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STRATIGRAPHY OF THE MONKTON FORMATION, NORTHWESTERN VERMONT

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ABSTRACT

The Monkton Formation (latest Early Cambrian) is a heterolithic unit recording fluvial to tidally-influenced deposition on the western Vermont portion of the Iapetus margin. Twelve lithofacies are recognized in the Monkton, representing the architectural elements of a marginal marine setting comprising a fluvial, carbonate shelf, intertidal to subtidal sand flat, carbonate pond, and subtidal sand bar deposystem. Monkton lithofacies contain evidence of both tidal and wave-dominated processes, interpretations based in analysis of sedimentary structures and paleocurrent data. The study area for this report extends from the northernmost exposure of the Monkton in Colchester, Vermont, south along strike to Burlington, and Pease Mountain in Charlotte, Vermont. The Monkton Formation was deposited during the transgression over the underlying Dunham Dolostone and the lowest 50 meters of the Monkton are dominantly carbonate in composition. The Monkton becomes more clastic-rich up section as sediment input caught up sea level rise, and carbonate horizons become confined to portions of shallowing-up cycles (parasequences). Towards the top of the Monkton the rate of sea level rise slowed, as evidenced by changes in the thickness and architecture of parasequences. Facies changes parallel to strike occur in the Monkton Formation. In the Colchester area north of Burlington lies the shelf edge transition into the Franklin Basin. The red-colored tidally-influenced sandstones that characterize the Monkton in Burlington, Mt Philo, the top of Pease Mountain, and elsewhere in the Champlain Valley pinch out towards the north in Colchester. Shelf-edge sand bodies become the dominant Monkton lithology on the platform margin. Despite these along-strike facies changes the overall thickness of the unit appears relatively constant at 350-400 m however the presence ofyounger high angle faults, some exposed and some inferred, makes this thickness equivocal.

Measured stratigraphic columns for outcrops in the Colchester, Burlington and Pease Mountain regions, along with paleoflow rose diagrams and field photos are illustrated in three plates with accompanying text.

KEY WORDS: Cambrian, tidal, parasequences

INTRODUCTION

The Monkton Formation is one of the most recognizable rock units in western Vermont. Resistant cliffs of red sandstone form the tops of hillsides such as Mt Philo and Snake Mountain (Addison County) and the rock has historically been quarried for building stone. The Monkton is also one of the only shelf units in the Cambro-Ordovician stratigraphy that has yielded a biostratigraphically significant fauna of *Olenellus* zone age (Palmer and James, 1979 and references therein) (Figure 1). This study presents detailed measured stratigraphic sections of the Monkton from key localities in northwestern Vermont, including paleocurrent data, descriptions of lithofacies comprising the stratigraphy, and interpretations of the depositional environments represented by these lithofacies.

REGIONAL STRATIGRAPHY AND GEOLOGIC SETTING

The Monkton Formation is part of the Western Shelf Sequence (term after Dorsey et al., 1983) of alternating carbonate and siliciclastic units of Cambrian age that outcrop in western Vermont. The Western Shelf Sequence consists of an approximately 3 km thick package of shallow marine sediments of heterolithic compositions that formed on the Iapetus margin through the Cambro- Ordovician. Deep water sediments of the intrashelf Iapetus Basin (termed the Franklin Basin by Shaw, 1958) outcrop in northwestern Vermont, to the north of the shelf sequence. The southern edge of the intrashelf basin lies at the northern edge of this study area, in Milton, Vermont, and extends northward across the Canadian border (Dorsey et al., 1983). Outcrops of the Monkton Formation in the Colchester region are the northernmost exposures of this unit before it pinches out on the edge of the Franklin Basin (Figures 2 and 3) and passes into the Parker Slate. Along with other Cambrian units the Monkton lies on the upper plate of the Champlain Thrust and was therefore emplaced westward approximately 80 km (Stanley, 1987). Despite the presence of younger high angle normal faults, the paleogeographic relationship of the shelf units to those of the Franklin Basin in northwestern Vermont appear to be preserved (Figure 2).

The Monkton Formation overlies the Dunham Dolostone and is overlain by the Winooski Dolostone (Figure 1). The contact of the Monkton with the underlying Dunham in the Vergennes region was described by Goldberg and Mehrtens (1997). Their study was significant in that it described and interpreted the only exposed non-marine lithofacies of the Monkton Formation in western Vermont and the erosional nature of the Dunham/Monkton contact. In the Colchester region of northwestern Vermont (Niquette Bay State Park, Colchester (Plate 2, Figure 3)), a thin covered interval separates the Monkton from the Dunham. The upper contact with the Winooski is not exposed in any of the localities in this study but at the Salmon Hole locality in Burlington a thin covered interval of 5.25 m occurs between the units. Cady (1945) characterized the thickness of the Monkton Formation in the Champlain Valley as highly variable. In his study of the stratigraphy of the Champlain Valley, Welby (1961) reported that the Monkton was 1,100 to 1,150 feet (335 to 350 meters) thick, however at no localities did Welby see both the top and bottom contacts of the Monkton exposed. In this study the thickness of the Monkton appears to be fairly consistent between 350-400 meters however, the presence of younger high angle faults, some exposed and some inferred, makes this thickness equivocal.

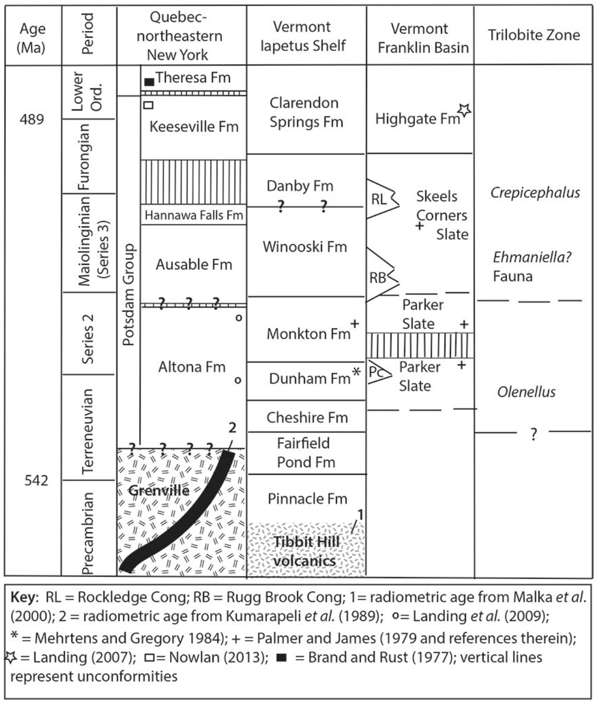

Figure 1. Correlation chart for Early Cambrian units in northwestern Vermont and adjacent northeastern New York. The key to this figure provides references for age control.

METHODS

Outcrops were measured and described at the centimeter scale with particular attention to sedimentary structures, which include cross lamination, hummocky cross stratification, oscillatory ripples, graded bedding, trough and planar cross stratification, herringbone cross stratification, horizontal laminations, mudcracks, and bioturbation. When available, measurements were taken of cross bedding and ripple crestline orientations to provide data on

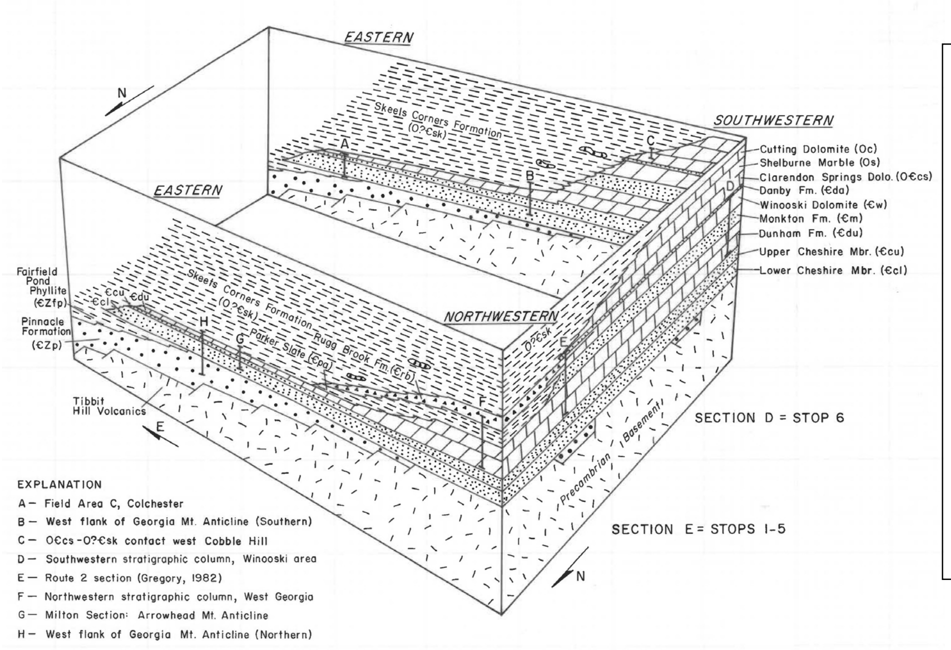

Figure 2. Block diagram from Dorsey et al. (1983) showing the platform to basin transition of Cambrian-Lower Ordovician units in western Vermont. The perspective of the view is to the southeast; the Burlington region is the southwestern corner of the block diagram.

paleoflow direction. Covered intervals within transects were measured by surveying and the gaps between the highest exposure of the Monkton and the lowest Winooski were determined by using average dips and measurement of distance in Google Earth©.

Lithofacies

Twelve lithofacies recording fluvial to shallow marine environments have been recognized in the Monkton Formation. For a detailed description of the non-marine Monkton lithofacies see Goldberg and Mehrtens (1997). Not all lithofacies are present at all outcrops of the Monkton in the Champlain Valley. The geographic variation in lithofacies represents the facies changes from south (Vergennes region) to north (Colchester). The lithofacies and summaries of their description and interpretation are presented in Table 1.

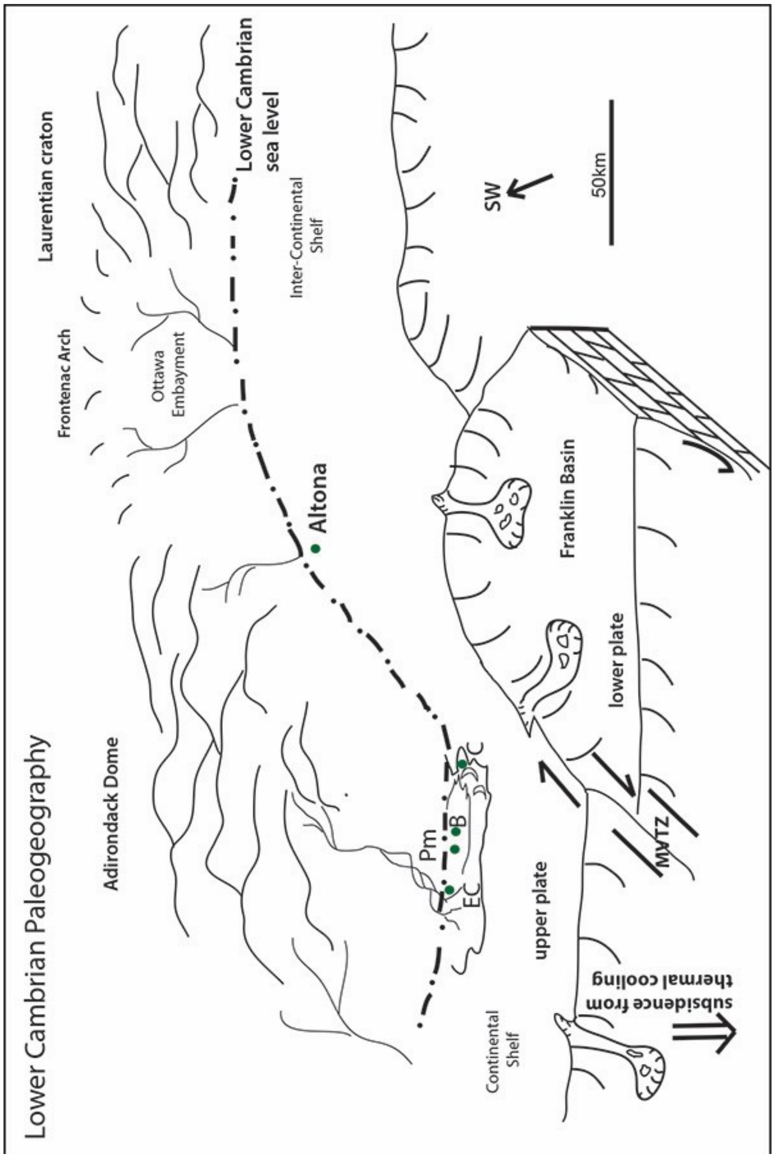

FIGURE 3. Schematic paleogeographic cartoon for northwestern Vermont, northeastern New York, and southern Canada (adapted from Maguire et al., 2018) showing the spatial relationships between Monkton outcrops and the Franklin Basin and the hypothetical Iapetus shelf margin. The dash-dot line represents the Iapetus paleoshoreline in the Early Cambrian. Localities of the Monkton Formation referred to in the text include: C-Colchester (including the Niquette Bay-I89 traverse, Route 2 and Grandview Road localities), B – Burlington area (including Salmon Hole, Redstone Quarry and Shelburne Bay/Red Rocks Park), Pm - Pease Mountain, EC-Ethan’s Cliff, Waltham (not included in this study; see Goldberg and Mehrtens, 1997). MVTZ= Missisquoi Valley Transfer Zone (see Cherichetti et al., 1998 for more information). In this cartoon the view is to the west. Compare the perspective for this paleogeography to that of Figure 4. The location of the Altona Formation type section is also shown; the Altona is at least partially coeval with the Monkton.

Table 1:

Lithofacies	Description	Interpretation	Architectural element
St	Sandstone containing granules and pebbles, scoured bases to beds, horizontal laminations, graded bedding and cross stratification common	2D and 3D current generated bedload deposition	fluvial channels and bars
Sx	Mdm to fine-grained sandstone with variable amounts of dolomite cement; decimeter scale planar and trough cross stratification common; herringbone and swaley cross stratification rare; clasts rare	2D and 3D wave and current generated bedload deposition	tidal sand bars
Sp	Large scale planar cross stratified sandstone	2D and 3D current generated bedload deposition	subtidal compound dunes
Shb	Well sorted white medium-grained sandstone, herringbone cross stratification common	Tempestite; tidally-influenced bedload deposition	intertidal to subtidal shelf
Fw	Poorly bedded, fine to medium-grained sandstone with oscillatory and combined flow ripples	2D and 3D wave and current generated bedload deposition	intertidal to subtidal shelf
Fr	Well bedded, moderately well sorted fine to medium-grained sandstone exhibiting ripple cross lamination	2D current generated bedload deposition	intertidal flat
Fl	Cm-scale thinly bedded siltstone to very fine-grained sandstone; rhythmically interbedded to produce a pinstripe appearance	Suspension sedimentation	subtidal shelf
Fm	Medium-grained sandstone with cross lamination	2D current and wave generated bedload deposition	subtidal shelf
Fms	Very poorly sorted micaceous sandstone, siltstone and mudstone with dewatering structures and bioturbation	tempestite	subtidal shelf
Dm	Poorly bedded dolostone; structureless unless cryptalgalaminite structures are present	biogenically influenced *in situ* deposition	subtidal; tidal pond
Ds	Arenaceous dolostone containing poorly sorted mdm-grained sand exhibiting graded bedding and cross lamination; trough cross bedding	Nearshore shelf adjacent to a terrigenous source, with periodic 2D and 3D bedload deposition	subtidal; tidal pond
Dslt	Silty dolostone to dolomitic siltstone	Nearshore shelf adjacent to a terrigenous source, with periodic 2D and 3D bedload deposition; eolian deposition	intertidal flat; tidal pond

TABLE 1. Lithofacies description, depositional environment and architectural element summary for Monkton Formation. Lithofacies codes are after Miall (1985).

Lithofacies Summary

Gravel and Sand Lithofacies (St)

Description:

This lithofacies is characterized as grey colored, moderately to poorly sorted medium to coarse-grained sandstone. Granule and pebble-sized grains often occur in laterally discontinuous, lenticular beds and the bases of beds may contain concentrations of pebbles. Sandstone beds commonly exhibit coarse-tail grading. Horizontal laminations and both trough and planar cross stratification are common. Reactivation surfaces are commonly found between cross bed sets. Coarser-grained sandstone beds commonly scour underlying finger-grained horizons. This lithofacies was described in more detail by Goldberg and Mehrtens (1997). In the study area this lithofacies is only found at Pease Mountain.

Interpretation:

Goldberg and Mehrtens' study (1997) included a Markov analysis of the fining-up cycles and results suggest a fluvial origin. Cross stratification was produced by the migration of both 2 and 3-dimensional dunes. Bedload transport and deposition is also recorded by the scoured bases of beds overlain by granule and pebble lag deposits. Coarse-tail graded bedding records deposition from decelerating currents. The horizontal laminations that underlie cross beds reflects bedload transport under upper flow regime conditions with current deceleration and dune formation. Goldberg and Mehrtens (1997) interpreted this lithofacies as representing either sheet flow or deposition within broad, shallow channels. Their modal analysis of sandstone composition revealed an abundance of the accessory minerals ilmenite, magnetite, rutile and apatite, which would be expected for an Adirondack provenance. This same accessory mineral suite is found in other sandstone lithologies in the Monkton. This is the only non-marine lithofacies in the Monkton.

Cross-stratified sandstone lithofacies (Sx, Sp, Shb)

Descriptions:

These lithofacies are characterized by the dominance of different types of cross stratification and are distinguished from Lithofacies St by their association with lithologies, sedimentary structures, and architectural elements that indicate a marine setting.

Lithofacies Sx is a grey to pink to red colored, moderately sorted, fine to medium-grained sandstone. This is the most common occurrence of cross stratification in the Monkton and it occurs at all outcrops but exposures are most common in the Burlington and Pease Mountain regions. Lithofacies Sx can be subdivided into three types based on differences in the types of cross-stratification. While planar and trough cross bedding are most common in Lithofacies Sx there are also rare occurrences of hummocky cross stratification (HCS), characterized by concave-down parallel laminations, ~15 cm in height. The second type of cross stratification is characterized as a simple dune with a sharp base overlain by individual sets of decimeter-scale cross stratification (see Plate 3, Figure 4, Photo 13). The majority of bounding surfaces of cross bed sets are parallel to wedge shaped, however trough cross bedding is locally common. The planar cross beds usually grade from very coarse sandstone at the base upwards to fine-grained sandstone. When not truncated, the tops of beds frequently exhibit cross laminations. The third occurrence of cross stratification in Lithofacies Sx are compound dunes characterized by superimposed sets of tangential to sigmoidal-shaped cross strata each of which are ~10-15 cm in height and are separated by reactivation surfaces (see Plate 1, Figure 6, photo 11). Mudstone or siltstone drapes between sets can be present but are not common. The riverbed portion of the Salmon Hole outcrop reveals one example of the wedge shape of a compound dune bedform (Plate 1, Figure 3, photo 1) and wedge-shaped bedding is well displayed by strata outcropping at Red Rocks Park (Plate 1, Figure 6, photo 9).

Lithofacies Shb is recognized by its distinct white to pale grey color, good sorting (medium-grained sandstone) and cross stratification indicating bipolar flow directions. This lithofacies is common in the Colchester region and thinner beds can be found interbedded with Lithofacies Fr and Fm elsewhere. Sets are commonly 10-20 cm in thickness but are thicker in the Colchester outcrops.

Lithofacies Sp is a grey colored fine to medium-grained, horizontally laminated, and large scale planar cross stratified sandstone. It is distinguished from the planar cross bedding of Lithofacies Sx on the basis of the thickness of sets and the restriction of Lithofacies Sp to the Colchester region, on the shelf margin adjacent to the Franklin Basin. Planar cross-bedded sets are 1-1.3 m in thickness, thin laterally down dip, and bedding contacts are parallel to slightly wedge shaped (Plate 2, Figure 11). Foresets show the same dip directions as bedding (Plate 2, Figure 10). Between sandstone beds there may be finer-grained material (Lithofacies Fl) but this material is commonly eroded away as the bases of beds are sharp. Clasts of the finer-grained material can occur as clasts at the base of sandstone beds. Beds often fine-upwards and cross-laminated tops to beds may be present but are commonly removed by subsequent erosion.

Interpretations:

Hummocky cross stratification (HCS) (Harms et al., 1975) present in Lithofacies Sx describes a bedform characterized by concave-down foresets produced by oscillatory (wave) flow. The origin of HCS is still hotly debated, with laboratory modeling suggesting that these structures can form from oscillatory flow, combined flow dominated by unidirectional currents, and combined flow dominated by oscillatory flow. All of these hydrodynamic conditions can be met by storm wave action but the bathymetries associated with them is less clear. A shallow subtidal setting would be in agreement with the interbedding of HCS sandstones with tidal flat sediments of Lithofacies Fr.

The remaining two types of Lithofacies Sx are interpreted to record deposition from the migration of two- and three-dimensional dunes within a tidal setting. This interpretation is based on the interbedding of Lithofacies Sx with other facies that record bi-directional flow. Simple dunes consist of a single set of cross strata recording bedload deposition from the lateral migration of the bedform. The majority of cross bedding in Lithofacies Sx are planar tabular and planar wedge sets, which form from migrating two dimensional dunes. Occurrences of trough cross bedding are produced by migrating three dimensional dunes. Compound dunes describe bedforms that are constructed by superimposed smaller dunes of a similar type and generally similar slipface orientations. The term "compound dune" is used to describe the internal structure of cross stratification within a bedform (for an example, see Plate 1, Figure 6, photo 11). Foreset orientations within a compound dune record the dominant flow direction but some sets indicate oblique or possibly bipolar flows. The tidal origin of compound dunes has been described by many authors (Dalrymple, 2010 and references therein). For example, in a study of modern tidal channel fill in the Oosterschelde estuary in the North Sea, Visser (1980) described compound dunes within channels in the shallow subtidal. Alternatively, Olariu et al. (2012 and references therein) attribute compound dunes to the migration of two different bedforms: tidal sand bars and tidal sand dunes. These two structures both occur at the same scale but are differentiated on the basis of their internal structures, presence or absence of associated tidal channels, and orientation relative to paleoflow directions. Desjardins et al. (2012) describe tidal bar deposits as exhibiting thinning-upward and fining-upward trends, both of which occur in Lithofacies Sx compound dunes. Regardless of whether the compound dunes of this lithofacies form in broad, shallow tidal channels or in tidal bars between channels, they record tidally-influenced deposition in the intertidal to shallow subtidal environment.

Lithofacies Shb, herringbone cross stratification, is produced by bedload transport of sediment under conditions of oblique to reversing current directions, one of the characteristics of a tidal setting (Dalrymple, 2010), although post-storm relaxation currents can also be oblique to dominant current flow directions (Aagaard et al. 2012). The sorting and grain size of Lithofacies Shb is responsible for its distinct light grey to white color (McElwee and Mehrtens, 2016) as the hematite that imparts the red coloration to most of the Monkton is concentrated in finer-grained and less well sorted lithologies. The trough and herringbone cross stratification characteristic of this lithofacies record the bedload transport of sediment by the migration of three-dimensional dunes and in the case of the herringbone structures, bipolar flow directions. The distinct color and textural differences of Lithofacies Shb to other Monkton lithofacies it is commonly interbedded with (see Plate 1, Figure 4, photo 4) reflects the result of hydraulic sorting which removed the iron-bearing accessory minerals with higher specific gravities that diagenetically alter to hematite. Lithofacies Shb is interpreted to be a tempestite deposit recording a discharge event from the fluvial system supplying the Monkton tidal flat. This sediment was subsequently reworked by tidal currents. The eroded tops of foresets would support this interpretation. Beds of this lithofacies are thicker in the Colchester region as a result of the greater water depths on the outer shelf; however, the effects of tidal currents were still felt by the sand.

The internal structures within Lithofacies Sp represent compound dunes. As previously described for Lithofacies Sx, compound dunes form from the migration of straight to slightly sinuous dunes under conditions of asymmetrical tidal currents. Olariu et al. (2012 and references therein) distinguish between compound dunes that result from the migration of both tidal sand bars (lateral (sideways) accretion) and tidal sand dunes (accretion parallel to paleoflow direction). Desjardins et al. (2012) also describe compound dunes resulting from migration of tidal sand ridges, although these features occur at a larger scale (10's km) on the shelf. Distinguishing between the compound dunes produced by bars and dunes depends on recognition of secondary cross strata recording migration in either a lateral (dune) accretion surface or down parallel to the master bedding surface (Olariu et al., 2012). Paleoflow data in the Monkton cross bedding in Lithofacies Sp indicates that these structures result from tidal sand bar migration.

Fine-grained sandstone and siltstone lithofacies (Fl, Fm, Fr, Fw, Fms)

Descriptions:

There are five lithofacies that are fine to medium-grained sandstones differentiated by different sedimentary structures, bed thickness, weathered color, grain size, and sorting.

Lithofacies Fm is a grey to red colored, ripple cross laminated, moderately sorted, medium-grained sandstone. Cross laminations are 1-3 cm in height. This lithofacies is distinguished from Lithofacies Fr by its coarser grain size and thicker beds.

Lithofacies Fl is characterized by its very fine grain size (clay to silt) and variable colors: grey, red, or purple. Millimeter-scale horizontal laminations are visible on weathered surfaces.

Lithofacies Fr is the most recognizable Monkton lithology, comprising much of the easily viewed portions of the stratigraphic sections at both the Salmon Hole and Redstone Quarry outcrops. Beds are red in weathered color and are often silt or mud-draped, forming wavy bedding (after Reineck and Singh, 1980). Sandstone beds are a fairly uniform 2-10 cm in thickness and have sharp bases that exhibit shallow (<1 cm) gutter casts. The tops of beds commonly exhibit cross laminations 1-2 cm in height. Sandstones are fine to medium-grained and moderately to poorly sorted. The finer-grained caps to beds exhibit horizontal bedding plane traces characteristic of the *Planolites* and *Cruziana* ichnofacies. Interbedded with the wavy bedding of clastic sediment are laterally discontinuous thin beds of dolostone, and differential compaction can produce nodular bedding in the carbonate. Mudcracks may be present in these finer-grained horizons but are not common. Horizontal laminations are common within beds, as is graded bedding. Bedding plane exposures of ripple crestlines show a range of orientations and include interference ripples. Ripples are form-discordant, with foreset laminae indicating unidirectional flow but with a rounded symmetrical profile.

Lithofacies Fw is a fine to very fine-grained, moderate to well sorted, red colored, cross-laminated sandstone. Bedding can be poorly developed and only rarely do beds weather apart into sets of thin (1-5 cm) wavy beds. Cross laminations are symmetrical in profile. When viewed in cross section, they are both form discordant and form-concordant (de Raaf et al., 1977) and exhibit upward bundling.

Lithofacies Fms is a poorly sorted sandstone with grains ranging in size from clay to medium-grained sand. Beds are 10 cm or more in thickness and are dark red to maroon in color, are rich inilmenite and magnetite and bright light reflectance off these minerals give this lithofacies a "sparkly" appearance. Beds have a mottled fabric (bioturbation index = 5; Taylor and Goldring, 1993) and lack both horizontal and cross laminations and grading. Dewatering structures are common.

Interpretations:
Lithofacies Fm is interpreted to be the product of bedload transport and deposition of sand by small wave and current-generated migrating ripples. The internal structures of ripples: inclined foresets within a rounded symmetrical profile, records unidirectional flow produced by a combination of low flow velocity currents and wave reworking (Dumas et al., 2005). As noted by Dumas and his colleagues (ibid.), combined flow conditions can be found over a broad range of environments and thus its presence is more indicative of flow conditions than a specific environmental setting. Based on association with other lithofacies containing sedimentary structures more diagnostic of tidal influence, Lithofacies Fm is interpreted to have formed in an inter- to shallow subtidal setting.

The fine-grained material in Lithofacies Fl was deposited by suspension fallout in a low energy setting of indeterminate bathymetry, an interpretation supported by the presence of horizontal laminations. Studies of modern shelves (e.g., Kämpf and Myrow, 2014) have documented that storm-generated, mud-rich sediment gravity flows are capable of moving fine-grained sediment offshore. It is also possible that suspension sedimentation occurred in low energy settings closer to shore, in lagoonal or estuarine conditions. Because this lithofacies is found interbedded with both Lithofacies Dm (algal-rich dolostone) and Lithofacies Sp (tidal sand bars), both depositional settings are possible.

The presence of sharp-based beds, horizontally laminated and/or graded beds, and cross laminated tops to beds in Lithofacies Fr indicates high velocity transport and deposition of sediment, possibly by post-storm flows, followed by wave-generated reworking and draping by finer-grained sediment. This type of internal structure records unidirectional flow, possibly from post-storm relaxation currents (Aagaard et al., 2012), combined with wave reworking (Dumas et al., 2005). Wave generated bedforms could be produced by wind blowing over water above a sheet of sand. The multiple flow directions indicated by variable crestline orientations is indicative of tidal influence in deposition. Periodic exposure is also suggested by mudcracks. All of this evidence suggests that sediment was introduced onto a sand and mud-dominated tidal flat through periodic high energy events, with sediment subsequently reworked by tidal and wind-generated currents.

The combination of grain size, sorting, wavy bedding and the type of abundant cross laminations indicates that Lithofacies Fw records bedload deposition from migrating 2D and 3D ripples from oscillatory wave motion. Both 2D and 3D upward bundling ripples are interpreted to represent aggrading bedforms that form in oscillatory flows, with a minor unidirectional flow component, and a consistent sediment supply (Harms et al., 1982; de Raff et al., 1977). These flow characteristics could occur within an intertidal to shallow subtidal setting. Evidence of unidirectional currents, either from post-storm flow or tidal currents, is lacking. This implies a position on the shelf in the subtidal, further offshore than Lithofacies Fr, and within wave base. This lithofacies is most similar to the red-colored sandstones of the Lower Cambrian Altona Formation in northeastern New York (Brink et al., 2019).

Any interpretation of Lithofacies Fms must account for its poor sorting and mottled fabric. The characteristic mottled fabric suggests intense bioturbation during conditions of slow, continuous sedimentation. The diffuse shapes of the burrows do not permit identification of the ichnofauna responsible. Alternatively, the unsorted nature of Lithofacies Fms, along with dewatering structures, suggests that sediment was deposited from resuspension or reworking from storm activity followed by rapid deposition. In this scenario, bioturbation results from escape burrow activity accompanying the post-storm deposition. Rapid deposition is also suggested by the abundance of iron-rich minerals with high specific gravity that have not undergone any hydraulic sorting (Rittenhouse, 1945), an interpretation supported by the absence of evidence of bedload transport. Both interpretations (slow continuous sedimentation vs. tempestite) could occur within the intertidal zone.

Dolostone lithofacies (Dm, Ds, Dslt)

Descriptions:

There are three lithofacies that are predominantly carbonate in composition. Lithofacies Dm is a beige-colored crystalline dolostone. It is characteristically structureless with bedding not well developed unless there are silt-rich laminations present, some of which exhibit features associated with sediment binding by organic material. Associated with some laminations are small rip-up clasts and mudcracks. Lithofacies Ds has the same matrix as Dm; however, there are sand-sized grains of quartz and feldspar present in varying amounts. In some cases, the ratio of clastic to carbonate is 50:50 and in others, a lesser percentage of clastic grains are floating in a dolostone matrix. When clastic grains are sufficiently abundant, cross stratification may be present. Lithofacies Dslt is predominantly carbonate but with varying amounts of very fine-grained sand and silt grains present. This lithofacies weathers pale pink to beige in color. Cross laminations exhibiting both symmetrical and asymmetrical profiles are often present, as is bioturbation (Bioturbation Index = 3, Taylor and Goldring, 1993). Silt laminations similar to those in Dm also occur.

Interpretations:

The deposition of carbonate sediment would require periodic "clear water" conditions, perhaps reflecting the presence of an adjacent shallow marine carbonate environment. The silt laminations present in lithofacies Dm and to a lesser extent in Dslt are interpreted to be organic in origin. This interpretation is based on the abundance of convoluted laminations of silt grains whose shape and orientation would require adhesion from organic material, either algal or microbial in origin (for example see Plate 2, Figure 15). These are identified as "cryptalgal structures" or "cryptalgalaminations" in this report.

The origin of the carbonate sediment of the dolostone lithofacies is interpreted to be the result of biomineralization from calcareous algae in shallow (photic zone) clear water conditions. More specific bathymetries are difficult to ascertain for Lithofacies Dm unless cryptalgalaminations are present. In this case, the abundance, association with mudcracks, and occurrences in cyclic packages with clastic sediment suggests a very shallow, intermittently subaerially exposed, setting proximal to a terrigenous sediment supply such that facies mixing (Mount, 1984) can occur. When these features are absent in Lithofacies Dm there are no constraints on bathymetry and it may represent deposition on an open shelf at a depth within the photic zone but spatially segregated from clastic input.

As with Lithofacies Dm, the carbonate sediment of Lithofacies Ds is interpreted to be algal in origin, recording clear water biogenic carbonate deposited within the photic zone but in this lithofacies, near to a terrigenous sediment supply. The presence of sedimentary structures such as cross-bedding records bedload transport of clastic material in both 2D and 3D migrating dunes. Sets of 2D and 3D cross strata are interpreted to represent migrating dune deposits from either/both shoreface currents or post-storm relaxation flows. It is likely that the carbonate sediment was deposited on the shelf but subsequently resuspended and transported when clastic sediment was introduced. The derivation of siliciclastic material and its segregation into "event beds" is characteristic of a punctuated carbonate/siliciclastic mixing model (Mount, 1984). Clastic grains floating in a dolomite matrix but lacking evidence of bedload transport may record sand deposition on the shelf by eolian processes. In both cases, proximity to a terrigenous source is required.

Lithofacies Dslt is similar to the other dolostone lithofacies in the organic origin of the carbonate material and, similarly to Lithofacies Ds, a nearby source for clastic material. The fine grain size of terrigenous sediment in Dslt implies a relatively low energy setting. Sets of cross laminae from both unidirectional and oscillatory flow suggest the close temporal association of both unidirectional bottom currents (longshore or rip) and wave processes. The mottled fabric that often occurs in these silty dolostones is interpreted to be the result of homogenization of dolostone-siltstone couplets through bioturbation in a regime of relatively low sedimentation rates.

Depositional Model

The twelve lithofacies for the Monkton Formation represent deposition on a tidal flat to subtidal complex. The facies characteristic of clastic tidal flat complexes have been extensively reviewed in the literature (Dalrymple, 2010 and references therein) and the Monkton strata contain most of the features associated with this depositional setting. The tidal flats, with associated carbonate ponds, lie seaward of a fluvial system draining the ancestral Adirondack (Figures3 and 4). The tidal flats, in turn, pass seaward into a subtidal region with tidal sand bars and a carbonate platform adjacent to the Franklin Basin. Rahmanian (1987) was the first to suggest that the red-colored sandstones that characterize much of the Monkton represented a northward prograding tidal flat system that passed basinward (northward) into subtidal sand bars before pinching out on the margin of the Franklin Basin. His initial results are supported by this study. The paleoenvironmental reconstruction in Figure 4 presents a model for the distribution of environments at an instant in time; facies migrated in response to allocyclic forces of base level change (sea level, sediment supply, and subsidence) as well as autocyclic processes (lateral facies migration). The model does reflect the proximity of various environments to one another so that allo- and autocyclic forces could, for example, juxtapose tidal flat sediments on top those of the subtidal sand bars.

Figure 5 illustrates the stratigraphic relationships between outcrops of the Monkton Formation included in this report. Among the significant changes parallel to strike is the pinch out of the intertidal facies from south to north, reflecting the south to northward progradation of terrigenous sediment across the carbonate platform. The lowest horizons of the Monkton are carbonate in composition, which the reflects the flooded carbonate shelf prior to the influx of clastic sediment and the onsetof a prograding tidal flat. There is an increase in the thickness and number of subtidal sand bodies in the north, a facies change recording the proximity of the platform margin along the edge of the Franklin Basin and its effect in localizing bottom currents. A modern example of thiscan be seen on the edge of the Bahamas Bank (Ball, 1967). Sea level fluctuations and lateral facies migrations result in a variety of shallowing-up cycles, or parasequences in the Monkton.

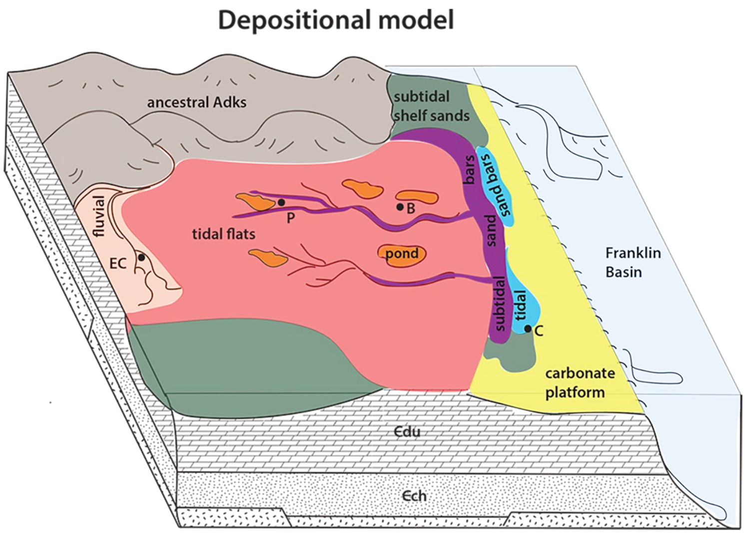

Figure 4. Schematic cartoon illustrating the depositional model for the Monkton Formation. View is looking west. Locality abbreviations: EC = Ethan's Cliff (see Goldberg and Mehrtens, 1997); P = Pease Mtn; B= Burlington region; C= Colchester.

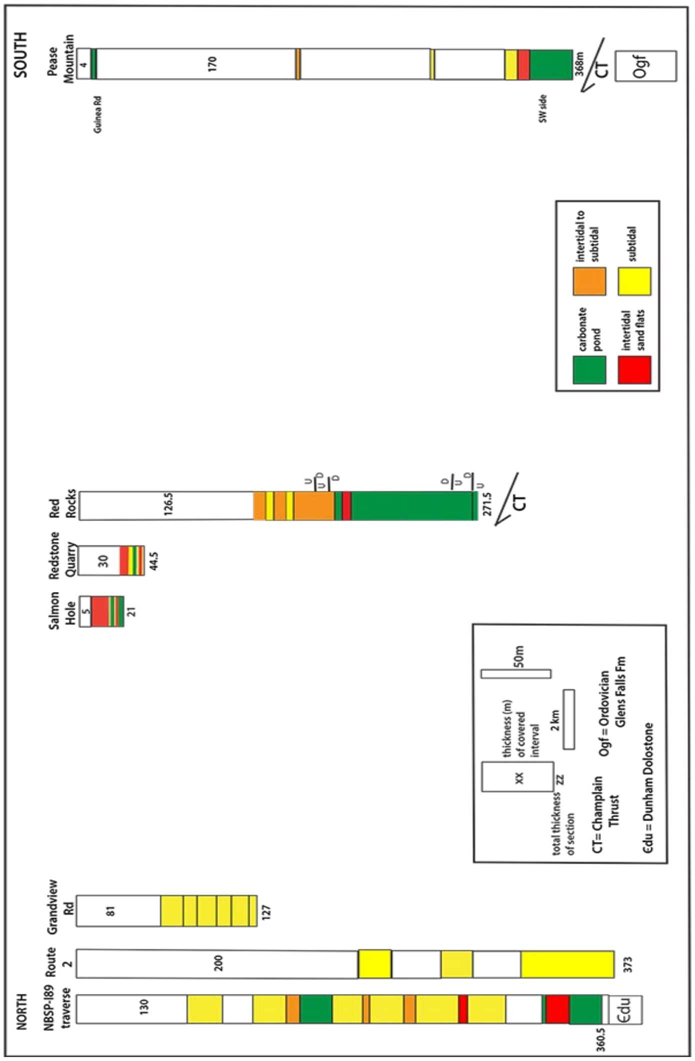

Figure 5. Outcrops included in this study are "hung" on the Winooski Dolostone. Spacing between outcrops represents distance along strike. Keys for the thickness data and lithofacies are on the figure.

Parasequence Architecture and the Record of Accommodation Space

Parasequences represent the cyclic deposition of a conformable succession of genetically related beds or bedsets bound by a marine flooding surface (Van Wagoner et al., 1988) and the identification of stratigraphic trends in parasequence architecture and thickness can be used to clarify how sea level changed and impacted accommodation space (Posamentier and Vail, 1988). Parasequences in the Monkton range from less than a meter to ~3 meters in thickness. Analysis of the architecture of parasequences in the Monkton reveals four patterns are present (Figure 6). Some cycle motifs capture shallowing-up as sediment accumulation exceeds available space (Types 1 and 2). Other cycle motifs capture clastic sediment "catch up" following rapid sea level rise (Types 3 & 4). Cycle Type 1 is a shallowing-upward cycle where tidal sand bars (Lithofacies Sx) are overlain by dolostones (Lithofacies Dm and Dslt) or tidal flat sands (Lithofacies Fr, Fm and Fl). Examples of this cyclicity can be seen in at the Salmon Hole and Redstone Quarry outcrops. These cycles may be autocyclic in nature, driven by lateral facies migration independent of sea level change. Cycle Type 2 is well exposed at Pease Mountain. In this motif, tidal sand bars (Lithofacies Sx) are capped by rippled sands and siltstones of the tidal flat (Lithofacies Fr, Fms or Fl). This type of cycle may also be autocyclic in nature, reflecting lateral migration of a tidal channel and the adjacent tidal flat. Cycle Type 3 is well exposed on the east wall of Redstone Quarry (see Plate 1, Figure 4, photo 1). In this cycle a flooding surface is overlain by dolostones with cryptalgalaminites of Lithofacies Dm which gradationally pass upwards into more clastic-rich horizons as clastic input "catches up" with sea level rise. Another example of "catch up" architecture is Cycle Type 4, found in the stratigraphy at the top of the Monkton in the Colchester region. The base of the cycle are dolostones that may or may not contain cryptalgalaminations which gradually pass upward into wave rippled sandstones (Lithofacies Fm) and ultimately into cross bedded sands of Lithofacies Sx or Shb. These latter two cycles are driven by changes in the equilibrium between sea level and sediment supply.

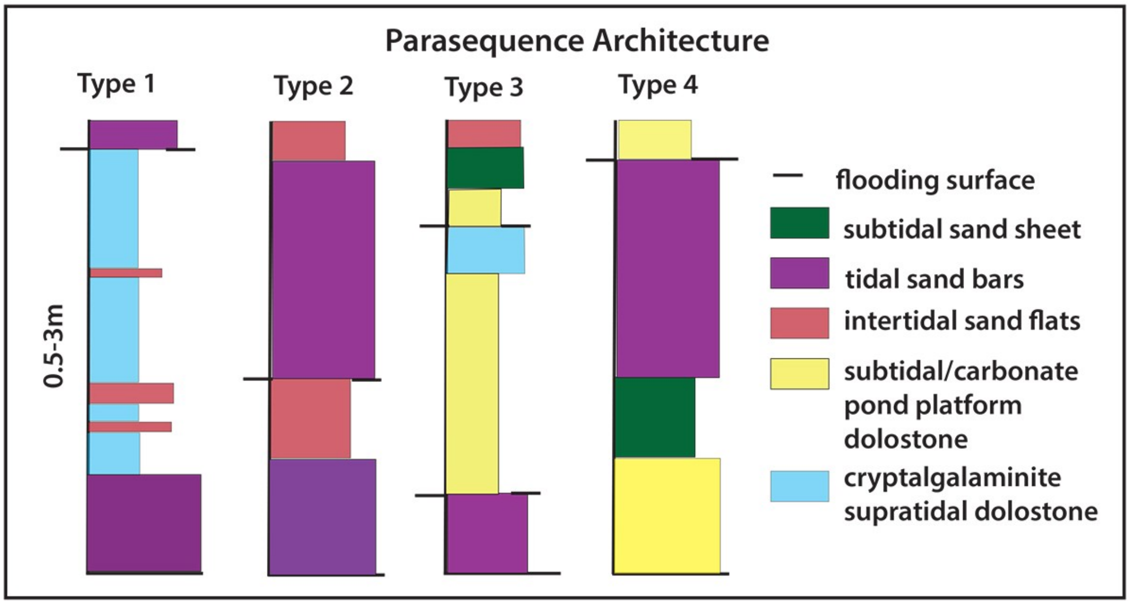

Figure 6. Parasequence architectures in the Monkton Formation

Using geophysical data, Kim et al., (2013) identified cycles in a subsurface well extending through the upper third of the Monkton Formation in Burlington, Vermont. This initial study was expanded on by Maguire et al. (2018a & b), who were able to identify parasequence architecture through analysis of gamma ray characteristics of different lithologies encountered in wells penetrating the Monkton. These authors were successful in characterizing stratigraphic trends in parasequence thicknesses. The parasequence and lithologic trends that were identified in the Monkton by Maguire and his coworkers indicates that the stratigraphy records progressive loss of accommodation space over time. The loss of accommodation space on a shelf reflects a change in the *rate* of sea level rise. The upward-thinning of parasequences indicates that, although the Monkton Formation was deposited as a transgressive systems tract (during rising sea level), the *rate* of rise decreased over time. The overall progradation of tidal flat sediments basinward is the result of sediment input outpacing sea level rise (assuming constant thermal subsidence rate). Plate 2 Figure 17 is an outcrop photograph of a prograding, offlapping tongue of tidal flat sediments as seen along I-89 southbound, Colchester, Vermont.

STRATIGRAPHIC COLUMNS (PLATES 1-3)

Description of the traverses and locations of measured sections
See Figure 1 on Plates 1 through 3 for maps indicating the locations of outcrops in each of the Burlington, Colchester, and Pease Mountain study areas.

Burlington

Stratigraphic thicknesses
Outcrops of the Monkton were measured at the Salmon Hole (20.5 m), Redstone Quarry (14.5 m),and the east shore of Shelburne Bay and Red Rocks Park above (144 m) (Plate 1, Figure 1). Both the Salmon Hole and Redstone Quarry sections can be "hung" on the contact with the overlying Winooski Dolostone. At the Salmon Hole this is a covered interval of approximately 5 meters while at Redstone Quarry it is approximately 25 m.

The Shelburne Bay section of Red Rocks Park was measured during the winter when it was possible to walk along the base of the cliff and use a stadial rod to measure and construct a composite section. The base of the Monkton is not exposed and the cliffs lie above the Champlain Thrust. Based on the carbonate-rich lithologies of the base of the exposed section, it is possible that the base of the Shelburne Bay section is near the base of the Monkton. The cliff exposure is cut by four high angle faults and while in most cases it is possible to correlate across the faults the basal 14 m of section cannot be correlated to any stratigraphy up section, so the measured thickness of 146 m is a minimum value. Outcrops on the top of the cliff, at Red Rocks Park, confirmed the stratigraphy seen on the cliffs although there was no evidence of the faults that were visible on the cliffs. Assuming a constant dip of 14°, projecting along strike, and using Google Earth© to measure covered interval to the base of the section at Redstone Quarry, there is space for another 600 meters of stratigraphy between Shelburne Bay/Red Rocks Park and Redstone Quarry. Clearly, there must either be a high angle fault, or faults, between Shelburne Bay/Red Rocks Park and the topographically higher Monkton exposures to the east. Alternatively, there may be basement structures beneath the Champlain Thrust that vary the dip of the Cambrian strata. The abundance of Cretaceous dikes and normal faults in the area suggests that antecedent geologic structures, perhaps related to rift topography, plays a significant role in the geologic evolution of Shelburne Bay. If the dip of the Monkton between Shelburne Bay/Red Rocks Park and Redstone Quarry was ~5°, there could be approximately 100 m of stratigraphy between the Red Rocks and Redstone outcrops, and the total thickness of the Monkton would be ~285 meters. This is a minimum thickness because the base of the unit lies on the Champlain Thrust but this value is in the same order of magnitude for thickness of the Monkton elsewhere.

Paleocurrent data
Paleoflow data was obtained from measurement of crestline orientations on bedding planes and from the inclination of foresets on cross-beds. Results are shown on the stratigraphic columns for two outcrops in the study area (Plate 1, Figures 3, 4 and 6). Data from ripple crestline orientations from Salmon Hole indicates a dominance of bipolar flow directions, with flow to the east and west, with less common northwest and southeast-directed flows. Redstone Quarry yielded paleoflow data from both ripple crestline orientation and cross bedding. Paleoflow from ripples is similar to that of Salmon Hole, with dominant east and west-directed flow. The few measurements on cross bed forests records flow to the southwest. Paleoflow data from Shelburne Bay/Red Rocks Park show a dominance of east-southeast directed flow but with much variation recording the orientation of the secondary dunes on compound dune bedforms.

Lithofacies and stratigraphic trends
The horizons near the base of the Monkton are exposed on the cliffs at Shelburne Bay (Red Rocks cliffs, Plate 1, Figure 5) are dominated by carbonate-rich lithofacies (Dm, Dslt) and fine-grained clastic lithofacies (Fm, Fls). Moving up section, coarser-grained sandstones of Lithofacies Sr and Sx dominate, and cyclic fining-upward interbedding of Sx overlain by Fr is characteristic. The trend over the 144 m section is coarsening-up and becoming more clastic-rich. The bulk of the stratigraphy between 46 and 96 meters records cyclic interbedding of dolostones of the carbonate pond environment and tidal flat sandstones (Cycle Type 1). Above 100 meters tidal sand bars become more common. These cross bedded sandstones are present as bedforms with broad, shallow channels capped by tidal flat sandstones (Cycle Type 2) or as migrating tidal bars acrossthe tidal sand flats. Above 132 meters depositional processes become more wave-dominated which may represent sea level rise and partial submergence of a portion of the tidal flat.

The Redstone Quarry outcrop (Plate 1, Figure 4) exposes stratigraphy from near the top of the Monkton. The stratigraphy here is characterized by cyclic interbedding of clastic (Fl, Fr) and carbonate (Dm) lithofacies (Cycle Types 1 and 3) recording alternation between carbonate pond and tidal flat environments. Many of the dolostone horizons contain cryptalgalaminite structures. These are punctuated by horizons of cross-stratified sandstone (Sx and Shb) that represent tidal sand bar deposits.

At the Salmon Hole outcrop (Plate 1, Figure 3) 20.5 meters of the uppermost Monkton is exposed immediately below the Winooski Dolostone. Broad bedding planes expose horizons of rippled, bioturbated, and mudcracked sandstones of Lithofacies Sr, recording deposition on a tidal flat. When Winooski River levels are low, horizons of cross-stratified sandstones (Sx and Ds), formed by tidal sand bars, are visible. At the base of the section, along the Winooski River, poorly bedded horizons of dolostone outcrop (Dm, Ds). The thickness of dolostone, the absence of any algal structures, and rare disseminated sand grains suggests that these dolostones are subtidal innature, representing deposition during a sea level rise that trapped clastic sediment onshore.

Colchester

Stratigraphic thicknesses

Three stratigraphic sections of Monkton were measured and described in the Colchester region: Route 2 roadcut, a traverse from Niquette Bay State Park east to Interstate 89 (hereafter NPSP-I89), and along Grandview Road. The locations of these sections are shown in Plate 2, Figure 1.

Route 2

The roadcut along the south side of Route 2 is oriented roughly perpendicular to strike. It includes two high angle faults oriented roughly north south. The displacement along both faults is as little as ~2m, based on matching dolomitic sandstone beds on either side. However, rocks on both sides of the fault are a common lithology in the Monkton in this area so this correlation is not a certainty. On the north side of Route 2, and stratigraphically above the outcrops on the south, are a series of ledges that continue up section for another 39 meters. Assuming constant dip of 18° east and using both pace and Google Earth© measurements, a covered interval of 35 meters between the south and north sides of Route 2 was calculated, as was an approximately 195 meter thick covered interval between the top of the ledges (the highest exposure of the Monkton), and the lowest outcrop of the overlying Winooski Dolostone, for a total of 368 meters. Plate 2, Figure 7 illustrates the measured section.

Traverse

The traverse between the uppermost Dunham Dolostone and the covered interval below the Winooski Dolostone (NBSP-I89) includes the stratigraphically lowest exposures of Monkton in this region, with only approximately 1.5 meters of covered interval between the Dunham and Monkton (Plate 2, Figure 3). The base of the Monkton was identified as the lowest dolostone horizons containing millimeter thick red siltstone laminations. The composite stratigraphic section was assembled by walking perpendicular to strike from ledge to ledge, calculating covered interval by using a stadial rod, measuring horizontal distance and the dip of beds. Within the traverse are several faults, the first of which is near the base of the unit, which has a trend oriented east-west, and has offset of less than a meter based on unambiguous matching of units on either side. The second observed fault occurs immediately east of Niquette Bay Road (18T 644403E 4938453N). This fault also trends east-west and the stratigraphy can be matched from one side to the other with only meters of offset. A total of 286 meters was measured in the traverse, however the uppermost contact with the overlying Winooski Dolostone is not exposed. In order to estimate the thickness of this covered interval, the strike of the lowest exposure of the Winooski Dolostone was projected south along strike to the transect location and the horizontal distance between the uppermost Monkton and the inferred base of the Winooski was measured. Based on calculations of the horizontal distance measured off Google Earth© and assuming a constant dip of 18° east between the uppermost Monkton and lowest Winooski a covered interval of approximately 40 meters was calculated. This would yield a total thickness for the Monkton on the traverse to be approximately 327 meters.

Grandview Road

The southernmost traverse in the Colchester region runs parallel to Grandview Road in an east-west oriented series of cliffs comprising 69 meters of section (Plate 2, Figure 6). The cliffs lie to the south of the suspected faulted region south of the NBSP- I89 traverse. Using the horizontal distance between the top of the Grandview outcrops to the stratigraphically lowest exposure of the overlying Winooski Dolostone to the east of the interstate highway, based on Google Earth©, and a dip of 18°E, there is an approximately 80 m of covered interval between the Monkton and Winooski, for a total of 149 meters (Table 2).

Colchester correlations

Comparison of the stratigraphic sections for the three outcrops in the Colchester area are shown in Figure 7. Lithologic correlations between the outcrops are possible, for example the upper most 70 meters of section of the NBSP-I89 traverse are correlative to the entire Grandview Drive section and the top 20 meters (and extending into the covered interval below) along Route 2. However, discrepancies between sections clearly indicate evidence of faulting. There is approximately 95 meters of stratigraphy above the contact with the Dunham Dolostone on the NBSP-I89 traverse that is not exposed on Route 2. If we add 95 meters to the measured thicknessof the Route 2 outcrop, plus the calculated thickness of the covered interval at the top, the total thickness of the Monkton on Route 2 would be 463 meters, an anomalously high thickness for this unit in the Champlain Valley. It is possible that the base of the Winooski Dolostone lies further west than the existing outcrop, which would reduce the thickness of the covered interval at the top of the unit. However, the influence of high angle faults on thicknesses in the Colchester region cannot be discounted.

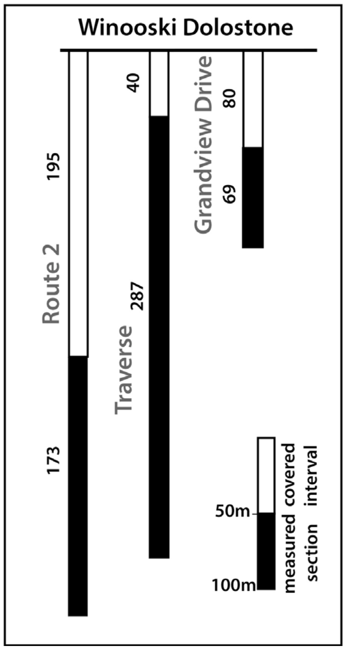

Figure 7. Correlation of outcrops in the Colchester region, hung off the distance below the lowest outcrop of the overlying Winooski Dolostone. Covered intervals were calculated using average dip and horizontal distance as measured in Google Earth©

Projecting the exposed faults on Route 2 to the south indicates that they would intersect with the stratigraphy in the NBSP-I89 traverse. It is plausible that these faults repeat stratigraphy in both the Route 2 and NBSP-I89 traverse, and that the portions of the stratigraphy repeated lie above 95 meters in height in the traverse measured section. As examination of Plate 2, Figure 3 shows, much of the traverse includes covered interval between widely spaced ledges. It is entirely plausible that faults are present within any one of these covered intervals. Because of the agreement in cyclic stratigraphy in the uppermost 70 meters of the traverse, the entire Grandview Drive stratigraphy, and the uppermost exposed Route 2 stratigraphy, the faulting most likely repeats stratigraphy between 95 meters and 200 meters of the NBSP-I89 traverse. In summary, the thickness of the Monkton in the Colchester region cannot be determined with any confidence.

Paleocurrent data

Inclination of foresets on cross-beds were measured for paleoflow. Results are shown on the stratigraphic columns for two outcrops in the study area (Plate 2, Figures 3 and 8). Data from cross bedding in the NBSP-I89 traverse indicates a dominance of bipolar flow directions, to the NE and SW with less common NW flow. Data from cross bedding on Route 2 indicates a predominance of NW-directed flow.

Lithofacies and Stratigraphic Trends

Unlike outcrops of the Monkton in the Burlington area, the Monkton in the Colchester region is dominated by clastic lithologies, with Lithofacies Sx, Shb, and Sp dominant. Lithofacies Sp is only found in the Colchester stratigraphy. The base of the Monkton is dominated by dolostone (Dm) and dolostone interbedded with rippled sandstones, characteristic of Cycle Type 1, carbonate pond and tidal flat intertonguing. Above 28 meters in the NBSP-I89 traverse, tidal sand bar deposits are interbedded with tidal flat sediments with carbonate present in variable amounts as dolomite cement in sandstones, often reaching levels to produce arenaceous dolostone. Above 82 meters in the traverse tidal sand bars dominate the stratigraphy with fewer exposures of Cycle Type 2 interbedding of sand bars and tidal flat sandstones. Between 82 and 151 meters in the traverse the stratigraphy is dominated by large scale composite dunes of the shelf edge sand bars. The stratigraphy at the top of the traverse records overall shallowing as sand bars thin and become tidally reworked. The top of the NBSP-I89 stratigraphy records overall decreased clastic sediment supply as sand bars are composed of arenaceous dolostones and Type 4 cycles record cyclic increased inputs of clastic material. The red-colored sandstones of Lithofacies Fr occur at three intervals above the base of the section in the Colchester stratigraphy.

The stratigraphy of the Route 2 outcrop mimics that of the bulk of the NBSP-I89 traverse. The uppermost 20 meters of the section are the best examples of complete Type 4 cycles. The stratigraphy along the cliffs of Grandview Road are also similar to the uppermost exposures along the traverse, recording migrating tidal sand bars.

Despite the presence of faults, the overall stratigraphic trend in the Colchester Traverse is coarsening-upwards from carbonates and finer-grained sandstones at the base to cross bedded coarser-grained sandstones through the bulk of the stratigraphy. The sandstones become more carbonate cemented up section. Sedimentary structures indicating shallow water, including cryptalgalaminite structures, which occur at the base of the Monkton, reappear towards the top (see Plate 2, Figure 15).

KARST HORIZONS

Solution collapse breccias are present in the Monkton in two outcrops in the Colchester study area. The first of these can be found southeast of the traverse (Plate 2, Figure 1; 18T 0644533E, 4937544N), near the unexposed faults. The breccia consists of angular clasts of various sizes ranging from centimeters to 10's of centimeters in long axis length (Plate 1B, Figure 11). Clasts are composed of dolostone, arenaceous dolostone, and sandstone in an arenaceous dolostone matrix.

The Route 2 outcrop contains a second occurrence of the solution collapse breccia. Occurring near the top of the roadcut (Plate 2, Figure 1, 18T 64492E, 4939259N) on the south side of Route 2, between 107 and 113 meters in the stratigraphy, this interval is characterized by clasts of varying sizes reoriented in the dolomite matrix. Despite the presence of rotated bedding there is no evidence of faulting here. Flanking the brecciated interval are herringbone cross-bedded quartz arenites below and arenaceous dolostones above (Plate 2, Figure 10).

Because all of the clasts and rotated beds are lithified, the timing of solution collapse is inferred to be post-Monkton.

Pease Mountain

Stratigraphic thickness
Outcrops of the Monkton Formation are on the upper plate of the Champlain Thrust, which has emplaced the Monkton on top of the Ordovician strata exposed at the base of the mountain. Plate 3, Figure 1 shows a simplified geologic map of Pease Mountain used in this study. There is no outcrop of the Champlain Thrust on the west side of Pease Mountain and the thrust is located on the map immediately below the topographically lowest outcrop of the Monkton. Evidence for the fault is the juxtaposition of Ordovician strata topographically below the Cambrian Monkton. The Ordovician stratigraphy is inverted on the lower plate, with the Glens Falls limestone lying above the Iberville Shale in the overturned limb of a syncline. The composite measured section of the Monkton at Pease Mountain was constructed from a traverse near the base of the southwest side of the mountain, at the lowest exposure of the Monkton above the Champlain Thrust, up the slope to its top (Plate 3, Figure 1). At least one visible intraformational bedding parallel thrust occurs in the Monkton, recognized only by cleavage developed in less competent lithologies in this unit. The intraformational fault(s) is part of the broad damage zone produced by the Champlain Thrust. The thrust generated a strain gradient such that strain is distributed along small intraformational thrust faults within the Monkton stratigraphy and by cleavage development in siltstone and mudstone horizons; the more competent sandstone beds show no cleavage. Dolostone beds near these small thrusts may exhibit fractures. The shallow dip of the intraformational thrust(s) appears to follow bedding planes and are interpreted to produce minimal vertical offset. The dolostone beds near the top of Pease Mountain might be mistaken for the Dunham Dolostone, however upon examination sedimentary structures characteristic of the dolostones of the Monkton, specifically cryptalgalaminites and ripple cross laminations, are visible. The Pease Mountain stratigraphic section illustrates the interval in the stratigraphy that might be impacted by bedding plane parallel slip (Plate 3, Figure 4, yellow bar: 24-35 m). At a regional (geologic map) scale, the bedding plane slip surfaces in the Monkton can be ignored as

they do not play a significant role in changing the thickness of the unit. This interpretation is based on the similarity of the overall stratigraphic trends in lithofacies seen at Pease Mountain, which are similar to more structurally coherent exposures in the Burlington area (Red Rocks).

Additional outcrops of the Monkton were identified between Pease Mountain and Guinea Road to the east, where the rocks recording the gradational transition into the Winooski Dolostone are exposed. These outcrops are placed in the stratigraphy by calculations of the covered interval using the average dip of the beds and the horizontal distance determined in Google Earth©. Based on these assumptions the composite stratigraphic section, constructed by measurement of bed thickness and calculations of covered intervals between beds, has yielded a section ~361 meters in thickness. However, there is a thick covered interval (~168 m) between the stratigraphically highest outcrops on the east side of Pease Mountain (along the Mt Philo Road) and the interbedded dolostones and red-colored siltstones exposed along Guinea Road to the east and the Winooski Dolostone outcropping nearby (east side of Guinea Road). The thickness of this covered interval was calculated using the location of Champlain Thrust on the west side of Pease Mountain, the 14° east average dip of the unit, and the horizontal distance of 2000 meters between the uppermost outcrop of Monkton on Pease Mountain and the Winooski Dolostone (measured in Google Earth©). This calculation indicates that there is 499 m of stratigraphy possible between the Champlain Thrust and the Winooski Dolostone. Subtracting the measured 104.5 meters of Monkton on the southwest side of Pease Mountain above the Champlain Thrust from the 499 meters of space below the Winooski, the calculated possible thickness of Monkton here is 394 meters. This is not an unreasonable value compared to the estimate by Welby (1961) of 335-350 meters for the Monkton in the Champlain Valley.

Paleocurrent data

Paleoflow data was obtained from measurement of crestline orientations on bedding planes and from the inclination of foresets on cross-beds. Results are shown on the stratigraphic columns for two outcrops in the study area (Plate 3, Figure 16). Data from ripple crestline orientations from Pease Mountain indicates a dominance of bipolar flow directions. The data from ripples indicates flow to the northeast and southwest. Data from migrating dunes record flow to the north-northeast.

Lithofacies and Stratigraphic Trends

The Monkton at Pease Mountain contains almost all of the lithofacies described in this report (only St, Sp, and Shb are absent). Similar to the Burlington outcrops to the north, the stratigraphy at Pease Mountain near the exposed base of the unit is dominated by dolostones (Dm and Ds) recording a carbonate pond environment. The bulk of exposures on Pease Mountain are tidal sand flat sediment of Lithofacies Fr and Fms. Above 43 meters in the section the cross bedded sands of Lithofacies Sx record migrating tidal sand bars capped by tidal flat sediments of Cycle Type 2. Similarly to Red Rocks Park, there is an interval in the Pease Mountain stratigraphy where wave reworked sandstones (Lithofacies Fw) are common. This suggests sea level rise flooded a portion of the tidal flat. At several intervals in the Pease Mountain stratigraphy these horizons recording wave reworking of sediments are overlain by dolostones (ex, 32 to 34 meters; 16-18 meters) which also suggests that sea level rise may have temporarily halted clastic input.

Above a very thick covered interval the uppermost meter of the Monkton is interbedded red rippled tidal flat sandand dolostone. It is not clear if the dolostones represent carbonate pond or open shelf settings.

In general, the dolostones dominate the lowest exposed horizons on Pease Mountain and the stratigraphy becomes more clastic-rich up section until the contact with the Winooski Dolostone is approached and rocks become interbedded dolostones and rippled sandstone. This is the same trend seen in the Burlington area (Red Rocks). Because of the numerous covered intervals within the Monkton on Pease Mountain, as well as the extensive covered interval between Pease Mountain and Guinea Road to the east, it is not possible to note any trends in cycle architecture and thickness. In general, there are more horizons exposed that contain coarser-grained sandstones or sandy dolostones than other Monkton outcrops studied elsewhere for this report. Compared to the Monkton in the Burlington area (Redstone Quarry in Burlington (Plate 1, Figure 4), the fine and medium-grained sandstones on Pease Mountain exhibit many more wave-influenced sedimentary structures such as symmetrical ripples and upward-bundling ripples (Lithofacies Fw).

References

Aagaard, T., Hughes, M., Baldock, T., Greenwood, B., Kroon, A., Power, H., 2012, Sediment transport processes and morphodynamics on a reflective beach under storm and non-storm conditions: MarineGeology, v. 326-328, p. 154-165.

Ball, M.M., 1967, Carbonate sand bodies of the Bahamas: Journal of Sedimentary Petrology, v. 37, p. 556-591.

Brand, U. and Rust, B.R., 1977, The age and upper boundary of the Nepean Formation in its type section near Ottawa, Ontario: Canadian Journal of Earth Sciences, v. 14, p. 2002-2006.

Brink, R., Mehrtens, C., and Maguire, H., 2019, Sedimentology and petrography of a late lower Cambrian transgressive sequence: Altona Formation (Potsdam Group) in northwestern New York: Bulletin of Geosciences, v. 94, no. 3, p. 1-20.

Cherichetti, L., Doolan, B., Mehrtens, C., 1998, The Pinnacle Formation: A Late Precambrian Rift valley fill with implications of Iapetus rift basin evolution: Northeastern Geology, v. 20, p. 175-185.

Dalrymple, R.W., 2010, Tidal depositional systems *in* James, N.P., and Dalrymple, R.W., eds, Facies Models 4: Geological Association of Canada IV Series: GEOtext 6, p. 201-232.

deRaaf, J.F., Boersma, J.R., van Gelder, A., 1977, Wave-generated structures from a shallow marine succession, Lower Carboniferous, County Cork, Ireland: Sedimentology, v. 24, p. 451-483.

Desjardins, P.R., Buatois, L. A., Pratt, B.R., and Mangano, M.G., 2012, Sedimentological–ichnological model for tide-dominated shelf sandbodies: Lower Cambrian Gog Group of western Canada: Sedimentology, col. 59, no. 5, p. 1452-1477.

Dorsey, R., Agnew, P.C., Carter, C. M, Rosencrantz, E.J., and Stanley, R.S., 1983, Special Bulletin 3: Bedrock geology of the Milton quadrangle, northwestern Vermont: Vermont Geological Survey Special Bulletin, 14 p., 4plates, scales 1:62,500 and 1:24,000.

Dumas, S., Arnott, R.W.C., Southard, J.B., 2005, Experiments on oscillatory-flow and combined-flow bedforms; implications for interpreting parts of the shallow-marine sedimentary record: Journal of Sedimentary Research, v. 75, no. 3, p. 501-513.

Goldberg, J. and Mehrtens, C., 1997, Depositional environments and sequence stratigraphy interpretation of the Lower Middle Cambrian Monkton Quartzite, Vermont: Northeastern Geology,v. 20, p. 11-27.

Harms, J.C., Southard, J.B., Spearing, D.R., and Walker, R.B., 1975, Depositional environments as interpreted from primary sedimentary structures and their stratification sequences: Society of Economic Paleontologists and Mineralogists Short Course, no. 2, 161 p.

Kämpf, J., and Myrow, P., 2014, High density mud suspensions and cross shelf transport: On the mechanism of gelling ignition: Journal of Sedimentary Research, v. 84, no. 3, p. 215-223.

Kim J., Romanowicz, E., Mehrtens, C., 2013, Using deep bedrock well logs to constrain stratigraphic and structural problems in Vermont, Abstracts with Programs, Proceedings of NGWA Conference on Groundwater in Fractured Rock and Sediments, Middlebury, Vermont, 3 September 2013.

Kumarapeli, P.S., Dunning, G.R., Pintson, H., and Shaver, J., 1989, Geochemistry and U-Pb zircon age of comenditic metafelsites of the Tibbit Hill Formation, Quebec Appalachians: Canadian Journal of Earth Sciences, v. 23, p. 202-213.

Landing, E., 2007, Ediacaran-Ordovician of east Laurentia; geologic setting and controls on deposition along the New York Promontory region: Bulletin - New York State Museum (1976), 510, p. 5-24.

Landing, E., Amati, L., and Franzi, D. A., 2009, Epeirogenic transgression near a triple junction; the oldest (latest Early-Middle Cambrian) marine onlap of cratonic New York and Quebec*:* Geological Magazine, v. 146, no.4, p. 552-566.

Maguire, H., Mehrtens, C., Kim., J., Romanowicz, E., 2018a, Lower Cambrian gamma log data from wells in western Vermont and northeastern New York: Vermont Geological Survey Open File Report VG2018-7.

Maguire, H., Mehrtens, C., Kim, J., Romanowicz, E., 2018b, Application of geophysical methods to stratigraphic problems in the Lower Cambrian Monkton Formation, northwestern Vermont: Open Journal of Geology.

Malka, E., Stevenson, R. K., and David, J., 2000, Sm-Nd geochemistry and U-Pb geochronology of the Mont Rigaud stock, Quebec, Canada; a late magmatic event associated with the formation of the Iapetus rift: Journal of Geology, v. 108, no. 5, p. 569-583.

McElwee, E. and Mehrtens, C., 2016, The origin of the color difference in sandstones of the lower Cambrian Monkton Formation: Vermont Geology Society Abstracts with Programs.

Mehrtens, C., and Gregory, G., 1984, An occurrence of *Salterella conulata* in the Dunham Dolomite (Lower Cambrian) of Northwestern Vermont, and its stratigraphic significance: Journal of Paleontology, v. 58, p. 1143-1150.

Miall, A. D., 1985, Architectural-element analysis: a new method of facies analysis applied to fluvial deposits: Earth-Science Reviews, v. 22, no. 4, p. 261-308.

Mount, J. F., 1984, Mixing of siliciclastic and carbonate sediments in shallow shelf environments: Geology, v. 12, no. 7, p. 432-435.

Nowlan, G.S., 2013, Report on two samples from Lower Ordovician strata in the vicinity of Rockland in eastern Ontario: Geological Survey of Canada, Paleontological Report 004-GSN-2013, 3 p.

Olariu, C., Steel, R. J., Dalrymple, R. W., and Gingras, M. K., 2012, Tidal dunes versus tidal bars: The sedimentological and architectural characteristics of compound dunes in a tidal seaway, the lower Baronia Sandstone (Lower Eocene), Ager Basin, Spain: Sedimentary Geology, v. 279, p. 134-155

Palmer, A.R., and James, N.P., 1979, The Hawke Bay Event: A circum-Iapetus regression near the Lower-Middle Cambrian boundary: Memoir—Department of Geological Sciences, Virginia Polytechnic Institute, Blacksburg, v. 2, p. 15-18.

Rahmanian, V.D., 1981, Mixed siliciclastic-carbonate tidal sedimentation in the Lower Cambrian Monkton Formation of west-central Vermont: Geological Society America Abstracts with Programs, v. 13, p. 170-1710

Reineck, H. E., and Singh, I.B., 1980, Tidal flats *in* Depositional Sedimentary Environments, p. 430-456: Springer, Berlin, Heidelberg. DOI: https://doi.org/10.1007/978-3-642-81498-3_26.

Rittenhouse, G., 1943, Transportation and deposition of heavy minerals: Geologic Society of America Bulletin, v. 54,p. 1725-1780.

Shaw, A.B., 1958, Structure and stratigraphy of the St. Albans area, Northwestern Vermont: Geological Society of America Bulletin, v. 69, p. 519-567. DOI: https://doi.org/10.1130/0016-7606(1958)69[519:SASOTS]2.0.CO;2.

Stanley, R.S., 1987, The Champlain Thrust at Lone Rock Point, Field Trip 50, *in* Roy, D., ed., Northeastern Section of the Geological Society of America: Decade in American Geology: Geological Society of America, p. 225-228.

Taylor, A.M., and Goldring, R., 1993, Description and analysis of bioturbation and ichnofabric. Journal of the Geological Society of London, v. 150, p. 141-148.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R. M., Vail, P.R., Sarg, J.F., Loutit, T.S. and Hardenbol, J., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions *in* C.K. Wilgus, Hastings, B.S., Posamentier, H., Van Wagoner, J., Ross, C.A., Kendall, C.G.St.C., eds., Sea Level Changes-An Integrated Approach: Society of Economical Paleontologists and Mineralogists Special Publication, v. 42.

Visser, M.J., 1980, Neap-spring cycles reflected in Holocene subtidal large-scale bedform deposits: A preliminary note: Geology, v. 8, p. 543-546.

Welby, C.W. 1961, Bedrock geology of the central Champlain Valley of Vermont, Vermont Geological Survey Bulletin 14, 296 p.

The stratigraphy of the Lower Cambrian Monkton Formation Plate I: Burlington

Abstract

Measured stratigraphic sections of the Monkton Formation were completed at 3 localities in the Burlington, VT region and were also examined in two wells in the area. While no outcrop exposed a complete section through the unit, the 3 outcrops represent the lower (Red Rocks) and upper strata (Redstone Quarry and Salmon Hole) of the Monkton. The upper contact with the Winooski Dolostone is exposed above a covered interval at the Salmon Hole outcrop. The Monkton in this region consists of lithofacies representing intertidal flat to subtidal environments of deposition.

METHODS: Outcrops were measured and described at the cm scale at both the Salmon Hole and Redstone Quarry outcrops. The Red Rocks cliff exposure along the shore of Shelburne Bay was measured with a stadial rod and accessible sections of the cliff were described at the cm scale. Representative samples of each lithology were collected. Cross bed sets and ripple crestline orientations were measured and described for paleocurrent analysis. Covered intervals were measured using strike and dip data, stadial rod and tape measure.

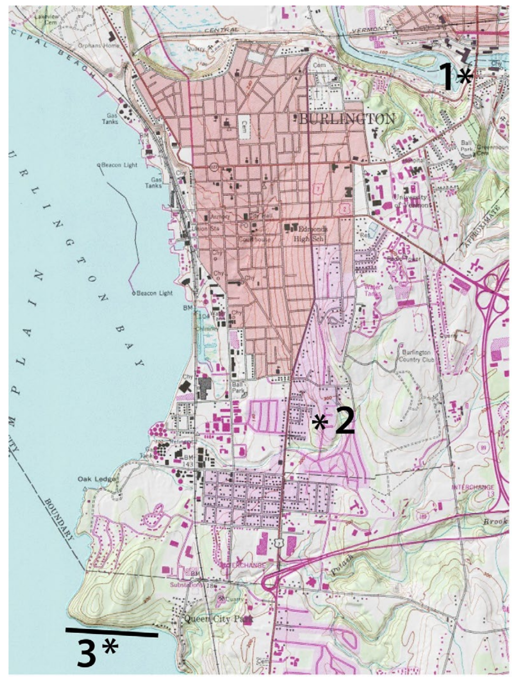

Figure 1. Locality map for Salmon Hole (1), Redstone Quarry (2) and Red Rocks shoreline (3)

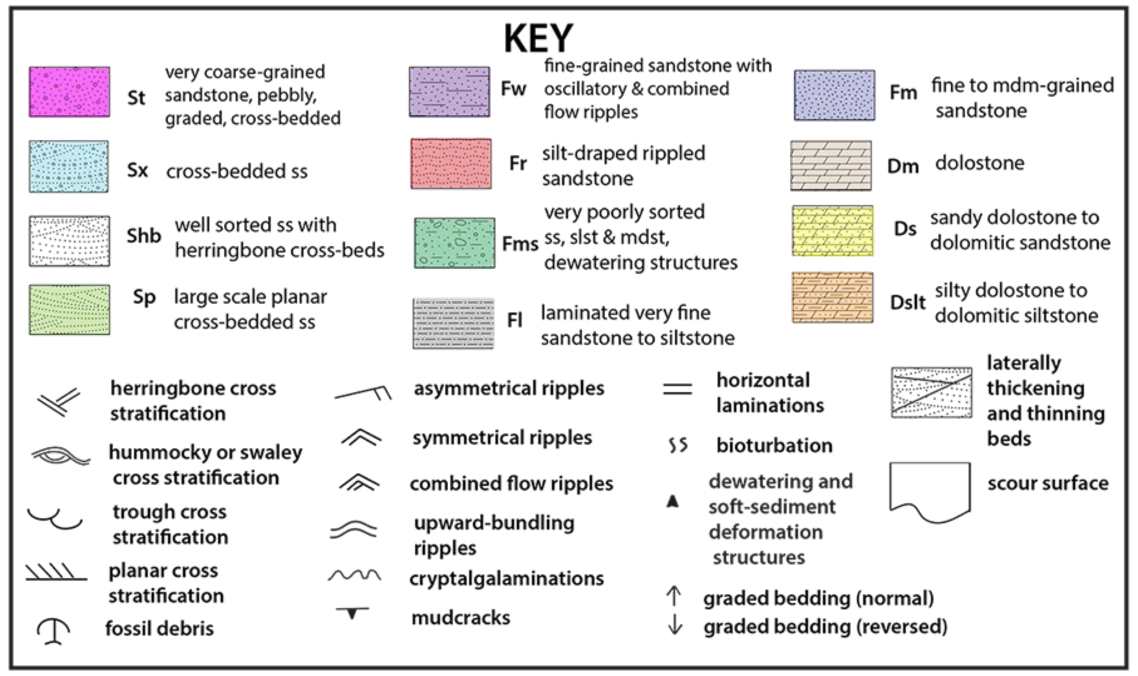

Figure 2. Key to symbols used in stratigraphic columns

Figures 3, 4, and 5 are measured stratigraphic sections and paleocurrent data from localities 1, 2, and 3 in the Burlington region . Circled numbers indicate the stratigraphic position of accompanying numbered field photos

FIGURE 3

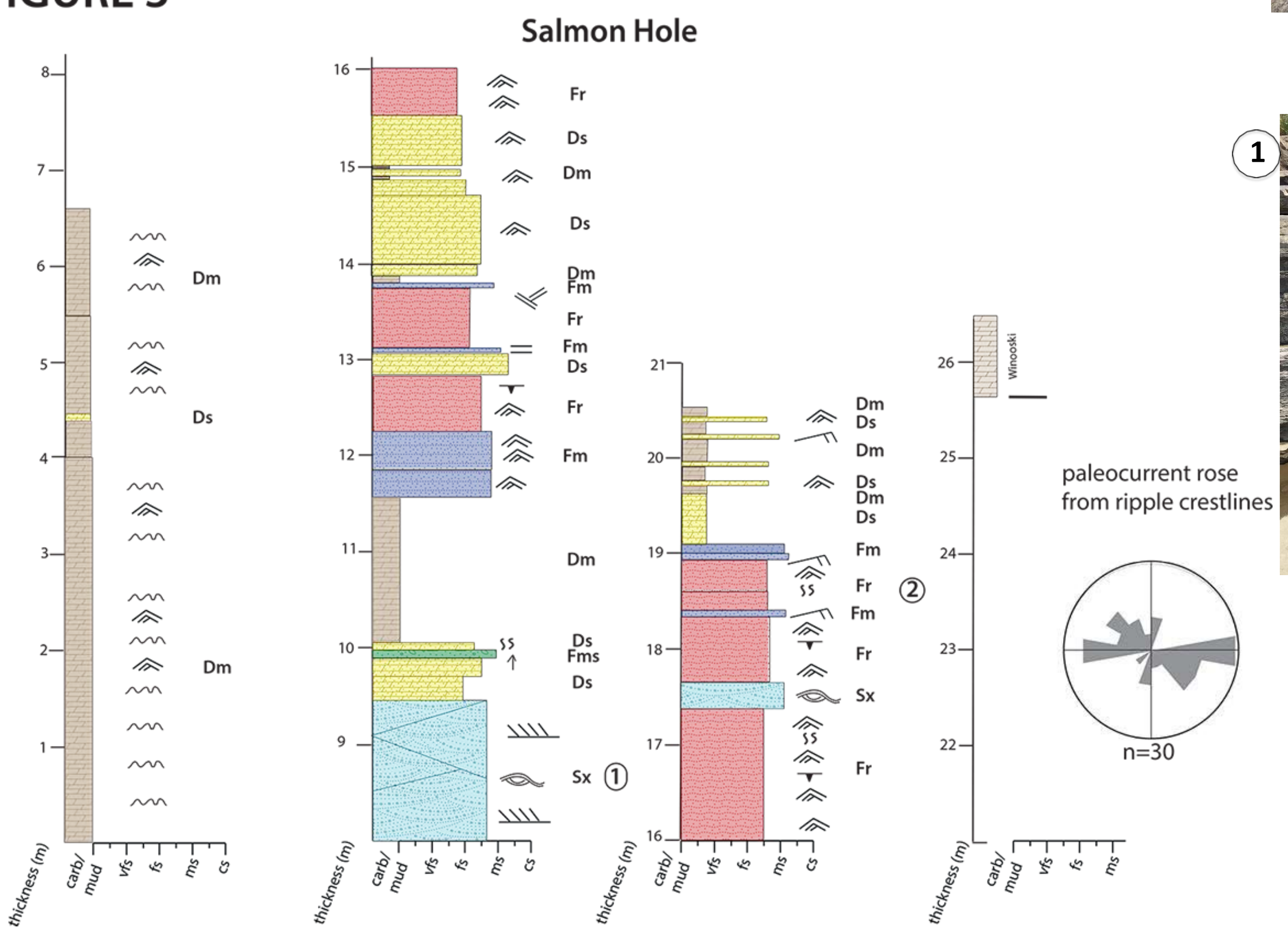

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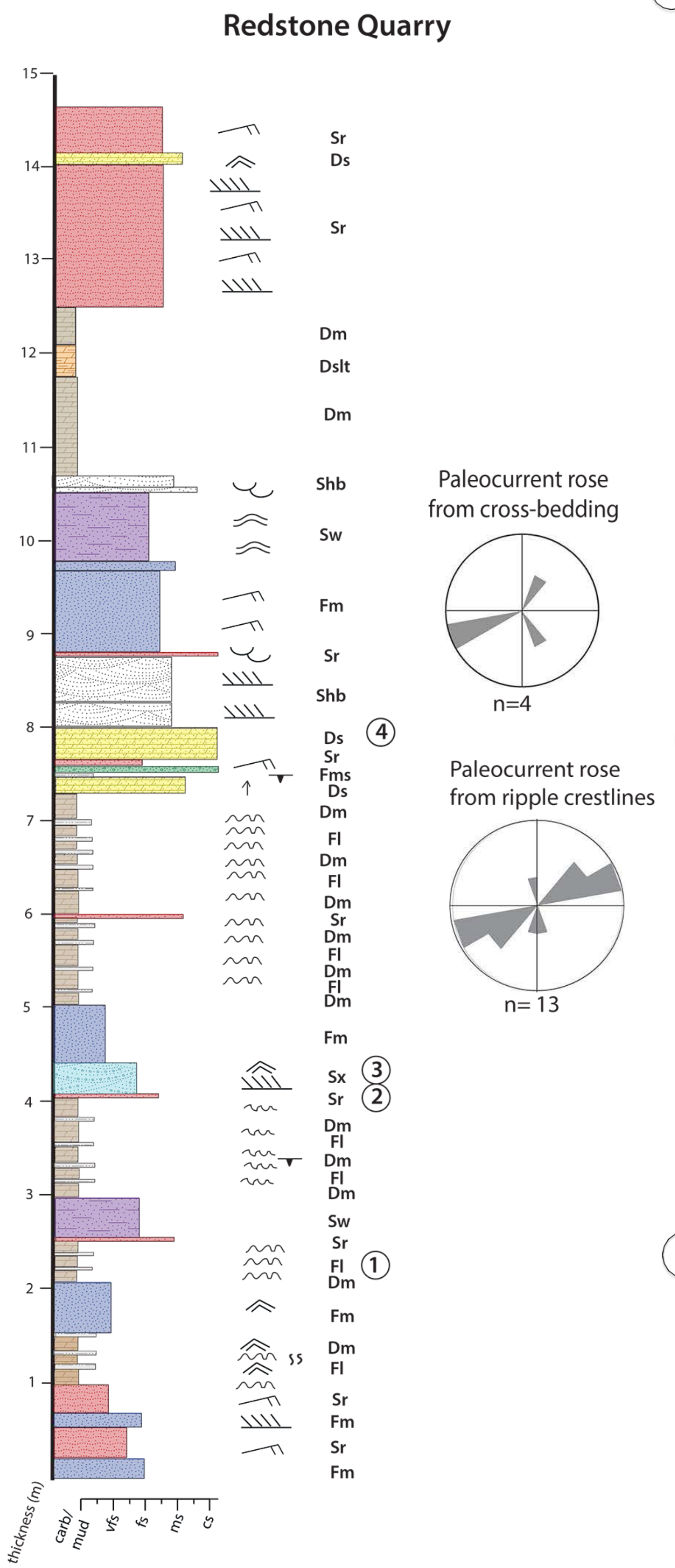
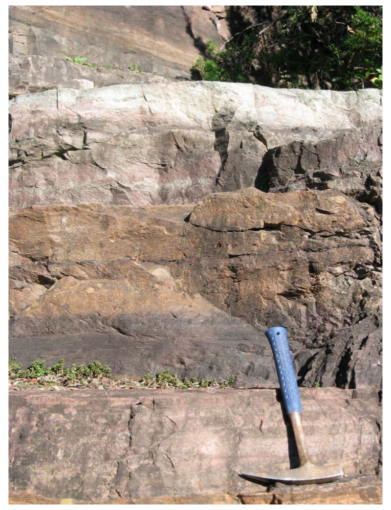
Photo captions: (1) wedge sets of cross-bedded sandstones (Sx) showing bipolar flow directions (rock hammer for scale);
(2) Bedding planes showing multiple orientations of interference ripples (right side of photo) and symmetrical ripples (left under compass) (Fr); Silva compass for scale.

Figure 4



④ 

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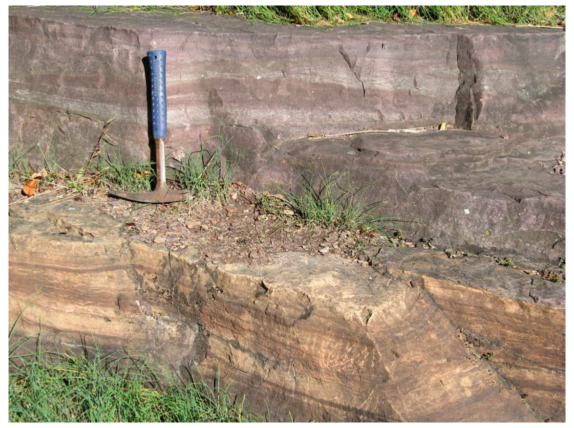
② 

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Photo captions: (1) close-up of cryptalgalaminites (Dm and Fl); hammer for scale; (2) contact between cryptalgalminite (Dm) and cross-bedded sandstones (Sx). Color variations in Sc highlight compound dune structures; (3) The bedding surface above the rock hammer contains interference ripples (Fm); yellow pencil is 15 cm long. (4) Behind the blue handle of the rock hammer is a bed of very poorly sorted ilmenite-rich sandstone (Fms). It is overlain by dolomitic sandstone (Ds) which in turn is overlain by well sorted white colored cross-bedded sandstone (Shb).

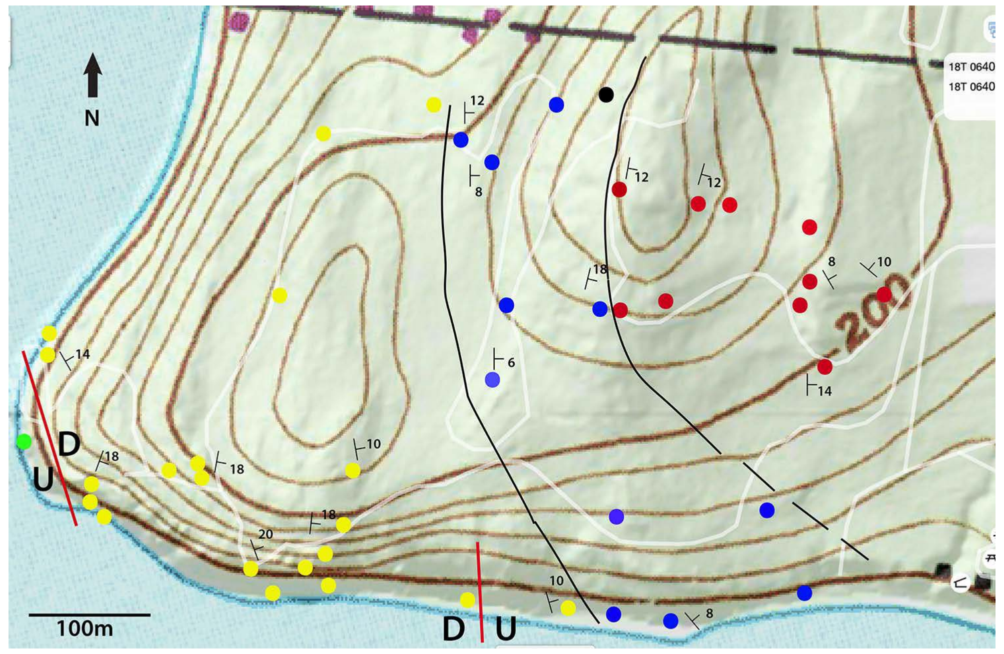
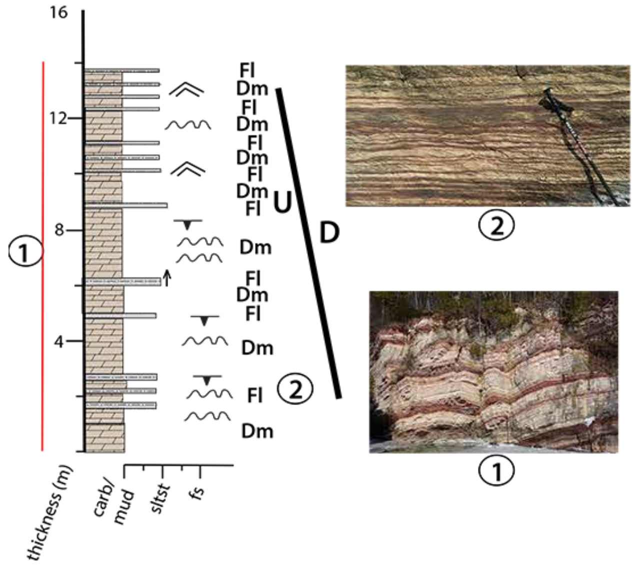


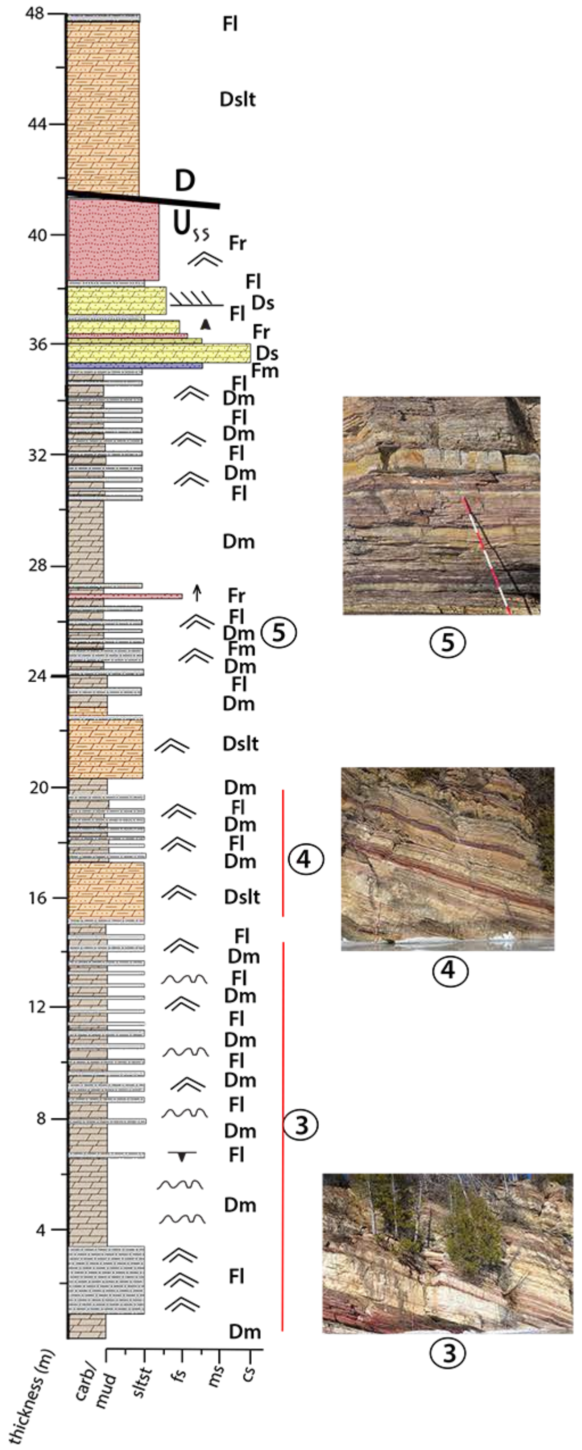
Figure 5. Base map for Red Rocks Park showing the location of outcrops. Two faults are mapped (in red) but their orientation is speculative. Smaller faults of minor offset, where the stratigraphy could be traced across, are not mapped. Yellow dots represent outcrops that are dominantly dolostone (Lithofacies Dm and Dslt) with subordinate amounts of fine-grained clastic material (Fl, Fm and Fr). Blue dots are outcrops of predominantly cross bedded sandstones of Lithofacies Ds and Sx with lesser Fr and Fm. Red dots represent outcrops of Lithofacies Fw, Fr, and Fm. The black dot represents an outcrop of an igneous intrusion into Lithofacies Sx. Black lines are contacts between the three groupings of lithofacies. All outcrops strike generally to the north and dip between 8 and 18 degrees to the east.

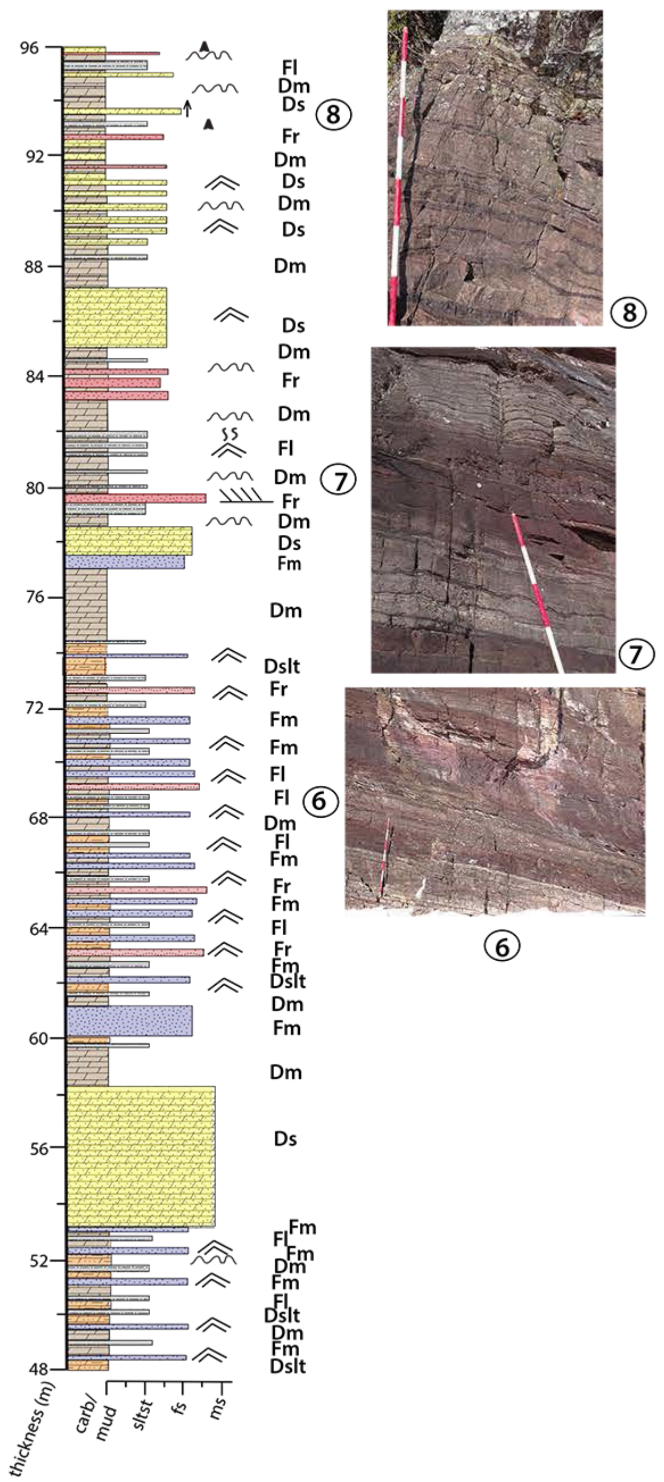
Figure 6. Measured stratigraphic section at Red Rocks. The section below 132 meters was measured along the southern cliff of the shore of Shelburne Bay. The section above 132 meters was measured from a continuous series of ledges in Red Rocks Park.

Figure 6

Red Rocks







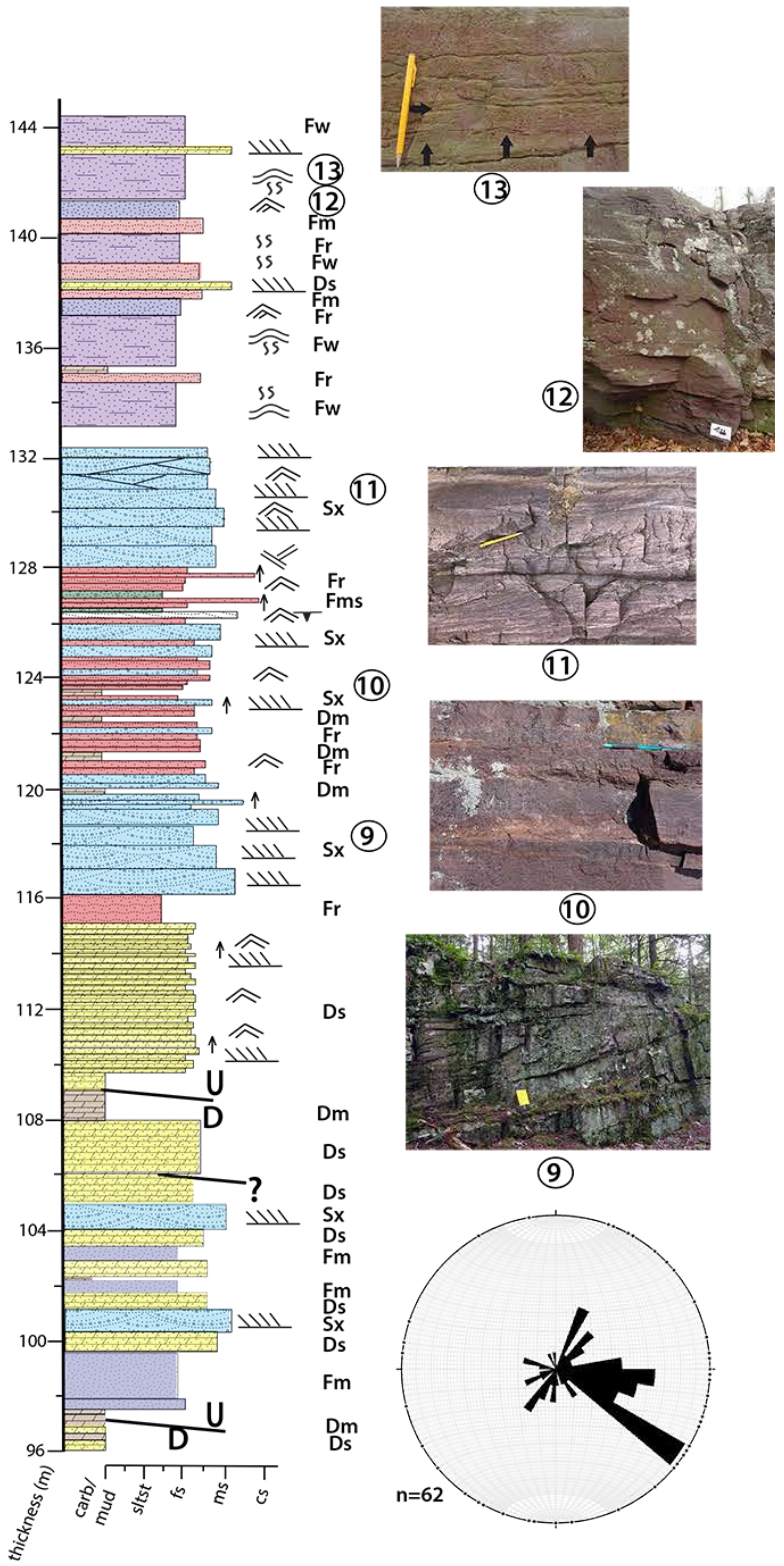
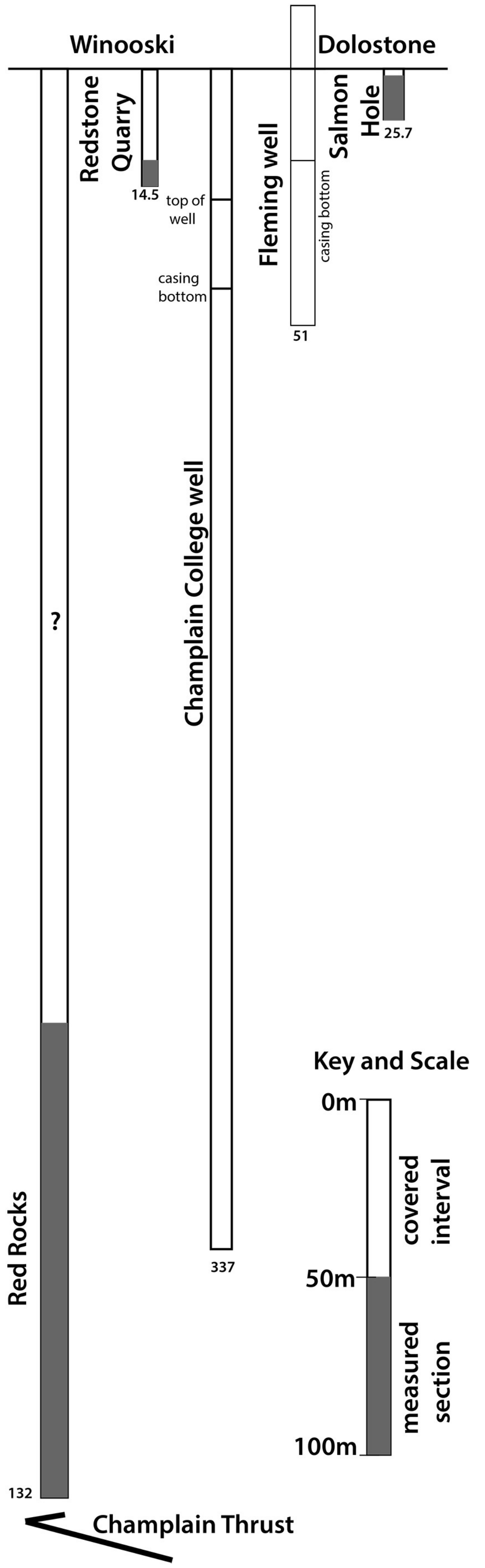


Photo captions: Field photographs correspond to numbered intervals on the stratigraphic columns. Photo 1 shows the entire stratigraphy of the lowest fault block, composed of cyclic beds of red-colored terrigenous sediment and white colored dolostone; stadial rod for scale. Photo 2, a closeup of an interval near the base of the lowest fault block, illustrates the centimeter scale of interbedding of cryptalgalaminite structures (Fl and Dm) and cross laminations; the black pole is 65 cm in length for scale. Photos 3 and 4 illustrate the stratigraphy above the lowest fault block; stadial rod for scale. Note the continued cyclic interbedded of the more terrigenous-rich red siltstone and very fine-grained sandstone (Fl) and the white dolostone (Dm). Photo 5 is a closeup of the rhythmic interbedding of clastic and carbonate sediment; stadial rod for scale. Photos 6, 7 and 8 illustrate the architecture of more clastic-rich cycles higher in the stratigraphy. Photo 9 illustrates the wedge-shaped compound dunes in Lithofacies Sx; the yellow field notebook is 17 cm in length. Photo 10 illustrates graded bedding in Lithofacies Sx to Fr; the pencil is 15 cm in length. Photo 11 of Lithofacies Sx illustrates sets of cross-beds comprising a compound dune. Photo 12 illustrates Lithofacies Fw, a fine-grained sandstone overlying planar laminated beds of Lithofacies Fm. Photo 13 illustrates oscillatory and combined flow ripples in Lithofacies Fw. The rose diagram presents paleocurrent data from cross bedding (n=62) indicating dominant flow to the east-southeast, however the abundance of other flow directions results from secondary dunes superimposed on the larger bedforms in the compound dunes.

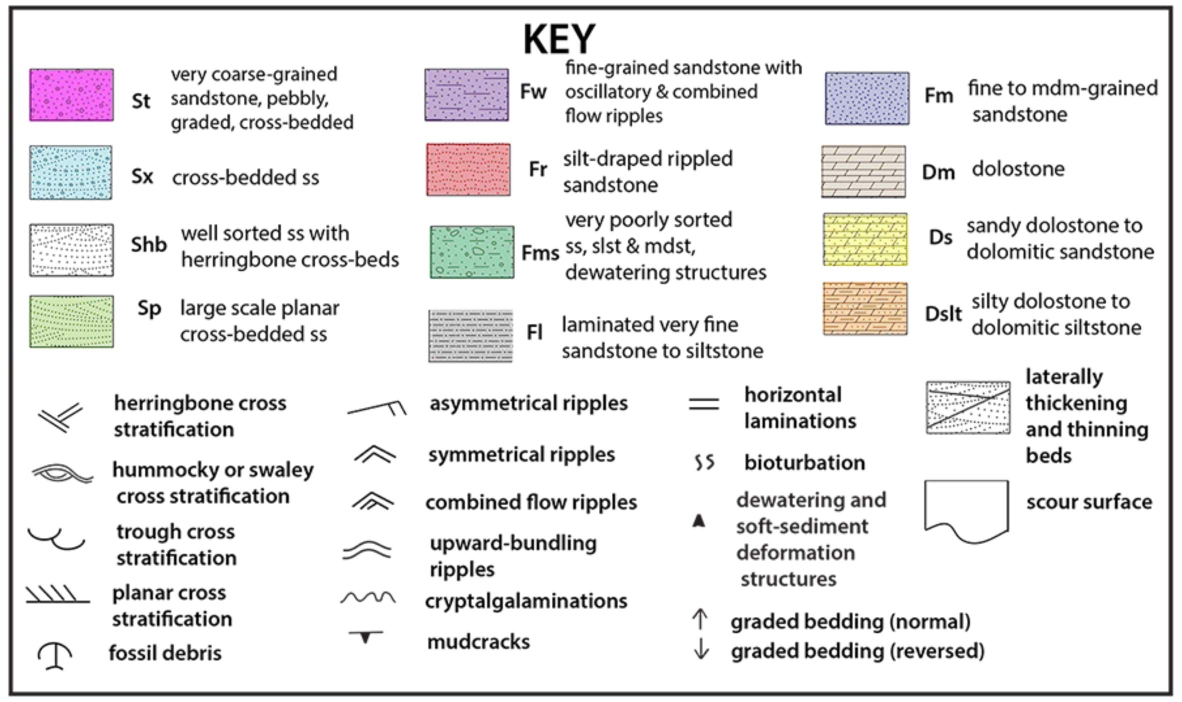
Figure 7. Correlation of outcrops in the Burlington area, based on measurement of covered interval to the overlying Winooski Dolostone (for Salmon Hole and Redstone Quarry) and position above the Champlain Thrust, near the lower contact with the Dunham Dolostone, for Red Rocks. Thicknesses and stratigraphic position of two wells in the Burlington area (from Maguire, et al., 2018) are also shown. Using Google Earth and assuming an average dip of 14° the covered interval between the top of the Red Rocks outcrop and the base of Redstone Quarry would be over 600 meters, making it likely that normal faults are present between the Red Rocks cliff exposures and outcrops of Monkton further to the east.



The stratigraphy of the Lower Cambrian Monkton Formation Plate 2: Colchester

Abstract

Three outcrops of the Monkton Formation were measured in the Colchester, VT region. The Route 2 and Grandview Road outcrops were fairly continuous west-east exposures but the Colchester Traverse contained many covered intervals. Several high angle faults are present in this area however in most cases it was possible to trace across these as offset was minor (meters). A possibility exists that larger unrecognized faults are present. However, using trigonometry and assuming a constant dip of ~14° a total thickness from the lowest exposure of the Monkton in Niquette Bay State Park (the base of the Colchester Traverse section) to the westernmost outcrop of the overlying Winooski Formation a total Monkton thickness of approximately 375 meters was calculated. This is in agreement with regional estimates of the thickness of this unit.



METHODS: Outcrops were measured and described at the cm scale. Representative samples of each lithology were collected. Thin sections were examined for each of the lithofacies identified. Cross bed sets were measured and described for paleocurrent analysis. Covered intervals were measured using strike and dip data, stadial rod and tape measure.

Figure 2. Lithofacies key for the Monkton Formation

Figures 3, 5, and 7 are measured stratigraphic sections of the Monkton Formation in the Colchester, VT region, with accompanying paleocurrent rose diagrams. Additional figures illustrate attributes of the stratigraphy. Figure 14 shows the correlation of outcrops in the Colchester region.

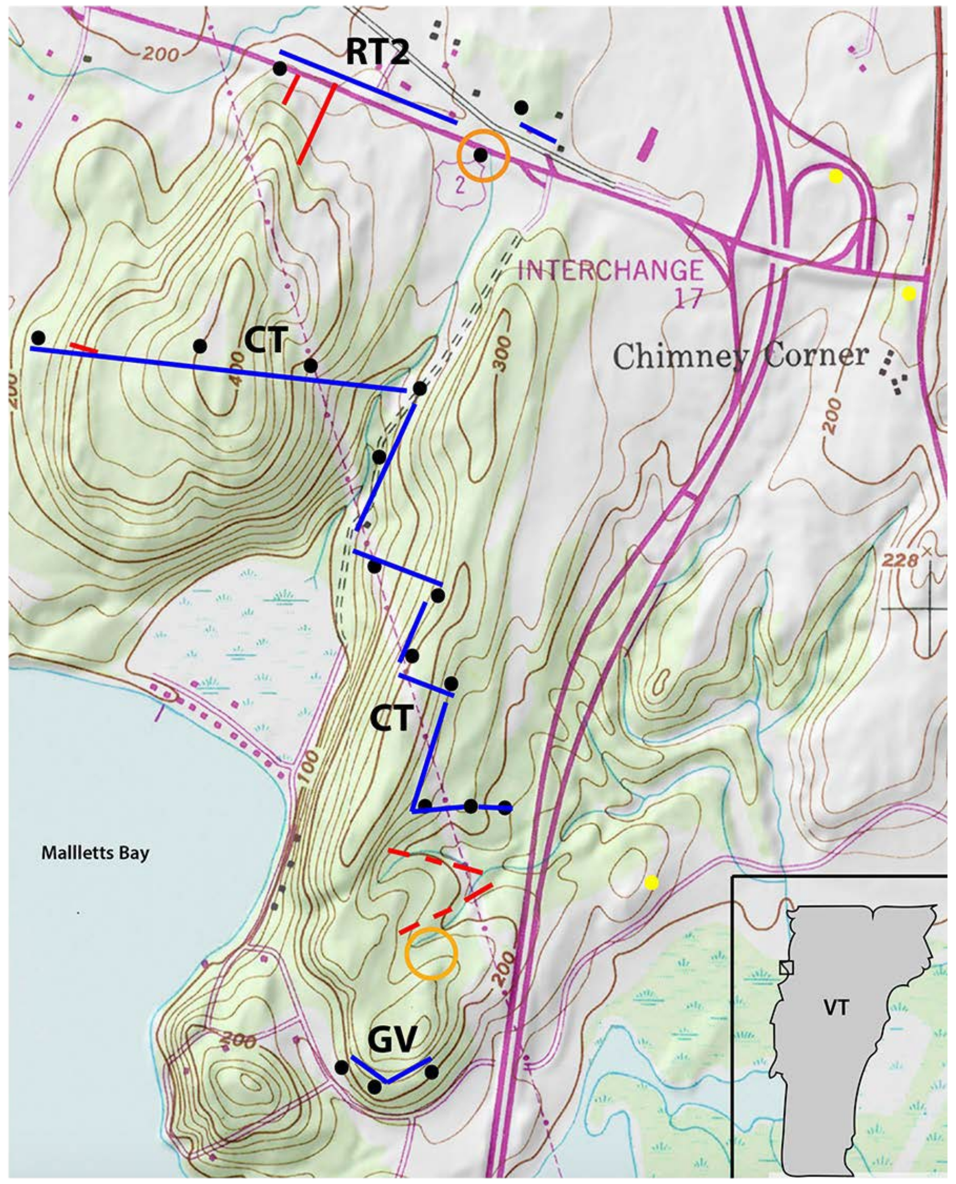


Figure 1. Locality map for the Colchester, VT area showing the location of the 3 transects measured: CT= Colchester traverse; RT2 = VT Route 2 roadcut; GV= Grandview Road. Blue lines show the paths of transects; red lines are faults (dashed if inferred). Black dots are reference stations along transects; yellow dots represent outcrops of the Winooski Formation. Orange circles indicate outcrops of probable karst features within the Monkton.

Figure 3

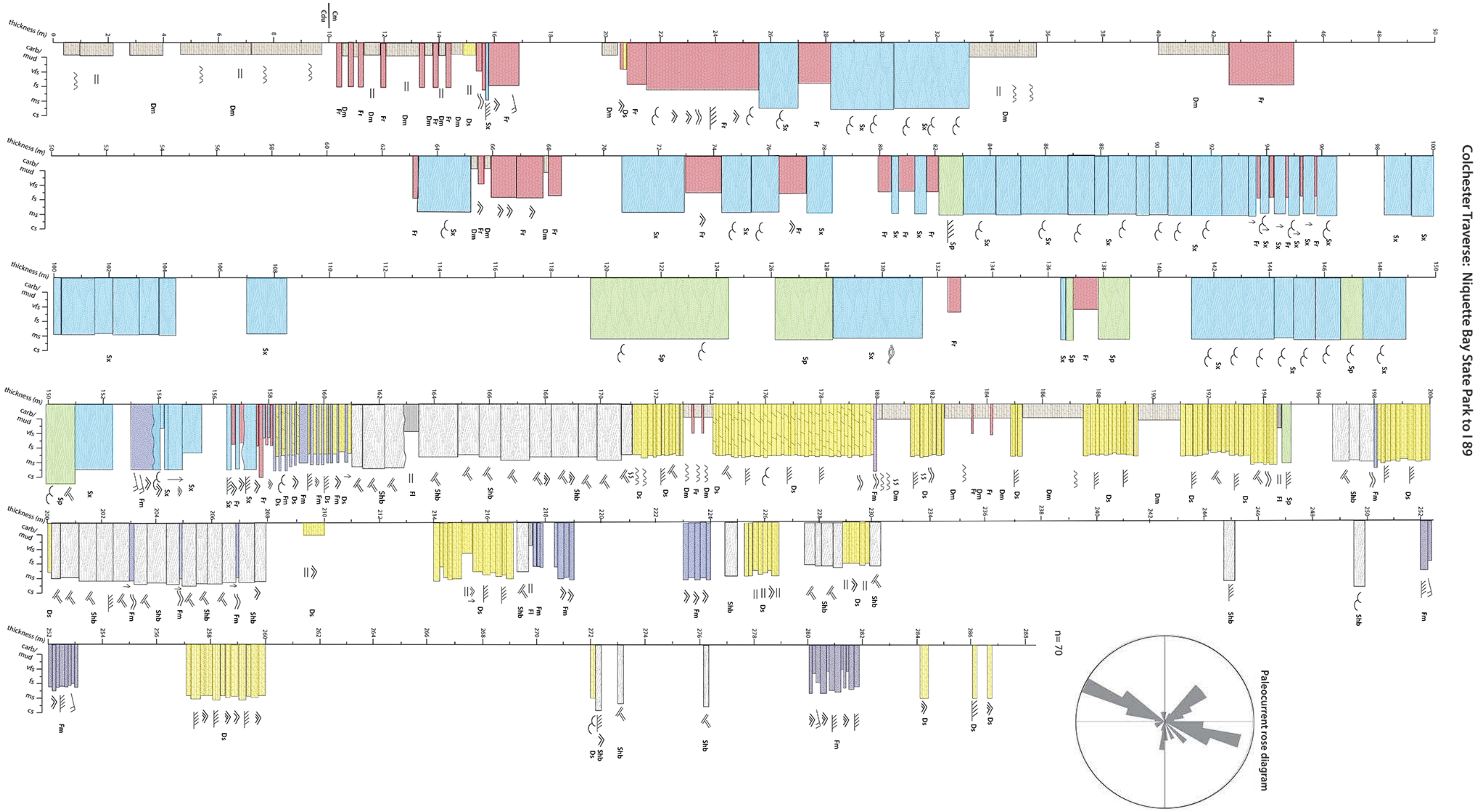


Figure 4. Lithofacies Shb from 218 m in the Colchester traverse stratigraphic column, Figure 3. The pencil for scale is 15 cm in length.

Figure 6

Grandview Road

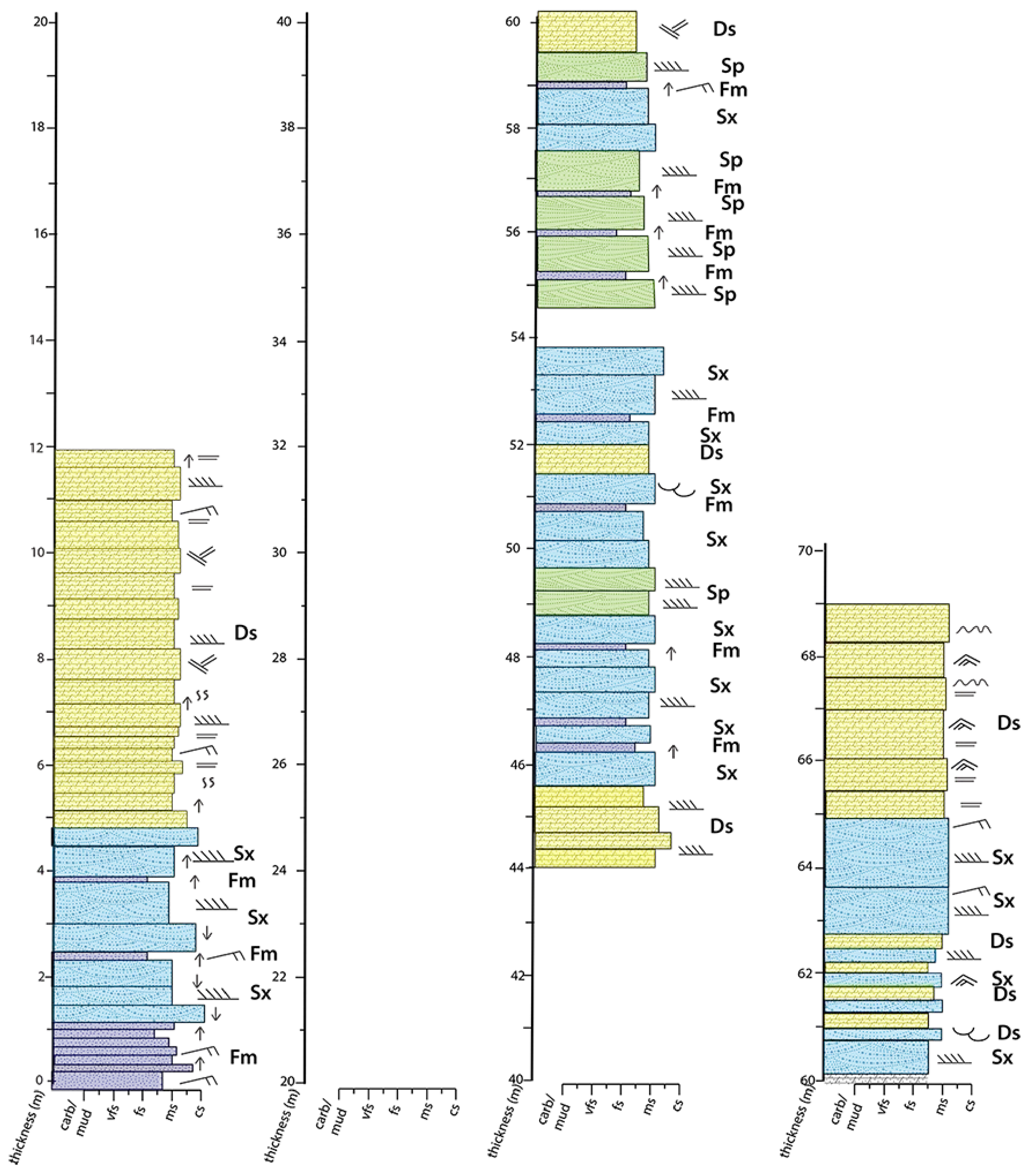


Figure 5. Hummocky (blue arrow) and swaley (black arrow) cross stratification at 130 m in the NBSP-I89 traverse. Hammer for scale.

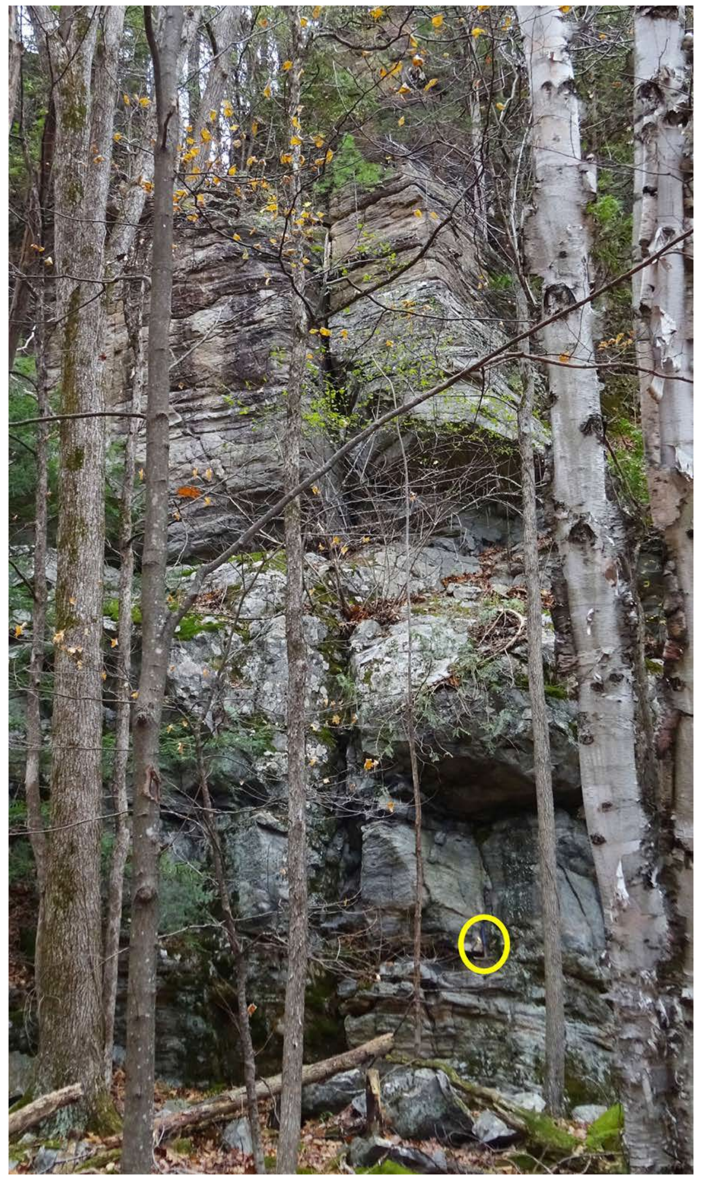
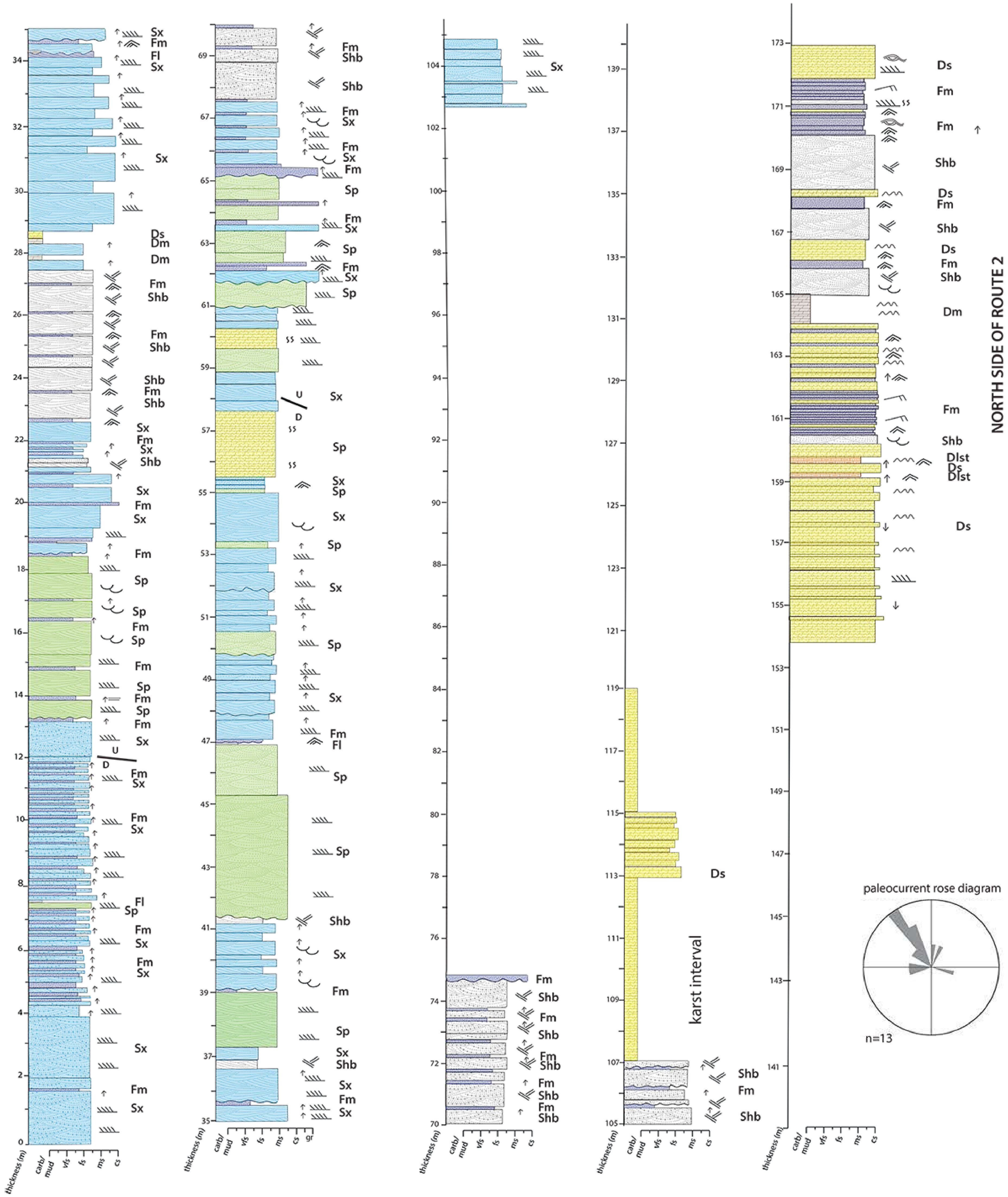


Figure 7. Photo of the westernmost cliff on the north side of Grandview Road, from the 0 to 12 meters stratigraphic interval in Figure 5. The sandstones become more dolomitic up section, a trend interpreted to reflect a decrease in clastic sediment supply. The yellow circle surrounds a rock hammer (for scale).

Figure 9. Detail of cycle at the top of Route 2 from 159.5-161 m on the stratigraphic column, Figure 7. Lithofacies Dlst at base is overlain by Lithofacies Ds, containing cryptalgalaminites and combined flow ripples (blue arrow). Sharp, scoured contact with Lithofacies Shb (red line), which grades up into rippled sand (black arrow). The notebook for scale is 16.5 cm in length.

Figure 8

Colchester Rte 2



Photographs illustrating features in the Monkton Formation along Route 2 are shown in Figures 9-15.

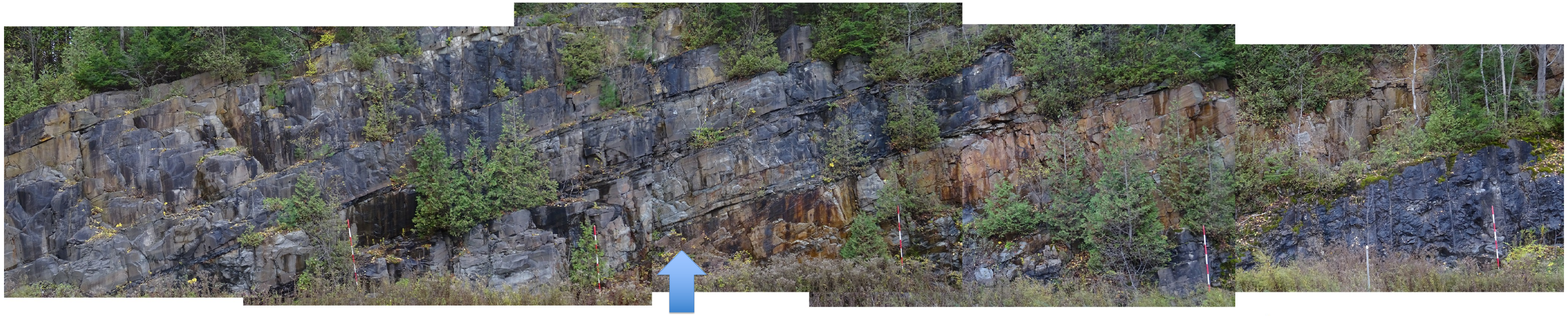


Figure 10. Photomosaic of a portion of the eastern end of the Route 2 outcrop where stacked beds of Lithofacies Sp are well displayed. The blue arrow points to the region of the outcrop that is enlarged in Figure 11.

Figure 11. Enlargement of a portion of the Rte 2 outcrop to show large scale planar cross- bedding of Lithofacies Sp (ex: "1") and the pinchouts of fine-grained horizons of Lithofacies Fl (labeled "2") that cap them, or are scoured out.

Figure 12. Photomosaic of the top of the Route 2 exposure of the Monkton. At the right edge of the photograph are herringbone cross-stratified sandstone beds of Lithofacies Shb (red arrow) and to the left of these (yellow arrows) are horizons containing clasts and rotated beds. The stratigraphy within the blue circle is shown in detail in Figure 13. These horizons of rotated beds and clast are interpreted to be solution collapse (karst) in origin.

Figure 13. Detail of the interval highlighted in the blue circle in Figure 12. The arrow points to a horizon containing clasts of dolostone and arenaceous dolostone

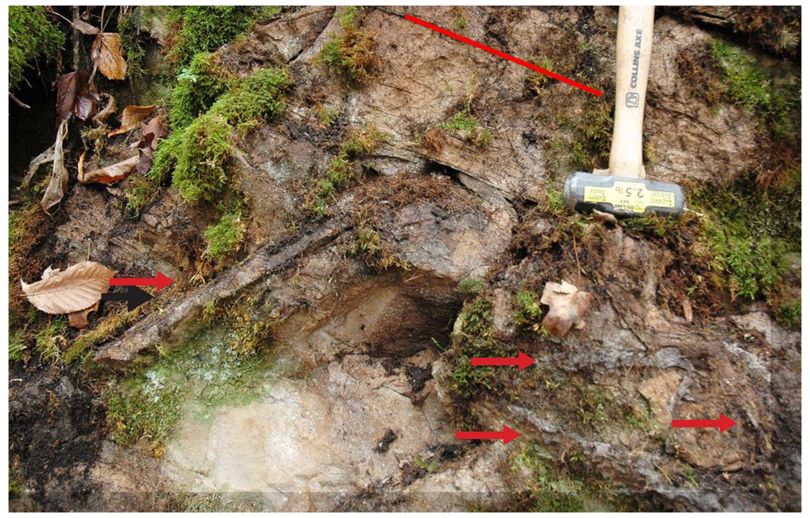


Figure 14. Photograph of the karst interval south of the Colchester Traverse composite section. Red arrows point to clasts; hammer for scale

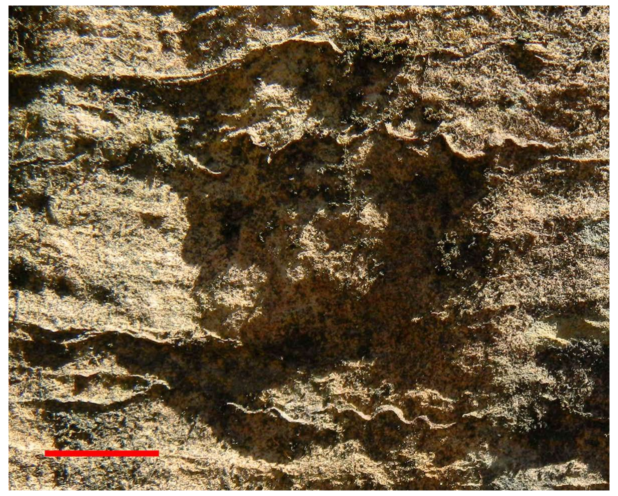


Figure 15. Photograph of cryptalgalaminations in Lithofacies Ds, 158 m in Route 2 section Figure 8. The red bar is 2 cm for scale.

Figure 16. Contact between Lithofacies Sp and Shb at 57.5 m on Route 2 section, Figure 8. The field notebook for scale is 16.5 cm in length

Figure 17. Photograph along I89 southbound (18T 0643112E, 4933554N) that illustrates a northward prograding, offlapping tongue of the tidal flat facies. Note that the lower contact of the bed indicated by the yellow arrows truncates underlying horizons. The basin lies to the north of this outcrop. The reflector on the roadside is ~1 m in height.

The stratigraphy of the Lower Cambrian Monkton Formation Plate 3: Pease Mountain

Abstract

A measured stratigraphic section of the Monkton Formation were completed on Pease Mtn, Charlotte. The base of the section is the lowest exposed dolostone above the Champlain Thrust. The top of the section is the gradational interval outcropping on the west side of Guinea Road, east of Pease Mountain. The composite stratigraphic section for the Monkton is approximately 361 meters in thickness. At least one intraformational thrust can be identified within the Monkton on Pease Mountain based on occurrences of cleaved fine-grained clastic rocks. These bedding plane parallel thrusts are not thought to have significant vertical offset to impact the thickness of the unit.

METHODS: The composite stratigraphic section was compiled from outcrops above the Champlain Thrust using a stadial rod and dip data to determine thickness. Outcrops were measured and described at the cm scale. The covered interval between Pease Mtn and the base of the Winooski Dolostone on Guinea Road east of Pease Mtn was determined from horizontal measurement of distance in Google Earth© and the average dip of the Monkton Formation. Representative samples of each lithology were collected. Cross bed sets and ripple crestline orientations were measured and described for paleocurrent analysis.

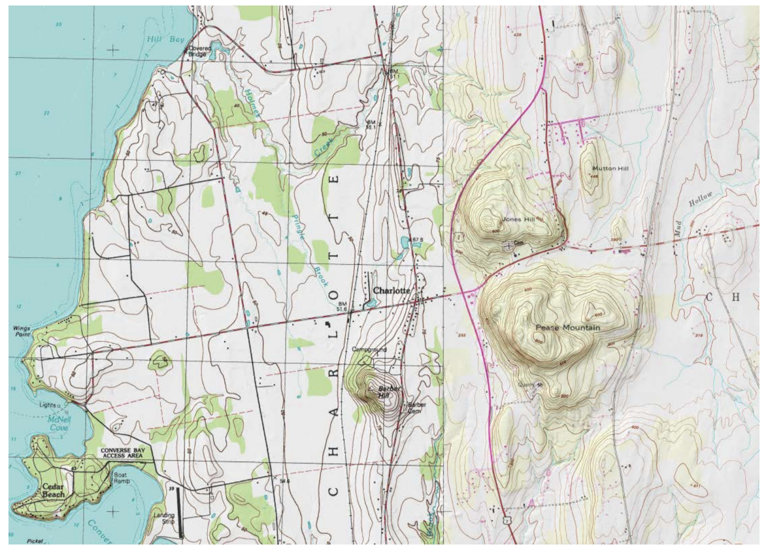


Figure 1. Location of Pease Mtn, Charlotte, VT

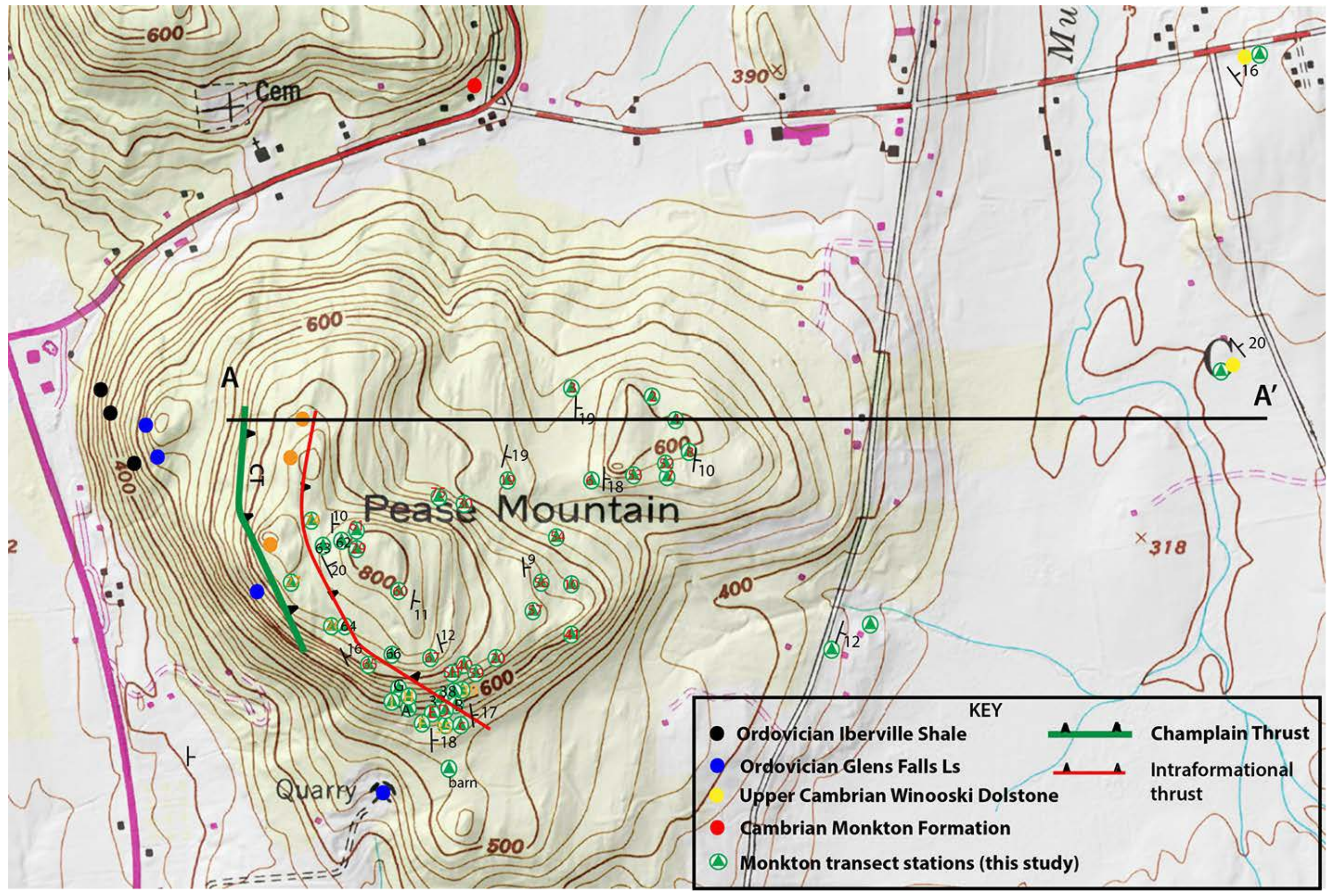
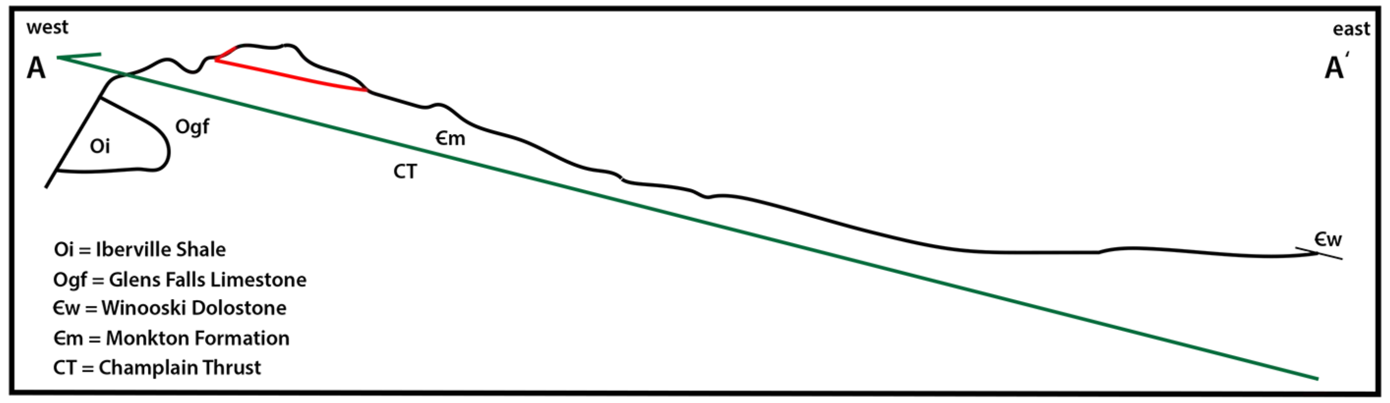


Figure 2. Geologic map and simplified cross section of Pease Mountain. The Champlain Thrust (green) has emplaced the Monkton on top of an overturned syncline in Ordovician limestones and shales. A zone of strain in the Monkton is indicated by the presence of horizons of cleaved fine-grained clastic rocks that are thought to be related to small bedding plane parallel thrusts in the unit. The approximate position of this zone is indicated by the red colored thrust fault symbol. The contact with the overlying Winooski Dolostone is indicated.



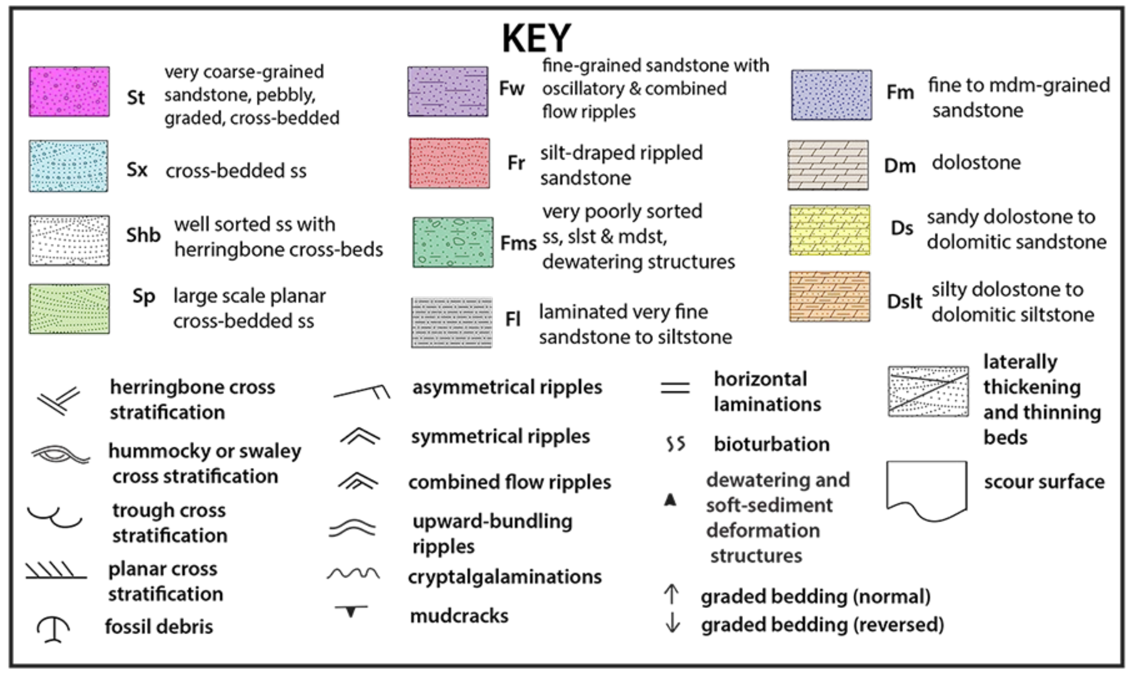


Figure 3. Key to symbols used in stratigraphic columns

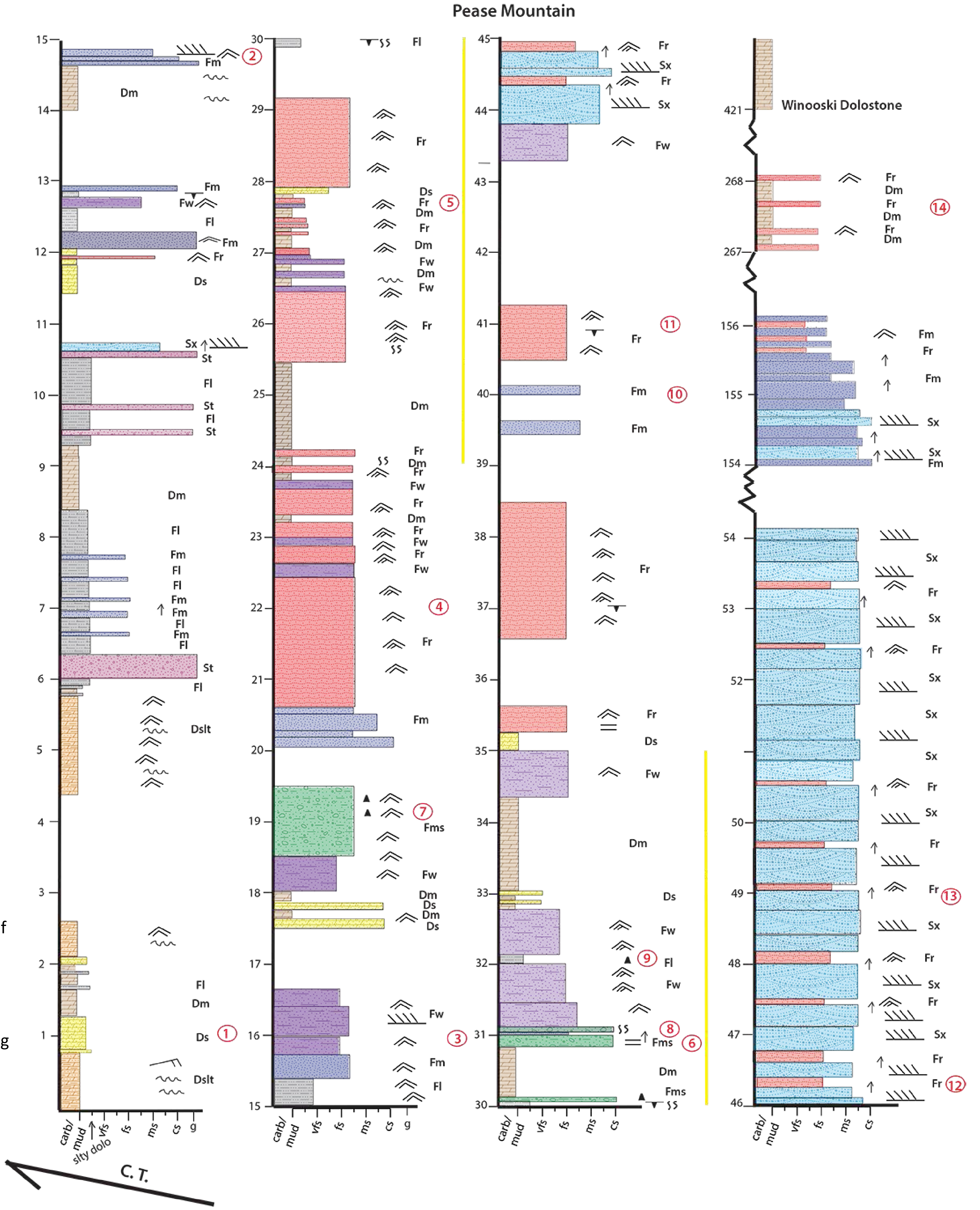
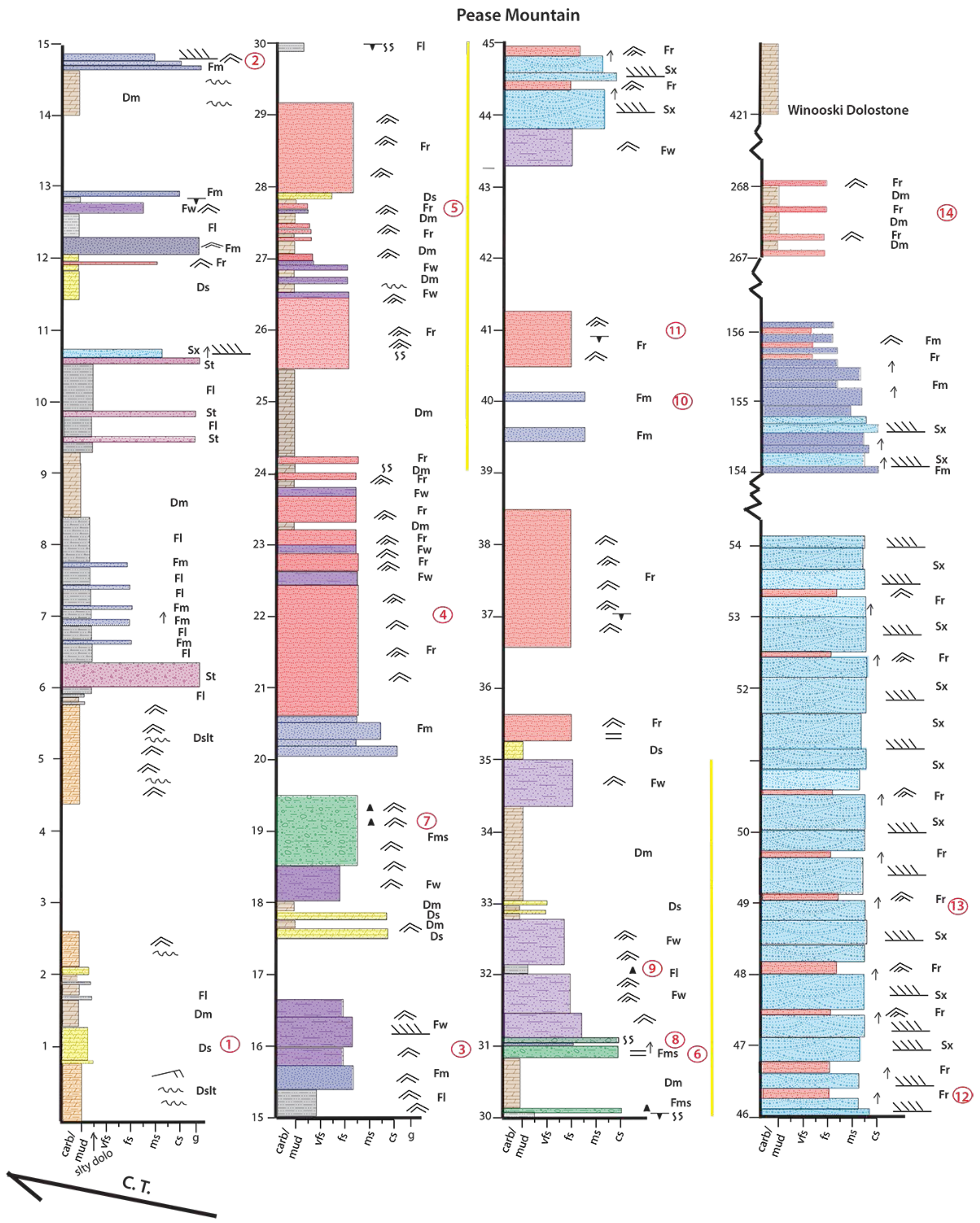


Figure 4. Composite stratigraphic column for Pease Mountain. The interval between 24 and 35 meters (yellow bar) is the portion of the stratigraphy where cleavage is well developed in less competent horizons, reflecting the proximity of an intraformational bedding plane parallel thrust. Red circled numbers refer to the location of accompanying field photographs.



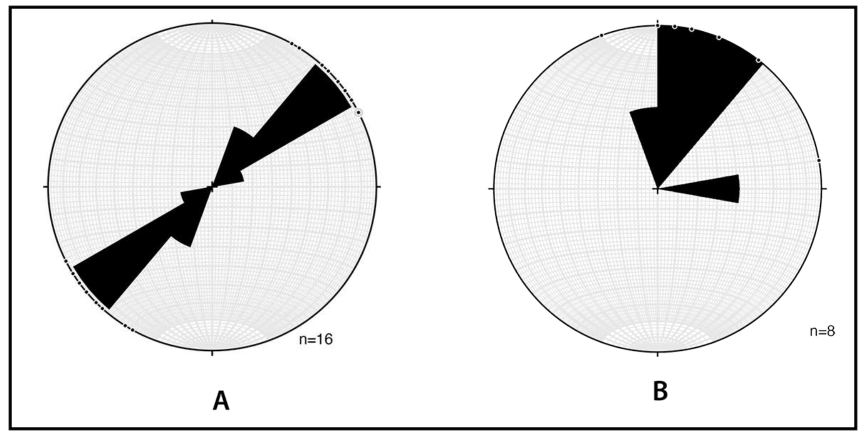
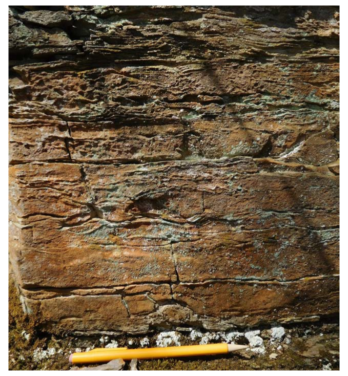


Figure 16. Paleocurrent rose diagrams for Pease Mountain ripples (A) and cross-bed sets (B). Symmetrical ripple crestline trends (A) indicate oscillatory flow is NE-SW. Cross bed sets (B) indicate flow is primarily to the north.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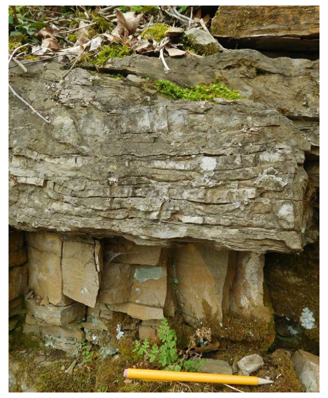
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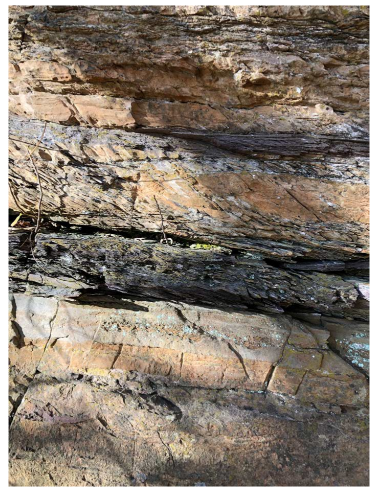
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The numbered field photographs correspond to intervals in the stratigraphy keyed to the red circled numbers on the stratigraphic column. The pencil for scale is 15 cm in length. 1. Lithofacies Ds containing symmetrical ripples. 2. Lithofacies Fm, a fine to medium-grained sandstone lies above Dm, a structureless dolostone. The sandstone beds exhibit interbedded small scale planar cross bedding and oscillatory ripples. Planar cross bedding, seen here, is present but not common in this lithofacies. 3. Closeup of the wave ripples present in lithofacies Fm. 4. The stratigraphically lowest interval of the horizontally and cross laminated interbedded red-colored sandstone (Fr) with very fine sandstone or siltstone drapes. This is the lithology most similar to the Monkton exposed at the Salmon Hole and Redstone Quarry in Burlington. 5. An interval in the stratigraphy from ~34 meters showing dolostone (Dm) sharply overlain by siltstone (Fl) followed by red-colored sandstone (Fr). 6. An unusual lithology in the Monkton, lithofacies Fms is a dark red to maroon colored very poorly sorted sandstone that contains dewatering structures 7. Lithofacies Fms is also characterized by abundant ilmenite that often sparkles in sunlight. 8. Bedding plane exposures are limited on the slopes of Pease Mountain but when found they often exhibit horizontal burrows of the *Planolites* ichnofacies. 9. Illustration of cleavage developed in the stratigraphy ~40 meters. 10. The very fine-grained sandstone of lithofacies Fw often appears poorly bedded, compared to the fine to medium-grained, well bedded sandstone (see 4 and 11). 11. This outcrop of Lithofacies Fr near the top of the western slope of Pease Mountain exhibits interbedded sandstone and very fine-grained sandstone that is characteristic of the Monkton in the Burlington area (also see 4). The black bar in the upper right is 10 cm in length. 12. Closeup of Lithofacies Sx exhibiting two amalgamated beds of cross-bedded sandstone. The arrows point to laminations of very coarse-grained sandstone that are overlain by planar cross-bedding. Black lines highlight the orientation of cross laminations, which suggest bipolar flow directions and possible herringbone cross stratification. 13. Multiple sets of graded and planar cross-bedded sandstones of Lithofacies Sx are exposed on the eastern slopes of Pease Mountain. At this outcrop the cross-bedded sandstones exhibit a thick fine-grained rippled cap of siltstone (Fl). In most cases the fine-grained tops are eroded by the overlying beds. Hammer for scale. 14. Field photo of the gradational interval of the uppermost Monkton found west of Guinea Road. The actual contact of the Monkton with the Winooski is not exposed but lies within the ~7 m covered interval below a massive dolostone bed of the Winooski found across the road.


15A

15B

Figure 15A and B. A: Photograph of the intraformational thrust within dolostone horizons in the Monkton (station 64 on Figure 2). The black bar below the fault surface is 20 cm for scale. B: Eastward dipping cleavage developed in dolostone above the fault. The white bar is 20 cm for scale.