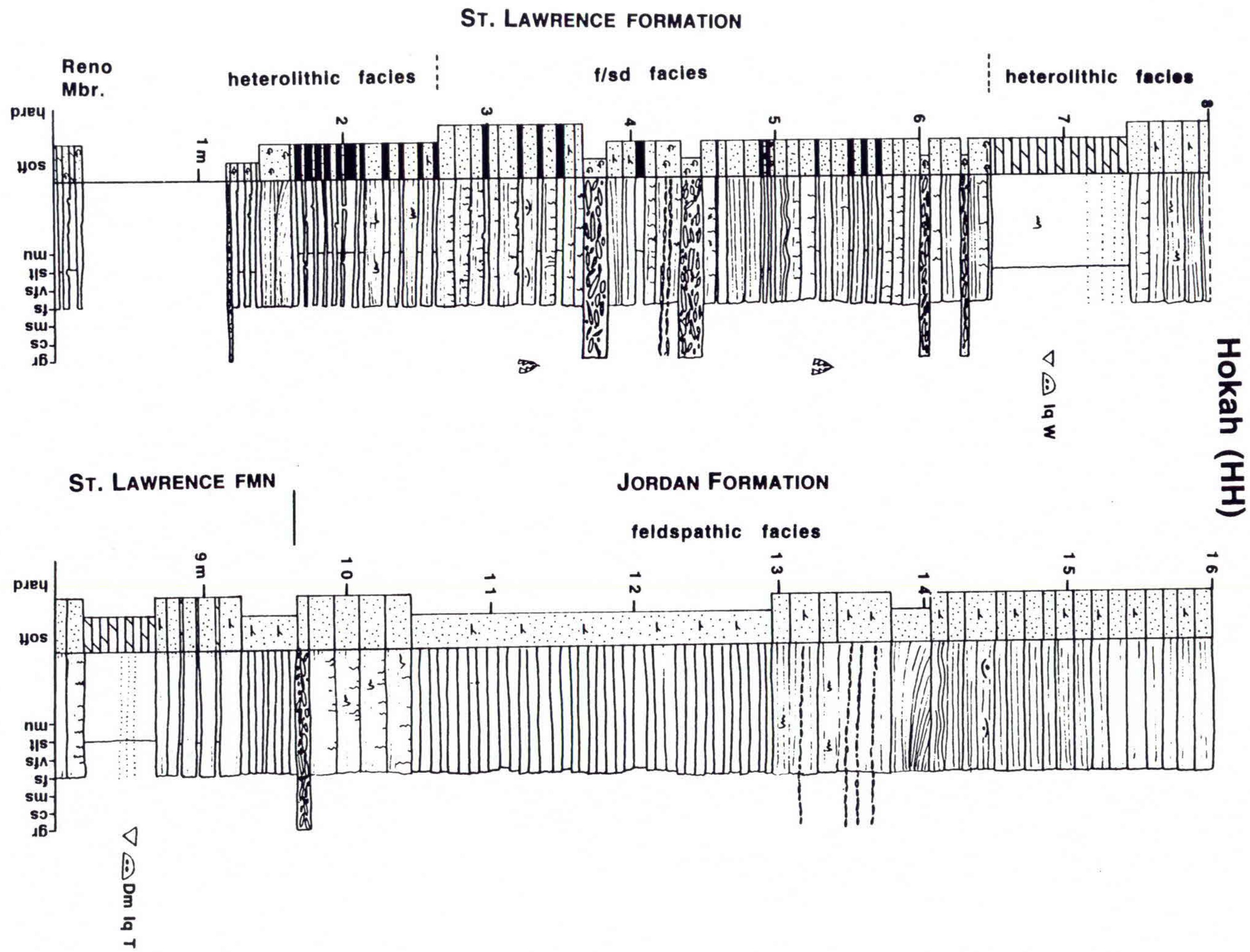
Eagle Cave (EC)



Hickory Flat Road, Muscoda (MCa)

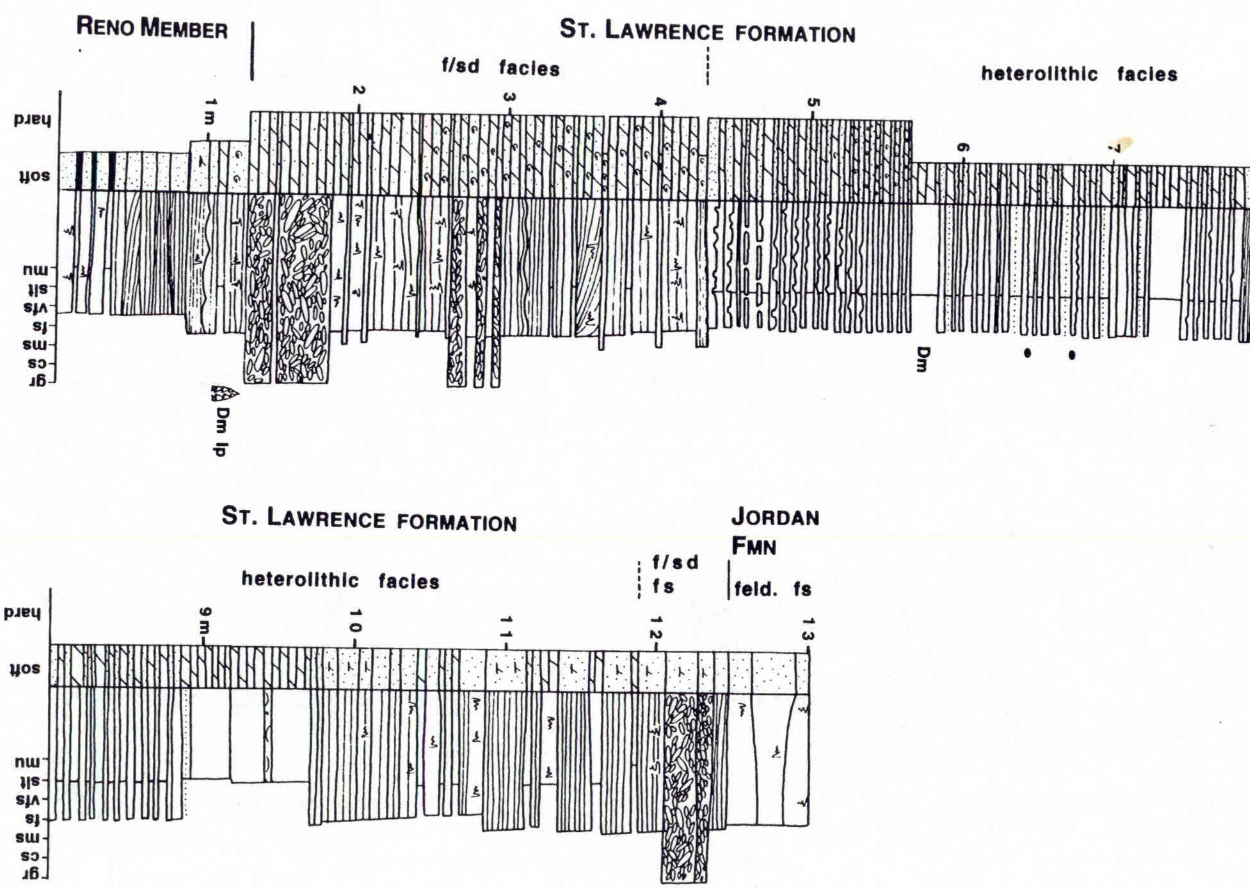


Hokah (HH)

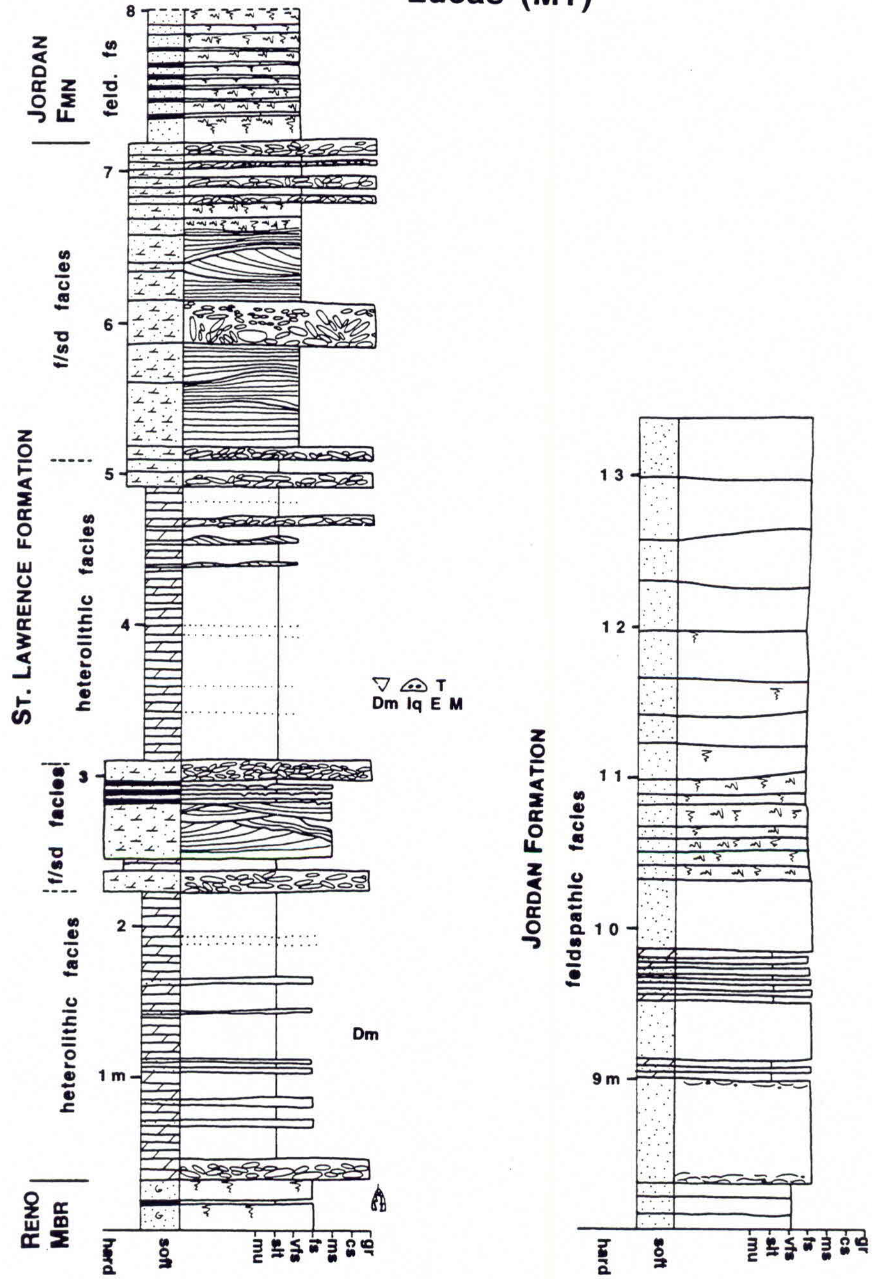


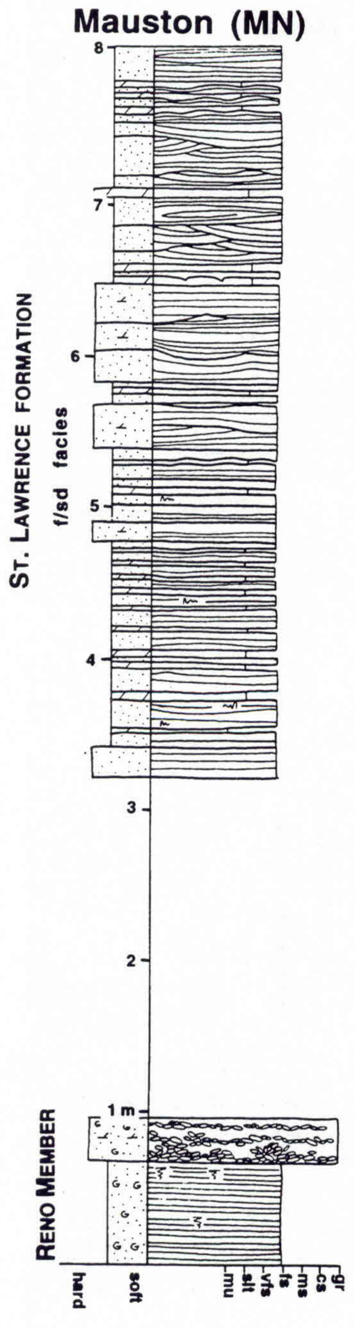
ST. LAWRENCE FORMATION
Reno Mbr.
heterolithic facies
f/sd facies
heterolithic facies
hard
soft
mu
slt
vfs
fs
ms
cs
gr
1 m
2
3
4
5
6
7
8
lq W
ST. LAWRENCE FMN
JORDAN FORMATION
feldspathic facies
9m
10
11
12
13
14
15
16
Dm lq T

Lansing (LSa)

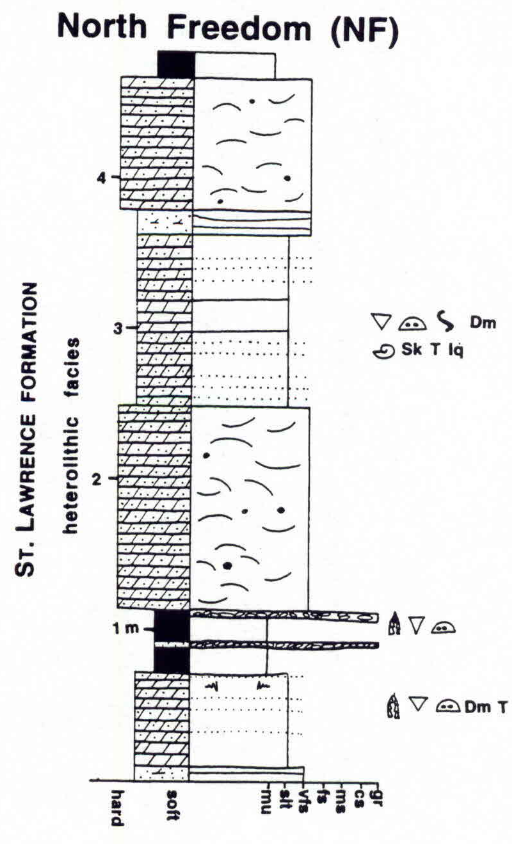

RENO MEMBER
ST. LAWRENCE FORMATION
f/sd facies
heterolithic facies
hard
soft
mu
silt
vfs
fs
ms
cs
gr
1 m
2
3
4
5
6
7
8
Dm lp
Dm
ST. LAWRENCE FORMATION
heterolithic facies
f/sd
fs
JORDAN
FMN
feld. fs
9 m
10
11
12
13

Lucas (MT)

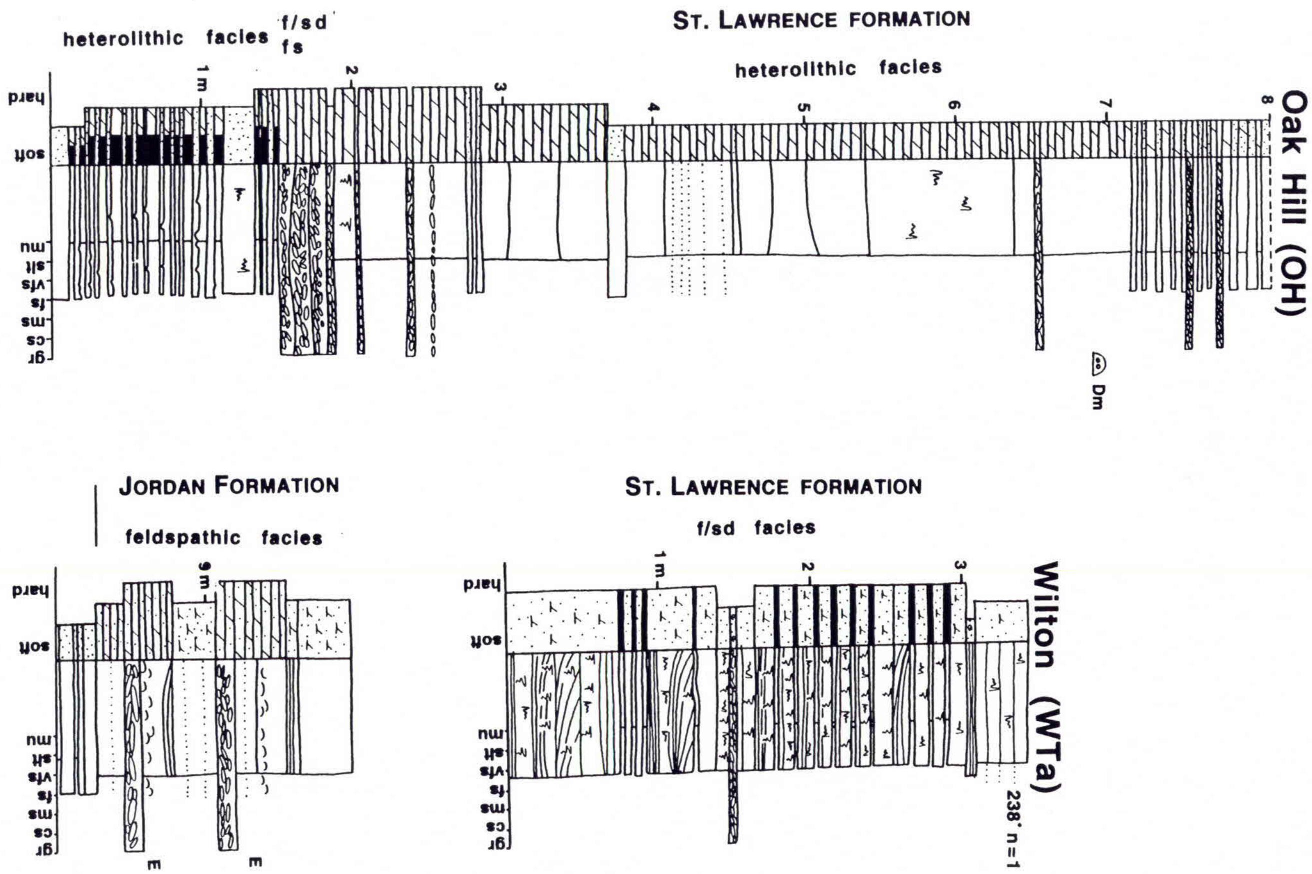

JORDAN FMN
feld. fs
ST. LAWRENCE FORMATION
f/sd facies
heterolithic facies
f/sd facies
heterolithic facies
RENO MBR
Dm Iq E M
T
Dm
1 m
2
3
4
5
6
7
8
hard
soft
mu
slt
vfs
fs
ms
cs
gr
JORDAN FORMATION
feldspathic facies
9 m
10
11
12
13



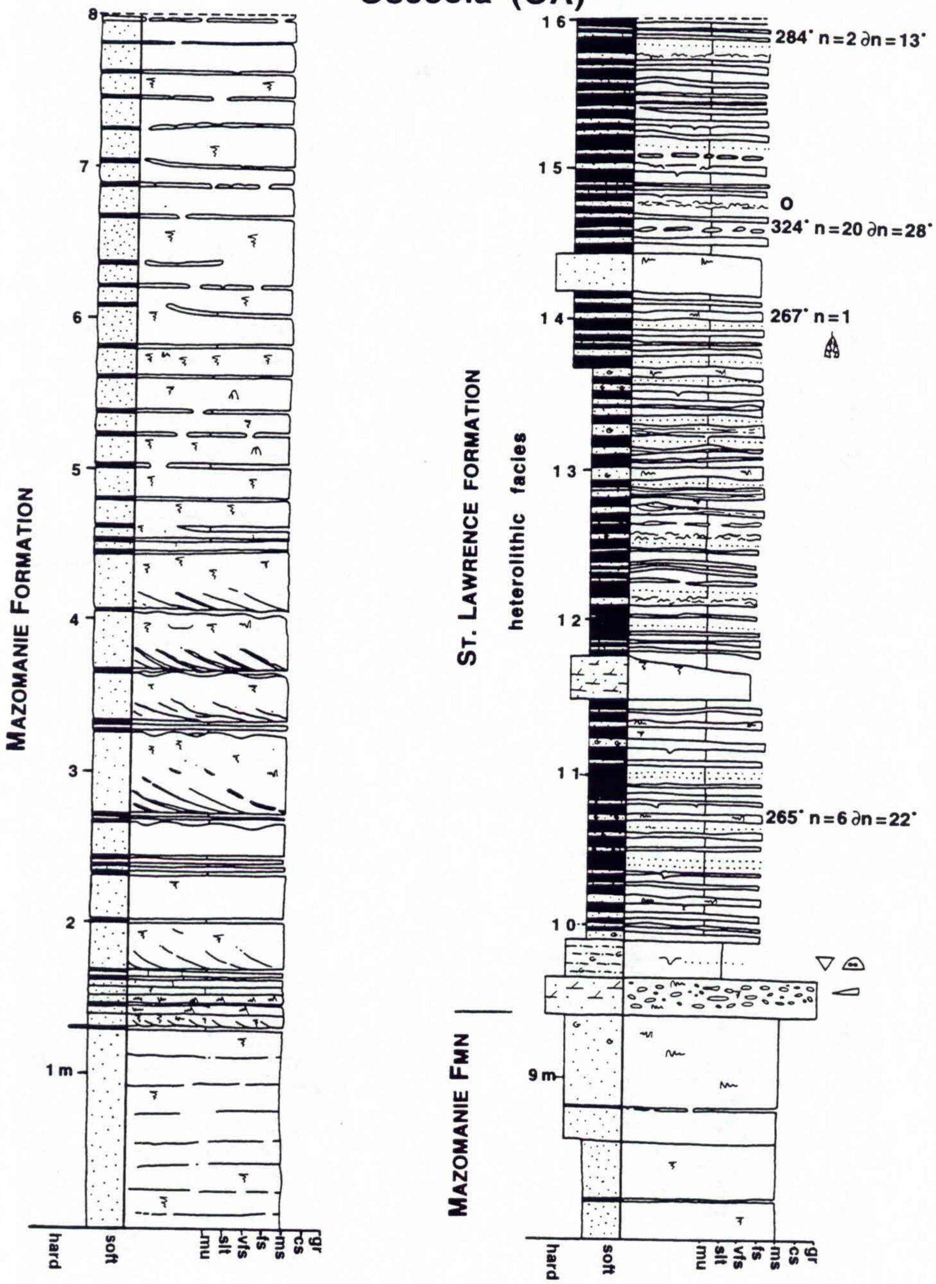
Mauston (MN)
St. Lawrence Formation
f/sd facies
Reno Member
1 m
2
3
4
5
6
7
8
hard
soft
mu
slt
vfs
fs
ms
cs
gr



North Freedom (NF)
St. Lawrence Formation
heterolithic facies
1 m
2
3
4
Dm
Sk T Iq
Dm T
hard
soft
mu
slt
vfs
fs
ms
cs
gr

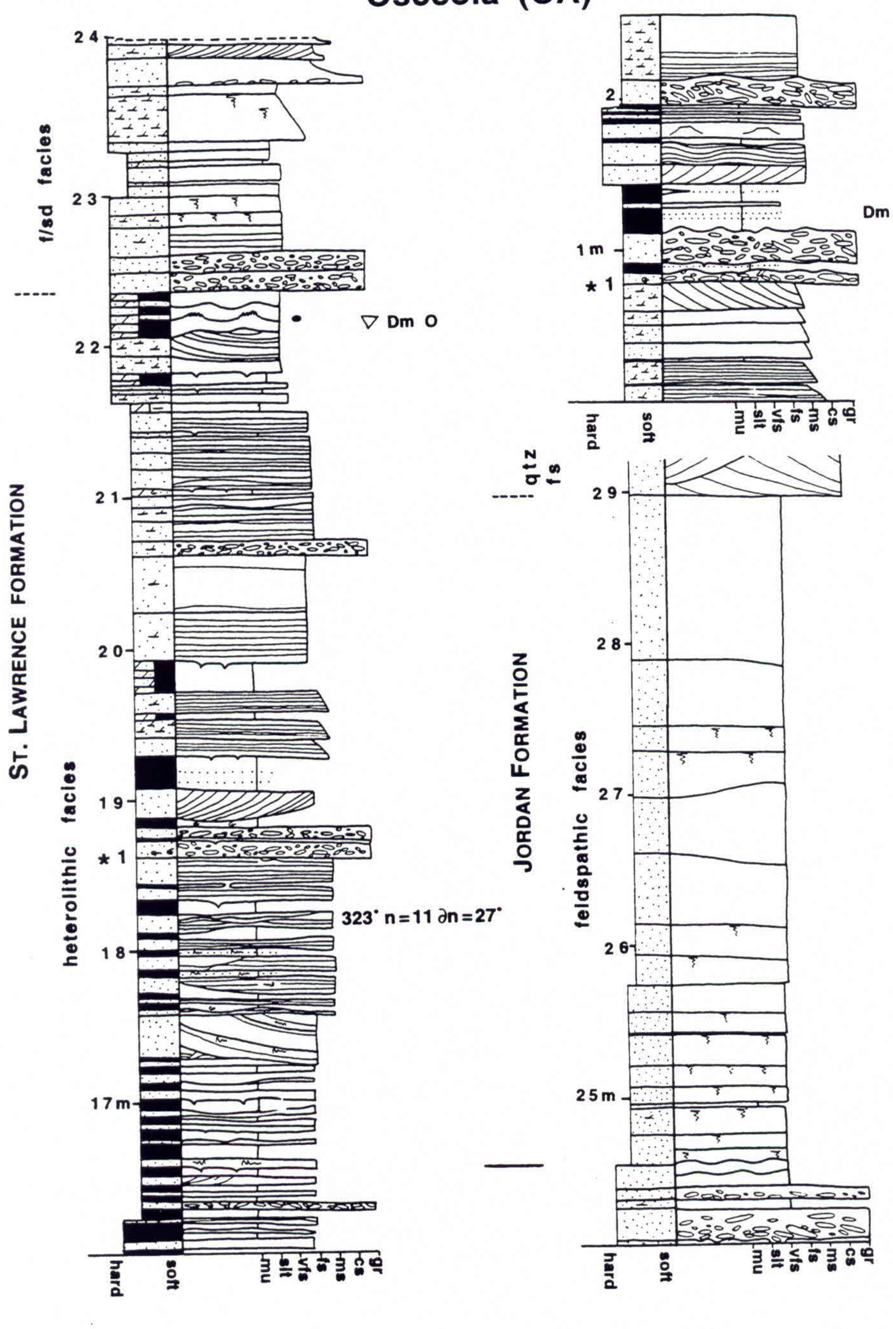

Oak Hill (OH)
heterolithic facies
f/sd
fs
ST. LAWRENCE FORMATION
heterolithic facies
1 m
2
3
4
5
6
7
8
hard
soft
mu
slt
vfs
fs
ms
cs
gr
Dm
Wilton (WTa)
JORDAN FORMATION
feldspathic facies
9 m
ST. LAWRENCE FORMATION
f/sd facies
1 m
2
3
238° n=1

Osceola (OA)

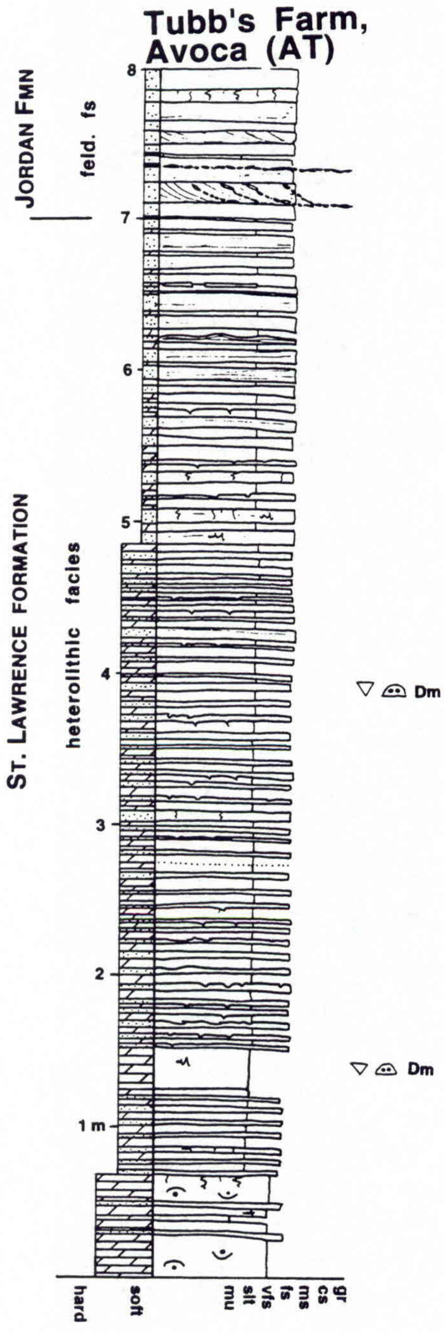


Mazomanie Formation
St. Lawrence Formation
heterolithic facies
Mazomanie Fmn
284° n=2 ∂n=13°
324° n=20 ∂n=28°
267° n=1
265° n=6 ∂n=22°
O
1 m
9 m
hard
soft
mu
slt
vfs
fs
ms
cs
gr

Osceola (OA)



24
23
22
21
20
19
18
17m
f/sd facies
▽ Dm O
ST. LAWRENCE FORMATION
heterolithic facies
* 1
323° n=11 ∂n=27°
hard
soft
mu
slt
vfs
fs
ms
cs
gr
2
Dm
1m
* 1
qtz
fs
29
28
27
26
25m
JORDAN FORMATION
feldspathic facies



Tubb's Farm, Avoca (AT)
Jordan Fmn
feld. fs
St. Lawrence Formation
heterolithic facies
8
7
6
5
4
3
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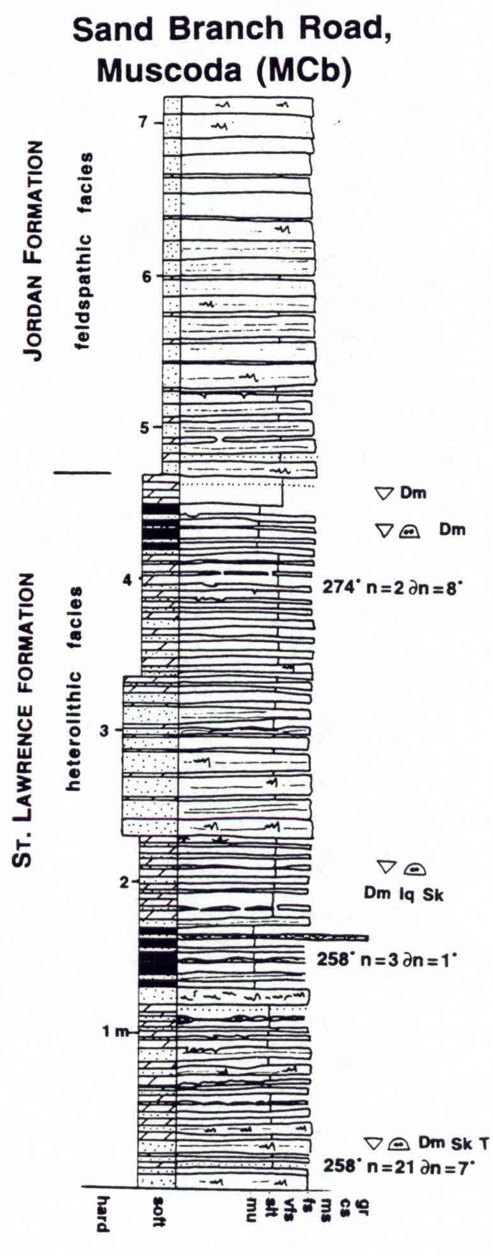
1 m
Dm
Dm
hard
soft
mu
slt
vfs
fs
ms
cs
gr



Sand Branch Road, Muscoda (MCb)
Jordan Formation
feldspathic facies
St. Lawrence Formation
heterolithic facies
7
6
5
4
3
2
1 m
Dm
Dm
274° n=2 ∂n=8°
Dm Iq Sk
258° n=3 ∂n=1°
Dm Sk T
258° n=21 ∂n=7°
hard
soft
mu
slt
vfs
fs
ms
cs
gr