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Sedimentology of the Goldenville-Halifax transition in the Tancook Island area, South Shore, Nova Scotia.

John W.F. Waldron,

Saint Mary's University,

Halifax, NS B3H3C3.

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Abstract

The Cambro-Ordovician Meguma Group is a thick succession of sandy turbidites (Goldenville Formation) overlain by black slates (Halifax Formation) in the Meguma Terrane of Nova Scotia. At the Goldenville-Halifax transition in the Mahone Bay area several distinct members are recognized. The sediments are metamorphosed at low grade and deformed into sub-horizontal folds with axial planar cleavage. Strain markers on bedding surfaces indicate strain ratios in the range 1.7 - 2.0.

The New Harbour Member of the Goldenville Formation consists of massive sandstones with very minor slates. The sandstones were probably deposited by high-concentration turbidity currents.

The Tancook Member overlies the New Harbour Member; it consists of alternating sandstones and slates. The sandstones include classical turbidites with Bouma sequences, massive sandstones, laminated to massive sandstones, and internally scoured sandstones. Paleocurrent data (corrected for strain) indicate flow towards the north and west. Bioturbation structures, particularly Teichichnus spreiten, become common towards the top of the member, indicating a decline in the frequency of turbidity currents. The vertical succession of facies suggests that external factors such as sea-level change in the source area were important in controlling sand input.

The overlying Mosher's Island Member consists of grey green laminated slates and argillites with no trace fossils and only low-amplitude ripple cross-lamination. Chlorite flakes visible in thin-section represent primary grains and may be of volcanic origin. Mn-rich carbonate beds and concretions are common; some carbonates formed early in diagenesis. Manganese was probably concentrated in anoxic waters within the sedimentary basin and precipitated as oxide under marginally oxidising conditions. Subsequent diagenetic reduction of Mn and oxidation of organic matter led to the precipitation of carbonate.

The highest strata exposed are dark carbon-rich slates and siltstones with abundant pyrite, assigned to the Cunard Member of the Halifax Formation. They are interpreted as fine-grained turbidites deposited under anoxic conditions.

1. Introduction

a. Regional setting

The Meguma Terrane of Nova Scotia occupies a unique position in the Appalachians, having no obvious correlatives elsewhere in the orogen. The Terrane is characterized by the Meguma Group, a thick succession of sandy turbidites (Goldenville Formation) overlain by Early Ordovician black slates (Halifax Formation). This study deals with the complex transition between these two units, which is particularly well exposed in the Mahone Bay area of SW Nova Scotia.

Within the Meguma Group, the Goldenville Formation consists of interbedded buff poorly sorted sandstones and greenish slates, with sandstone/slate ratios generally greater than unity. Goldenville sandstones were interpreted as turbidites by Phinney (1961), Schenk (1970) and Harris and Schenk (1975). Waldron and Jensen (1985) showed that thick (up to 150m) sandstone-dominated packages within the Formation were laterally discontinuous when traced distances of several kilometres; we interpreted these packages as submarine-fan channel fills. In most areas approximately the uppermost 1km of the Goldenville Formation is thinner bedded and contains more slate than the bulk of the Formation.

The Halifax Formation is dominated by thinly interbedded black graphitic slates and cross-laminated siltstones, with occasional beds of sandstone. Much of the Formation is rich in pyrite. The top of the Formation, however, contains paler, locally bioturbated blue-grey slates and siltstones and rare paraconglomerates (Lane 1975). Rare graptolites in the Halifax Formation yield Tremadocian ages (Smitheringale 1960, Crosby 1962). Harris and Schenk (1975) interpreted the bulk of the Halifax Formation as turbidity current deposits, though Lane (1975) suggested that the upper part of the Formation records a progressive shallowing, with the establishment of a shelf or pro-delta environment. Diamictite at the top of the Formation may record a late Ordovician glaciation (Schenk 1972). Stow et al 1984, in an investigation of selected well exposed sections in the Halifax Formation, compared the Halifax sediments to deposits of dilute muddy turbidity currents in modern submarine fans.

Harris and Schenk (1975) suggested that the Goldenville and Halifax Formations are in part coeval, and predicted an interdigitational relationship between them. Nevertheless, the contact is generally sharp at map scale throughout most of Nova Scotia, being marked by a rapid upward decline in the sandstone/slate ratio over a stratigraphic thickness of only 10 to 20m. The lowest part of the Halifax Formation generally consists of manganiferous grey-green chlorite-rich slates, which in turn pass up into black graphitic slates and siltstones that constitute the bulk of the Formation. In the Mahone Bay and Lahave areas on the south shore of Nova Scotia the transition is considerably more complex. Recent work by O'Brien (1985, 1986) has demonstrated that a number of distinct lithostratigraphic units can be mapped within the Goldenville-Halifax transition, as shown in figure 1. The transition zone could be interpreted as an interdigitation of Halifax and Goldenville lithologies in this area. O'Brien (1986) used the informal designation "Green Bay Formation" for the sediments of the transition zone; in this report the older two-fold subdivision of the Meguma Group is retained.

Sediments of the Goldenville-Halifax Transition are particuarly well exposed on the northeast coast of Big Tancook Island in eastern Mahone Bay (figure 2). Part of the transition is also well exposed on Little Tancook Island. Neither island exposes the base of the transition satisfactorily, but this can be mapped on the adjacent mainland coast at Blandford, although the contact itself runs through a 20m gap in exposure. The top of the transition zone and the overlying black slates of the Halifax Formation are well seen on the south coast of Tancook Island.

All the units of the Meguma Terrane are folded in upright to steeply inclined open to tight macroscopic folds that trend SW-NE or W-E, with a steep axial planar cleavage, products of the mid-Devonian Acadian deformation. An earlier fabric locally pre-dates the main cleavage (O'Brien 1983). Gold-bearing quartz veins occur at many localities. Metamorphism varies from chlorite grade throughout the central part of the Terrane to sillimanite grade in metamorphic culminations in the extreme southwest and east (Keppie & Muecke 1979). Granitoid plutons mostly of Devono-Carboniferous age intrude and metamorphose the sediments. Post-intrusive deformation affects the northern edge of the Terrane, adjacent to the Cobequid-Chedabucto fault zone. Movement along this zone, or its precursor, the Glooscap Fault or Minas Geofracture, resulted in the juxtaposition of the Meguma and Avalon Terranes in their present configuration by Late Carboniferous time.

Much debate has surrounded the paleogeographic setting and source area of the Meguma sediments. Schenk (1970) made a regional survey of paleocurrent directions, bed thickness, and sand/slate ratio throughout the Group, and showed that the source lay to the south or southeast of present-day Nova Scotia. He suggested (Schenk 1971) derivation from northwest Africa, which lay adjacent to Nova Scotia prior to the opening of the Atlantic.

b. Stratigraphy of the Goldenville-Halifax transition

Most workers have divided the Meguma Group into two formations, a lower, sandy Goldenville Formation, and an upper, slaty Halifax Formation. However O'Brien (1985, 1986) showed that the Goldenville-Halifax Boundary had been mapped inconsistently within a Goldenville-Halifax transition zone in the Lahave area; several different upward transitions from sandstone to slate occur in this transition. O'Brien (1985) therefore mapped a succession of members which were subsequently in part traced into Mahone Bay (O'Brien 1986), where slightly different facies occur. In all, three different stratigraphic sequences may be inferred from O'Brien's maps as shown schematically in the stratigraphic column of figure 1.

In the area of this study, in eastern Mahone Bay, "typical Goldenville" massive to very thickly bedded (1-3 m) sandstones assigned to the New Harbour Member are overlain by thinly to thickly bedded (3 cm - 1 m) buff-weathering sandstones and greenish slates of the Tancook Member. The upper part of the transition zone, the Mosher's Island Member, consists mainly of finely laminated argillites which locally appear sandy in the field on account of their high content of metamorphic spessartine. Concretions and layers rich in manganese carbonate are found in this unit. Overlying the Mosher's Island Member are black, pyrite-rich, very thinly bedded slates and siltstones of the Cunard Member, representing "typical" Halifax Formation.

Further northwest, in the Chester area, the uppermost 200m of the New Harbour Member is represented by medium to thickly bedded sandstones without interbedded slates. The overlying sequence of interbedded sandstones and slates is generally thinner than the Tancook Member, and more thinly bedded; it is assigned to the West Dublin Member. The overlying Mosher's Island Member is identical to that in eastern Mahone Bay.

In the western, Lahave area the New Harbour Member is overlain by thinly interbedded green and grey-green slates and fine cross-laminated sandstones of the Risser's Beach Member. These in turn are overlain by medium bedded buff-weathering sandstones and slates of the West Dublin Member. In the Lahave Islands, a thinner-bedded middle portion of the West Dublin Member without buff-weathering sandstones appears to pinch out northwards. The highest unit in the transition zone, the Mosher's Island Member, is identical to that further east.

O'Brien (1986) informally defined a Green Bay Formation, encompassing all the members of the transition zone between the uppermost "typical Goldenville" massive sandstones of the New Harbour Member, and the lowermost "typical Halifax" black slates of the Cunard Member. The present study has shown that parts of the Tancook Member closely resemble units deeper in the Goldenville Formation previously described by Waldron and Jensen (1985). The fine-grained Mosher's Island Member has previously always been mapped as Halifax Formation, at least where well exposed in coastal outcrops. Thus the most easily mapped boundary in the area is that between the Tancook and Mosher's Island Members, which in the Tancook area closely corresponds with the Goldenville-Halifax boundary of Faribault (1929). In this report, the older stratigraphy is therefore retained. The Mosher's Island Member of O'Brien (1986) is regarded as the lowest Member of the Halifax Formation, whereas the Risser's Beach, West Dublin, and Tancook Members are assigned to the Goldenville Formation.

c. Methods

The east coast of Big Tancook Island, providing the most complete section of the Goldenville-Halifax transition, was surveyed by tape and Brunton compass. An outcrop map of the coast was prepared, and preliminary descriptions of the major rock units were made. For general descriptions, bed-thickness was described according to the scheme in figure 3. Stratigraphic thicknesses represented by each outcrop, and by the intervening unexposed intervals, were calculated trigonometrically, using strike and dip measurements taken at intervals along the coast. The stratigraphic column in figure 4 was constructed using these data.

Sedimentological descriptions were recorded on a bed-by-bed basis covering nearly half of the total exposed stratigraphic thickness of the transition zone. Measured sections are numbered from 1-13 in figures 2 and 4. Direct contact measurement of strata was used wherever the cliffs or wave-cut platform provided sufficient relief. However, much of the outcrop on Little Tancook Island is glacially smoothed; the "Jacob's staff" technique was used to construct a section through the upper part of the Tancook Member on this island. In some sections, bedding was too indistinct for either method to be used satisfactorily; in such areas, the horizontal outcrop widths of units were measured by tape, and converted trigonometrically to stratigraphic thicknesses using strike and dip measurements from immediately adjacent well bedded rocks.

Two styles of section measuring were used. Detailed measured sections were recorded in the field using a pictorial graphic log similar to figures 12-14. Grain sizes were determined using a grain size comparison chart bearing sieved samples of silt and sand. These determinations are subject to errors due to variations in sorting. The comparison chart bears well-sorted sand, whereas in poorly sorted samples only the coarsest grains are conspicuous in hand sample; the chart therefore over-estimates grain size in poorly sorted sediments such as those of the Meguma Group.

For more rapid coverage of thick sections, a symbolic style of section recording was adopted, in which only the thickness, gross lithology (sandstone or slate) and the sequence of sedimentary structures seen in each bed were noted, using a pre-arranged set of abbreviations. These records were converted by computer into the graphic logs shown in appendices 1-3.

Samples were taken from typical outcrops and from distinctive beds or units. Colours of samples were determined according to the Munsell system by comparison with a rock-color chart. Petrographic descriptions are based on thin sections prepared from these samples. The laminated argillites of the Mosher's Island Member were not measured in detail, on account of their uniformity and lack of large-scale bedding features. These sediments were studied using large-format thin sections.

2. Structural considerations

a. Introduction

Big Tancook Island lies on the axial trace of the Indian Path anticline (O'Brien et al 1986). A slaty cleavage, which is approximately axial planar to this fold, is everywhere developed in the finer grained sediments. The Indian Path anticline and the corresponding bedding-cleavage intersection lineation both plunge to the southwest in the western part of Big Tancook Island. A culmination point (identified by Faribault 1929) occurs on the fold hinge close to Big Tancook Island (figure 2); everywhere north of the axial trace on the east coast of Big Tancook Island, and on Little Tancook Island, the intersection lineation plunges northeast. On the mainland at Blandford it again plunges southwest. Presumably there is a depression point somewhere between Little Tancook Island and the Blandford shore. The sediments of the Goldenville-Halifax Transition have been subjected to a strain associated with regional folding and cleavage formation, which must be assessed and taken into account in any discussions of the thicknesses of strata and the orientation of paleocurrent flow. This assessment is attempted below.

A number of minor structures postdate the main deformation. These include kink bands and several northwest-striking faults, mostly with offsets of only a few metres; both dextral and sinistral offsets have been recorded (O'Brien et al 1986). In outcrop, the faults are represented by breccia zones 10 cm to 1 m in width, which are sometimes quartz cemented and erosion-resistant. Between Big and Little Tancook Islands corresponding strata are offset about 100m, suggesting that a fault with dextral offset is present, as shown by O'Brien et al (1986) and in figure 2. On the south coast of Big Tancook Island two mesoscopic asymmetric south-plunging fold pairs refold both bedding and cleavage, with eastward vergence. Their age is unknown, but they may be related to "transverse folds" associated with the intrusion of granitoid plutons, described by Faribault (1908) and O'Brien et al (1986).

b. Strain in bedding surfaces

i) Principles.

In order to restore paleocurrent direction indicators to their original orientations in deformed sediments, it is necessary to have fairly complete knowledge of the finite strain. Unfortunately this is rarely possible. In particular, there is no way of determining the rotational component of the strain in the Meguma rocks, so the absolute original orientations of the paleocurrents remain unknown. However the irrotational (pure shear) component of strain in the bedding surfaces can be estimated, allowing restoration of the original orientations of paleocurrents relative to each other. Thus where paleocurrent directions are found to be tightly clustered, restoration will show whether the clustering is original or merely due to tectonic strains. Estimation of the strain depends upon the availability of suitable strain markers, and is always dependent on two classes of initial assumptions. Firstly, the original shape or distribution of the strain markers must be known with confidence; secondly, the markers must have deformed homogeneously with their matrix, and homogeneously with the paleocurrent structures that are to be re-orientated. Since neither type of assumption is rigorously justifiable, a number of different types of marker must be used, to allow comparison of results. Four types of marker were used in five different methods of strain determination on the Tancook Islands. In each of the following sections a method is briefly described. The results are then given, and the validity of each class of assumptions is discussed.

ii) Intraclasts

Oval intraclasts of slate and siltstones are visible on bedding or lamination surfaces in some sandstones within the Tancook Member. Long axes of the intraclast outlines are approximately parallel to the intersection lineation. To use their shapes for strain determination it is necessary to assume (i) that the intraclasts, though not initially circular, had their long axes randomly oriented in the plane of bedding, and (ii) that they deformed homogeneously with their matrix. Aspect ratios (Rf) and orientations (phi) were measured for 67 intraclasts in a single bed; the results are shown in figure 5. Comparison with synthetic curves of Ramsay and Huber (1983), indicates a strain ratio in the range 2.0 - 2.5, with a best estimate of 2.2 obtained from the maximum and minimum Rf values from the main cluster in figure 5. The extension axis pitches 25° to the northeast, corresponding to an azimuth of 034° if beds are rotated to horizontal. The slight asymmetry of the figure suggests that some degree of preferred orientation existed prior to deformation, violating the first assumption (intraclasts would be expected to show some alignment parallel to current direction). Cleavage refraction in interbedded sandstone and slate shows that sandstone was more competent that slate during folding; the slate intraclasts might therefore be expected to deform inhomogeneously, and to give an over-estimate of the strain. The value obtained by this method must therefore be regarded as very approximate.

iii) Concretions

Large (about 1 m in diameter) ovoid carbonate concretions in massive sandstones appear perfectly elliptical. Assuming they were initially circular, they may be used to estimate the strain ratio, though too few concretions are seen in any one bed for a statistical approach to be used. A single concretion, close to the intraclast-bearing outcrop described above, has a long axis pitching 18° to the NE and yields a strain-ratio estimate of 1.47. However, the intersection lineation diverges slightly on approaching the concretion, suggesting that the concretion behaved more competently that the surrounding sandstone, and that it therefore under-estimates the bulk strain. The assumption of initial circularity might also be invalid if, for example, the shape of the concretion were controlled by a permeability anisotropy existing during diagenesis.

iv) Paleodictyon trace-fossil networks

Remarkable hexagonal trace-fossil networks of "Paleodictyon" type (figure 7) were observed in-situ on the base of one sandstone bed in the upper part of the Tancook Member, and on a number of large displaced slabs on the adjacent beach. Only the displaced slabs showed complete enough preservation of the networks for strain estimates to be made. Fortunately, the original orientation of the slabs could be accurately determined from the bedding and intersection lineation within them. Each three-way intersection of burrows was used to give a single strain estimate, using the Mohr circle construction described by Ragan and Sheridan (1972) for trilete glass shards in tuffs. The method depends upon the assumption that the burrows initially met at 120° angles. Figure 6 shows the strain estimates obtained from two slabs. Strain ratio estimates vary between 1.19 and 2.45, but the best preserved burrows yield estimates clustered about a value of 1.9. The average long axis of the strain ellipse in the bedding plane pitches at about 12° to the northeast, corresponding to a trend of 035° if beds are rotated to horizontal. There is again some asymmetry in the Rf/phi plot; it may be that the networks were not in fact regularly hexagonal, but showed some degree of preferred orientation due to the behaviour of the organism that created them. The assumption of homogeneous strain seems reasonable, because the networks are extensive and insubstantial compared to the sandstone beds on which they occur. Their dimensions, composition, and location are in fact closely comparable to those of the flutes and grooves from which most paleocurrents were measured.

v) Teichichnus spreiten: distribution of orientations

Trace fossils assigned to the ichnogenus Teichichnus are abundant in the uppermost sandstone beds of the Tancook Member, being particularly well displayed on the west coast of Little Tancook Island. Each "spreite" consists of a vertically stacked series of burrows as shown in figure 7. Because of differential weathering, each spreite appears as a parallel-sided slot on exposed bedding surfaces. If the burrows were initially randomly distributed (assumption i), and behaved as passive line markers during deformation (assumption ii), the present-day distribution of their orientations can be used to determine the strain ratio and the orientation of the strain ellipse on bedding surfaces. The maximum concentration of structures under these assumptions is equal to the strain ratio (Ramsay & Huber 1983, page 136). (Concentration is defined as the ratio of the actual number of structures within a given angular interval to the average number in intervals of the same size.) Figure 8 shows the distribution of spreiten with direction from two adjacent areas on the same bedding surface. The maximum concentration of orientations suggest strain ratios in the range 2.6 to 3.3. These values seem unreasonably high compared to those obtained by the methods described above. At several points on the bedding surfaces, parallel groups of burrows seem clustered in groups, violating assumption (i). The high apparent strain ratios obtained may thus be explained as the result of an initial preferred orientation of burrows, and not of tectonic deformation.

vi) Teichichnus spreiten: dimensions

The dimensions of Teichichnus spreiten were also measured. If their original lengths were reasonably constant, or varied within certain limits independently of direction, then their present-day lengths should vary as radii of the strain ellipse. Figure 9 is a plot of burrow length against direction in polar co-ordinates. Ideally, the cluster of points in such a plot should have the shape and orientation of the strain ellipse (Fry 1979). Though the cluster is elongated, its shape is not sharply defined; because of the strong concentration of burrows in certain directions, which reflects the inferred original preferred orientation of burrows, the ellipticity of the cluster in figure 9 probably over-estimates the strain ratio.

Widths of burrows were also measured. Unfortunately a Fry plot cannot be used for the burrow widths, because shear strain is non-zero along any burrow that is not parallel to a strain axis. Thus the measured widths represent lines that have rotated relative to the burrow sides during deformation; they will not, in general, represent lines that were perpendicular to burrow length in the undeformed state. However, the burrow sides do represent tangents to the strain ellipse, as shown in figure 10, suggesting the modified plotting method shown in figure 11, in which the widths are represented by pairs of parallel lines oriented parallel to burrow sides. These are statistically tangential to a strain ellipse, which is estimated from figure 11 to show a strain ratio of 1.7 and a pitch of 35 - 40°, corresponding to an azimuth of 20 - 25° in strata rotated to horizontal. Widths of burrows were presumably determined by the dimensions, not the behaviour, of the organism that produced them, and are therefore likely to be independent of burrow orientation. The non-random distribution of burrow orientations does not seriously affect estimation of the strain ellipse in figure 11. Furthermore, the burrows are compositionally similar to surrounding sandstones and are likely to have deformed homogeneously with their matrix. This method therefore provides one of the most reliable strain estimates.

vii) Discussion

The results from the Paleodictyon networks on Big Tancook Island and the widths of Teichichnus burrows on Little Tancook Island are probably the most reliable strain estimates, but the results from other methods are generally consistent. The slight difference between the two islands, in both the shape and the orientation of the strain ellipse, is probably significant. Correlation of the upper part of the Tancook member between the two islands (figure 4) shows that the sequence on Big Tancook is about 25% thicker. This discrepancy is explained by the higher strain suffered by the strata on Big Tancook, perhaps related to their position closer to a culmination point on the fold hinge or to the westward tightening of the Indian Path anticline noted by O'Brien et al (1986).

Despite these indications of strain inhomogeneity, the variations in strain detected are not of sufficient magnitude to be of major concern in the re-orientation of paleocurrents. All the paleocurrent measurements were taken from the east coast of Big Tancook Island. Accordingly, the paleocurrent data were restored to horizontal by rotation about the strike, and unstrained using a strain ratio of 1.9, with the long axis of the strain ellipse trending towards 035.

3. New Harbour Member

The New Harbour Member of the Goldenville Formation is exposed on the east coast of Mahone Bay between Blandford and New Harbour, where the deepest strata are exposed in the core of the Indian Path anticline. In this investigation, only the uppermost 33 m of the Member are described in detail, but reconnaissance of lower parts of the Member indicates no major changes in sedimentary characteristics.

The New Harbour Member is dominated by sandstones. The measured section (Appendix 1, section 1) at the top of the member contained no slate at all, but small gaps in exposure may have concealed thin slate layers, amounting to not more than 2% of the section in total. The sandstones of the New Harbour Member are greenish grey to olive grey on fresh and weathered surfaces. They are predominantly very fine to fine grained. In thin section, they are seen to be very poorly sorted, somewhat recrystallized sandstones that have been metamorphosed at chlorite grade. A fine grained matrix makes up 25 - 30% of the rock by volume. The matrix consists principally of quartz, metamorphic sericite, and metamorphic chlorite; no traces of the original grain shape or texture are preserved in the fine-grained material. The sand-size components are principally quartz (estimated at 50% by volume) and feldspars (about 20%). The feldspars comprise subequal amounts of polysynthetically twinned sodic plagioclase (albite to oligoclase) and untwinned alkali feldspar (albite and minor sodic orthoclase). The proportion of orthoclase is probably low, but no staining was carried out to confirm this. Large (up to 1 mm diameter) flakes of detrital muscovite (contrasting clearly with the metamorphic sericite in the matrix) are conspicuous in thin section but make up only about 1% of the rock by volume. Sand sized single crystals and polycrystalline aggregates of chlorite are relatively common (5%), and distinguishable by their size from the fine disseminated chlorite of the matrix. Their protolith cannot be determined; they could represent a volcanic contribution to the sandstones, but might equally be detrital fragments derived from an older chlorite schist. Tourmaline is the most abundant accessory mineral. The toumaline grains are generally subhedral and zoned from blue-green to brown. Zircon is present in lesser amounts. Scattered iron-rich carbonate grains (dolomite or ankerite) are probably of diagenetic origin. Small clusters of opaques are present; occasional pyrite crystals were observed in the field and in hand sample. The original shapes of all grains have been modified by metamorphic processes. Some quartz grains preserve rounded or subrounded outlines but the majority are subangular to angular and of moderate to low sphericity; rare angular broken fragments of originally rounded grains are seen.

The sandstones contain large (up to 50 cm diameter) concretions of yellowish grey carbonate-rich material, weathering moderate brown. In thin-section these show a poikiloblastic texture of large (1 mm) calcite crystals containing "floating" sand-sized grains of quartz, alkali and plagioclase feldspar, and muscovite. The detrital grains are not generally now in contact, suggesting that calcite was precipitated while detrital components were dissolved during some stage in diagenesis or metamorphism. The chemistry and mineralogy of these concretions is currently under investigation by M. Zentilli and M. Graves (Dalhousie University).

In the field the New Harbour sandstones show few sedimentary structures to indicate their mode of deposition. Massive sandstone beds, devoid of internal breaks that would indicate deposition by successive events, may be up to 18 m thick, though most are 0.5 - 5 m thick. Most beds are laminated to cross-laminated in their topmost 5 - 10 cm. Traces of convolute lamination, and poorly defined "ball and pillow" structure in the lower, massive portions of the beds, suggest that homogenization of the bulk of the sands was due to fluidization by water escape. This is confirmed at outcrops immediately north of New Harbour, where beds contain massive sandstone with dewatering pillars in their upper parts, immediately overlying laminated sandstone. Such beds were described elsewhere in the Goldenville Formation by Waldron and Jensen (1985) where they were interpreted as deposits of high-concentration turbidity currents (Lowe 1982). Similar beds, though generally thinner, are found in the Tancook Member (see discussion of laminated to massive sandstones, below). In the earlier study the sequences of laminated to massive sandstones were identified as fills of submarine fan channels. It is not known whether the New Harbour Member sandstones were also deposited in channels.

4. Tancook Member

a. Stratigraphy

The Tancook Member can be further subdivided on the basis of major lithological variations that have been correlated between the south of Tancook Island and the mainland coast at Blandford. To facilitate description, four informal subdivisions of the member are here established as shown in figure 4.

The base of the Tancook Member is not well exposed. At Blandford, interbedded sandstones and slates of the Member are separated from massive sandstones of the underlying New Harbour Member by a 20m gap in exposure. On Tancook Island, the lowest strata exposed in the core of the Indian Path anticline are thickly bedded sandstones that may correlate with the uppermost New Harbour Member.

The lower sandy unit of the Tancook member consists predominantly of very thinly bedded to medium bedded sandstones, interbedded with generally lesser amounts of slate. Figure 12 shows a typical section. Towards the top of the lower sandy unit, carbonate concretions become more common in the sandstones, and weather red-brown, instead of yellowish. Analytical work by M.Graves & M.Zentilli (personal communication) indicates that these concretions are significantly manganiferous.

At the top of the lower sandy unit there is a relatively abrupt transition (over about 2 m) into the lower slaty unit, shown in figure 13. These slates are locally sandy, and vary between laminated and mottled facies. In some of the mottled slates abundant burrows are picked out by concentrations of black-weathering carbonate material and pyrite. Only a diffuse banding of the concretionary material reveals the orientation of bedding in the mottled and bioturbated strata. In the laminated intervals, laminations are picked out on weathered surfaces by black manganese oxide coatings. Black staining also follows cleavage planes in some parts of this unit.

The lower slaty unit of the Tancook Member passes transitionally up into the upper sandy unit, in which sandstone again predominates. Sandstone/slate ratios vary between 50 and 100%, averaging around 70%. Bed-thickness is more variable in this section than in the lower sandy unit; thick (30 cm-1 m) and very thick beds (>1 m) are grouped in "packages", separated by intervals of thinly interbedded sandstone and slate. Near the top of the unit, a 44 cm brownish grey weathering bed of sandy bioclastic limestone is present, in which remains of shelly fossils and echinoderm fragments are seen in thin section. Figure 14 shows a measured section that includes this horizon. Attempts were made to trace this bed on to little Tancook Island, but its stratigraphic position corresponds to a short gap in exposure. Samples processed by G. Nowlan (Geological Survey of Canada) in a seach for conodonts proved difficult to dissolve, perhaps on account of their manganese content.

Towards the top of the upper sandy unit the sandstone/slate ratio declines. Abundant deeply penetrating burrows are seen in both sandstone and slate in this section. In an earlier report (Waldron & Graves 1987) the top of the Tancook Member was placed immediately above the upper sandy unit, beneath a long interval devoid of sandstone. However O'Brien et al (1986) have placed the base of the overlying Mosher's Island Member at the last occurrence of thickly bedded sandstone (here taken to mean beds 30 cm - 1 m thick), somewhat higher in the section. To avoid further confusing an already complex stratigraphy, O'Brien's boundary is used in this report. The slate-dominated sequence above the upper sandy unit of the Tancook Member is therefore here assigned to an upper slaty unit, despite the strong resemblance of its slate facies to the overlying Mosher's Island Member.

The upper slaty unit of the Tancook Member is dominated by greenish and blueish grey slates which vary between laminated and generally unlaminated facies. However, there are no conspicuous carbonate or pyrite-filled burrows such as those seen in the lower slaty unit. Some parts of the sequence are rich in pyrite concretions or disseminated pyrite grains, which give weathered surfaces a rusty appearance. Sandstones beds occur sporadically through the upper slaty unit. They are not haphazardly distributed, but grouped in packages. One such package, (at the base of section 10) is sufficiently distinctive to be recognized on both sides of the Indian Path anticline, on both shores of Little Tancook Island, and in a poorly exposed area at Blandford.

b. Petrology

i) Sandstones

Sandstones in the Tancook Member are petrographically similar to those of the underlying New Harbour Member. They are generally very fine grained texturally immature sandstones, ranging in colour from olive grey to light bluish grey but weathering yellowish grey to olive grey. Quartz is the most abundant detrital mineral but large amounts (up to 15%) of untwinned alkali feldspar and twinned sodic plagioclase are present. No staining was carried out, but on the basis of optic sign and 2V determinations the majority of the untwinned feldspar is albite. Muscovite flakes are conspicuous in thin section, though volumetrically minor; interlayered flakes of muscovite-chlorite and muscovite-biotite-chlorite are also seen. Chlorite flakes and polycrystalline aggregates are common. Chlorite aggregates, and some other sand-sized pockets of "matrix" chlorite and sericite probably represent original rock fragments. Zoned tourmaline is again the most abundant non-opaque accessory mineral in the majority of most sections. Zircon is also common. A sample from the distinctive sandstone package at the base of section 9 is extremely rich in zircon and relatively poor in feldspar.

A fine grained matrix is generally present in the sandstones, consisting of varying proportions of recrystallized chlorite and sericite. Samples from concretions show brown-weathering carbonate cement which is poikiloblastic and coarse grained in many beds; as in the New Harbour member, such samples generally show quartz and other detrital grains "floating" in cement, suggesting that partial replacement of silicates by carbonate has occurred. Other secondary minerals include abundant opaques; pyrite grains are occasionally visible in hand sample.

Near the top of the upper sandy unit of the Tancook Member, a 44 cm bed of silty sandy limestone occurs. The limestone weathers brownish grey. In thin section, the carbonate material is seen to consist largely of echinoderm and shell fragments; the shell fragments are recrystallized to prismatic calcite which retains a preferred orientation inherited from the original shell material, but have not been identified. The echinoderm fragments include distinctive circular cross sections of crinoid ossicles. This horizon has not been seen elsewhere; its position corresponds to unexposed intervals on both coasts of Little Tancook Island and on the south coast of Big Tancook Island.

ii) Slates

Slates in the Tancook Member are predominantly greenish to olive grey and blueish grey when fresh, and light olive grey when weathered, but are stained yellowish brown where pyrite-bearing and brownish grey where manganiferous.

In thin section, they are seen to be fine grained chlorite-sericite and sericite-chlorite slates with variable amounts of quartz silt concentrated in generally graded laminations. Scattered opaques, including pyrite visible in hand sample, are present in all the thin sections studied. Pyrite cubes post-date the cleavage.

Some slates contain small (0.2 - 0.5 mm) aggregates of quartz and relatively coarse chlorite, of circular to elliptical outline. These appear similar to sand grains in hand samples, and are definitely ovoid, rather than cylindrical, in three dimensions. They are especially common in slates of the lower sandy unit of the Tancook Member. The origin of these "quartz-chlorite balls" is unknown. One possibility is that they represent replacements of concretions of some other mineral, perhaps an iron sulphide precursor of pyrite. Small, roughly spherical concretions of greigite and mackinawite have been described from Quaternary muds in the Black Sea (Berner 1974).

In the upper slaty unit, large (0.05 - 0.3 mm) flakes of chlorite are common. They are concentrated in some silt bands, being locally more abundant than quartz, but are also distributed throughout much finer grained slate. They show preferred orientation parallel to bedding. Their subrounded outlines, orientation, and concentration in silt bands suggest a detrital origin, but they cannot have been hydraulically equivalent to the surrounding mud now represented by sericite and matrix chlorite. They are thus interpreted as volcanic ash particles from an unknown source, which were locally re-worked in the silt layers.

Slates in the lower slaty unit of the Tancook Member are highly bioturbated. Cylindrical burrows up to 15 cm long are oriented both parallel and at high angles to bedding, and are filled mainly with brown-weathering coarsely crystalline carbonate. Pyrite grains are also concentrated in some burrow fills. Elsewhere in the Tancook Member, slates in thinly bedded and sandstone-poor intervals are frequently mottled and contain disturbed laminations, but distinct burrows are rarely visible except immediately below sandstone beds, where sand-filled burrow structures are seen.

Slates in the upper slaty unit of the Tancook member contain laminae and beds (often discontinuous) of manganiferous carbonate. The carbonate is generally coarsely crystalline and poikiloblastic, containing quartz grains and mica flakes as inclusions. In the field, laminations are seen to diverge as they pass into lenticular carbonate beds, suggesting that carbonate cementation occurred early in diagenesis, before compaction was completed. The divergence is apparent even on cleavage surfaces, and cannot easily be attributed to inomogeneous tectonic strain. (Because the carbonate layers consistently behaved more competently than the surrounding slate, they would be expected to show less, rather than more, extension in the vertical direction during tectonic deformation.)

c. Sandstone facies

i) Introduction

Sandstones in the Tancook Member display a wealth of sedimentary structures. The thinner beds typically display graded bedding, lamination, and ripple cross-lamination (locally with climbing ripples). Thick and very thick beds show, in addition, internal scour-and-fill structures, convolute lamination, pseudonodules, dewatering pillars and sheet structures. Basal surfaces of sandstone beds show load casts, groove casts, flute casts, and other flute-like scour structures. Horizontal burrows and trails are common on basal surfaces of sandstone beds in the lower part of the Tancook Member; vertical and steep burrows and spreiten become more common higher in the Member.

Sandstone beds are here classified into a number of facies. The majority of very thin to medium sandstone beds display a vertical sequence of sedimentary structures that can be accommodated within the Bouma sequence (Bouma 1962), typical of turbidites. These beds are here termed classical turbidites, following Walker (1978). Like most sandy turbidite sequences, the Tancook Member includes a proportion of massive sandstone beds with neither laminations nor cross-laminations. Such beds, usually termed Tae or Ta-e sequences, are here described with classical turbidites. Many thickly bedded sandstones show structures and vertical sequences that cannot be regarded as variations of the Bouma sequence. Most commonly, these beds contain a massive structureless interval overlying a laminated interval. In some cases, a laminated interval within the bed shows deep scour and fill structures (termed "scoop" structures by Waldron and Jensen 1985). Beds with scour-and-fill structures are classified as internally scoured sandstones; other units in which massive sandstone overlies a laminated interval are laminated to massive sandstones.

ii) Classical turbidites and massive sandstones

Classical turbidites comprise the largest number of sandstone beds in the Tancook and Mosher's Island Members. The beds are generally graded, having sharp, scoured bases and gradational tops; grading is commonly most conspicuous in the upper 2 to 5 cm of the beds. Many beds show partial Bouma sequences in which basal or other divisions are missing (Walker 1967). Beds are subdivided into three categories according to the unit present at the base of the bed. Complete Bouma sequences, and other beds posessing a massive basal division are classified as type Ta; those in which deposition started with a laminated "b" division are designated Tb, and those with only the cross-laminated c-division are described as Tc turbidites. Structureless beds showing neither lamination nor cross-lamination are designated Tae. Figure 4 shows variations in the proportions of these types with height in the stratigraphic section.

Ta turbidites are interpreted to represent the highest energy conditions; the massive basal division is produced by rapid suspension sedimentation from a dense turbidity current, without significant bed-load transport (traction). The laminated b division represents traction sedimentation under "upper flow regime" conditions from a less dense, turbidity current; Tb beds therefore represent generally lower-energy flow than Ta beds. Finally Tc beds represent the lowest energy sandy turbidites, in which only lower flow-regime current ripples were produced.

Structureless Tae beds present problems of interpretation. When thickly bedded, such sandstones fall into Walker's (1978) category of "massive sandstone"; these beds are probably high-energy high-concentration turbidites, in which deposition was too rapid for the development of lamination, or in which internal structures have been obliterated by post-depositional dewatering. However, some featureless beds in the Tancook Member are very thin; these may represent very low-velocity turbidity currents, in which currents were too slow to develop lamination, or they may be beds which have been homogenized by bioturbation after deposition, or in which lamination is not observed because of poor exposure. Tae beds were arbitrarily divided into two subcategories at a thickness of 3 cm, in the hope of distinguishing high-energy "massive sandstones" from very low energy beds without cross-laminations. However, the abundance of very thin Tae beds is not correlated with that of other low-energy turbidites (category Tc). Thus it is likely that outcrop conditions, bioturbation, and textural characteristics of the sandstone are the major factors that determine the proportion of beds recorded as structureless in any given sequence.

iii) Laminated to massive sandstones

Figure 15 summarizes in diagrammatic form the sequences of sedimentary structures observed in 49 laminated to massive beds found in a nearly continuous 70 m section (section 5) in the upper Tancook Member. The 49 beds average 43 cm in thickness. Most commonly, laminated sand immediately overlies a basal scoured surface and passes upward either directly or via an interval of convolute lamination into massive sandstone. Overlying the massive sandstone there is usually a second laminated interval and a thin zone of wavy or ripple cross-lamination. In two cases the upper massive division was mottled and contained irregular textural variations suggestive of intense bioturbation; both such examples lacked rippled or laminated tops and were less than 10 cm in thickness.

In a few cases, the lower laminated portion of a laminated to massive sandstone beds contains broad, 1-2 cm thick laminations marked by changes in grain size and sorting. Thin sections show that such laminations display inverse grading; grain size and sorting steadily increase upwards through the lamina and abruptly decrease at its top. Similar structures have been described as "near-horizontal stratification" by Hiscott and Middleton (1979) and as "stratification bands" by Lowe (1982). They are ascribed by Lowe to "traction carpets" - thin layers of concentrated interacting grains maintained in a "grain flow" condition at the base of a high concentration turbidity current.

The high average thickness of the laminated to massive beds suggests that in some way they represent higher energy turbidites than those showing complete Bouma sequences. Disregarding the lower laminated interval, the sequence of sedimentary structures does indeed closely resemble that of the thicker, more massive Bouma sequence turbidites. The laminated to massive sandstones are therefore interpreted as deposits of higher-concentration higher-energy turbidity currents than those which deposited classical turbidites.

iv) Internally scoured sandstones

The thickest sandstone beds in the Tancook Member often contain laminated intervals with internal scour and fill structures similar to "scoop" structures described from the Goldenville Formation in a previous study (Waldron & Jensen 1985). The structures are 50 cm to 1 m in diameter and elongated in the direction of the intersection lineation. Their aspect ratio on bedding surfaces is comparable to the strain ratio, suggesting that they were approximately equidimensional in original outline. However, the scours were probably flute or dune-like in shape; their up-current lips are sharper than their down-current margins. Laminations in sandstone overlying each scour represent progressive infilling of the depression, but are often cut by subsequently developed scours. The scours are not confined to single horizons that could represent amalgamation surfaces between successive turbidite beds; instead, they are distributed throughout an interval of sandstone, typically in the lower part of a bed.

Figure 16 represents the sequence of sedimentary structures observed in 28 beds from measured section 5. Internal scour and fill structures clearly occupy a position analogous to that of the lower laminated interval in the laminated to massive sandstones. The 28 units were all thick or very thick beds (thicker than 30 cm) and averaged 1.23 m in thickness, considerably thicker than the laminated to massive sandstones. This lends support to the hypothesis of Waldron and Jensen (1985) that internally scoured sandstones represent still higher energy turbidites. Their sequence of sedimentary structures (figure 16) resembles that described by Lowe (1982) as typical of high-concentration turbidites.

d. Paleocurrents

Sandstones of the Tancook Member show a variety of current structures that can be used to estimate paleocurrent directions. These include ripple marks and cross-lamination, generally developed in the upper portions of sandstone beds, and sole marks such as flutes and grooves.

The directions of ripple crests, and the orientations of flutes and grooves, were measured wherever possible during section measurement on Big Tancook Island and the Blandford coast; the glacially smoothed section on Little Tancook Island yielded no measurements because bedding surfaces are not exposed. The sense of flow was recorded in the case of flutes and for ripples that produced visible cross-lamination; senses of current flow deduced simply from the asymmetry of ripples are not reliable because of the possible effects of tectonic strain. The effects of deformation on the relative orientations of the structures were removed by the methods described in section 2.

The resulting current directions are shown beside the stratigraphic column of figure 4, and summarized in circular histograms in figure 17. The most obvious peculiarity of the paleocurrent distributions is the significant difference between the mean current direction derived from ripples and that derived from flutes and grooves. Three hypotheses may be advanced to explain this difference. First, the ripples may have been generated on the top surfaces of sand layers by currents different in origin from those which deposited the lower parts of each sand layer. Such a situation would arise if, for example, turbidites were re-worked by contour currents after deposition. However, if this were the case, some increase in sorting might be expected between turbidite sands and the overlying ripple-laminated contourites. Intervening slate layers would contain beds or lenses of re-worked sandstone or siltstone. In fact, the ripple laminated portions of most beds appear, if anything, less well sorted than the underlying sands. The second possibility is that some factor caused turbidity currents to be deflected to the left during the deposition of a single turbidite. Such factors might include coriolis forces or the influence of a slope oriented at an angle to the direction of the impinging turbidites. Thirdly, the apparent difference could result from some systematic error in strain estimation, such as would be produced if the top and bottom surfaces of beds had suffered different strains.

The paleocurrent data show some significant patterns when examined in more detail. Current directions derived from ripples are tightly clustered, but show a steady change from predominantly northwestward in the lower part of the section to predominantly westward at the top of the Tancook Member. In contrast, flute and groove current directions show very varied orientations. The variability is particularly evident in the thickly bedded sandstone-dominated upper sandy unit of the Tancook Member. Current directions from thinly and evenly bedded sandstones in the lower Tancook Member of section 3 are much less variable.

e. Trace fossils

Trace fossils are extremely abundant in the Tancook Member, and require further study from a paleontological perspective. Only a brief discussion of their distribution and possible environmental significance will be given here.

In the lower sandy unit of the Tancook Member, the majority of trace fossils occur as sole marks on the basal surfaces of sand layers. These traces are mainly meandering furrows (preserved in cast form as ridges) varying in width from about 1 mm to over 2 cm. Towards the top of the unit occasional burrows perpendicular to bedding are seen, penetrating one or more sand layers. They are approximately 1 cm in diameter, and resemble the trace fossil Skolithos, described from a variety of environments, ranging from coastal to deep marine (e.g. Ekdale et al 1984). The uppermost sandstone bed of the lower sandy unit is spectacularly biotubated by deeply penetrating burrows with spreiten. In general, the overall shape of these structures cannot be distinguished because of the intensity of bioturbation, but locally derived float contained a bed-parallel spreite resembling a simple form of Zoophycos.

In the lower slaty unit cylindrical burrows 0.5 to 1 cm in diameter are conspicuous when filled with black-weathering carbonate and pyrite. These burrows are oriented both parallel to and at high angles to bedding. Such burrows are confined to certain horizons within the unit. The remainder of the lower slaty unit varies between finely laminated slate and slate that is diffusely laminated or mottled, with indistinct, sometimes slightly curving laminations picked out by brownish-weathering carbonate material. Large format thin-sections of the slate reveal discontinuous, disturbed silt laminations, and bulbous carbonate-cemented burrow-fills, confirming that much of the mottled slate is in fact pervasively bioturbated.

Thickly bedded sandstones in the upper sandy unit commonly display flutes and grooves on their basal surfaces, but thinly bedded intervals again display fine (1 mm wide) tracks and trails. One bed showed a small (1 cm) Rusophycus - a coffee-bean shaped trace made by a trilobite (e.g. Hantzschel 1975, pW101). Towards the top of the unit, hexagonal networks of burrows characteristic of Paleodictyon are found; this form was previously described from the Meguma Group by Pickerill and Keppie (1981). Towards the top of the upper sandy unit, deeply penetrating spreiten of Teichichnus (figure 7) become increasingly abundant as the sand/shale ratio decreases. One Teichichnus cuts the Paleodictyon network.

Teichichnus burrows are also spectacularly developed in sandstones of the upper slaty unit, reaching a maximum abundance at the base of section 10, where they were used in strain determination (section 2, above). Above this package, closely similar, ripple cross-laminated sandstones and siltstones are completely devoid of definite bioturbation structures, suggesting that a change in environment destroyed or severely reduced the bottom fauna at this time.

Following the pioneering work of Seilacher (1967), many studies have attempted to use trace fossils as indices of water depth. At first sight the array of trace fossils displayed by the Tancook

Member presents a confusing picture. In most simple depictions of Seilacher's scheme, for example, Skolithos characterizes an extreme shallow-water, coastal ichnofacies; Teichichnus and Rusophycus occur most abundantly in outer shelf environments (Cruziana ichnofacies); the Zoophycos facies is characteristic of intermediate-depth, continental slope conditions; and Paleodictyon occurs in the deep-water Nereites ichnofacies, characteristic of turbidite successions.

More recent studies have emphasized caution in attributing trace fossil zonation directly to the influence of depth. Ichnofacies cannot be interpreted on the basis of single trace fossils: Skolithos, for example, occurs in almost all environments from subaerial to pelagic Ekdale et al 1984), and Teichichnus is abundant in some modern deep-sea sediments (Wetzel 1984). Rhoads (1975), Howard (1978) and Wetzel (1984) emphasize factors such as physical instability of sediments, amount of dissolved oxygen, salinity, temperature, and perhaps most importantly, sedimentation rate. Below wave-base, depth of water is a factor only because of its correlation with many of these more direct controls. Wetzel (1984) and Ekdale et al (1984) report on investigations of recent pelagic environments that show that bed-parallel, surface traces characteristic of the Nereites ichnofacies are preseved only where sedimentation is episodic; in areas where the sedimentation rate is more even, trace fossils produced by deeply burrowing organisms are preserved, and generally obliterate the bed-parallel traces. These observations can be used to explain the distribution of deep spreite burrows (especially Teichichnus), which are concentrated within and immediately below slate-dominated intervals of the succession. In particular, the uppermost bed of the lower sandy unit, which is overlain by about 40 m of slate, is intensely bioturbated, whereas the underlying strata are not. Thus during prolonged intervals of mud deposition, sedimentation rate was relatively constant, allowing deeply burrowing sediment-feeders to operate, whereas at other times the periodic influx of turbidites prevented their establishment, and allowed preservation of bed-parallel burrows such as Paleodictyon. Nonetheless, Teichichnus burrows are peculiarly abundant in the Tancook Member, compared with turbidite/hemipelagic sequences elsewhere. Ekdale et al (1984) discuss the distribution of Teichichnus in Mesozoic and Tertiary chalks, and report that its distribution represents a problem that has yet to be solved. It may thus represent a group of organisms whose distribution was controlled by some specific, but as yet unknown environmental factor.

f. Vertical sequences and depositional environments

Significant changes in sedimentary facies occurred during deposition of the Tancook Member. Figure 4 shows the distribution of sandstone facies and the changes in sandstone/slate proportion throughout those sections that were measured in detail, and summarizes the general characteristics of other parts of the stratigraphic column.

The lower sandy unit of the Tancook Member, typified by section 3, shows a predominance of thinly to medium bedded turbidites in which Bouma Tb and Tc beds are common. Internally scoured and laminated to massive sandstones are correspondingly rare. A transition matrix, representing transitions between 159 sandstone beds (figure 18), shows little departure from the ordering expected in a random sequence of beds, except for a strong, and statistically significant tendency for the lowest-energy (Tc) beds to occur together. Bed thicknesses and the proportions of sandstone and slate vary relatively smoothly in this part of the section, which shows a general thickening, coarsening-upwards trend, suggesting progradation of an unchannellized turbidite sand body. Although only part of the lower sandy unit was measured, observations toward the top of the unit indicate that the thickening-upward trend continues, but that bed thickness varies more. Internally scoured and laminated to massive sandstones are common by the top of the unit (base of section 4). Facies at the top of the unit generally resemble those of the upper sandy unit (see below).

The base of lower slaty unit of the Tancook Member represents an abrupt cessation of the sand supply. Sediment-feeding organisms, taking advantage of the quiet conditions, caused thorough bioturbation of the topmost sand layer, and the overlying muds. However some parts of the slate are laminated and unbioturbated. It will be argued below that a similar change in the upper slaty unit represents an onset of anaerobic conditions at the sea floor; this represents the most likely factor controlling the intensity of bioturbation in the lower slaty unit also. In the unbioturbated parts of the section, the only sedimentary structures are thin laminations and very low amplitude starved ripples, indicating quiet water conditions. The lower slaty unit is interpreted as a hemipelagic deposit.

Sandstones immediately above the lower slaty unit are generally thinly bedded and interbedded with relatively thick intervals of slate, suggesting that sand deposition by turbidity currents resumed gradually. Nevertheless, the facies displayed are closely similar to those of the sandstones immediately below the slaty unit, suggesting that the energy of the renewed turbidity currents was about the same as before. For this reason it is likely that the cessation of sand deposition in the lower slaty unit was due to an external control on the supply, operating in the source area, and not a spontaneous re-arrangement of the depositional system (e.g. channel switching).

Vertical sequences in the upper sandy unit of the Tancook Member (sections 5 - 8) contrast markedly with those described in the lower sandy unit (section 3). Throughout the upper unit, thick sandstone beds are grouped into packages, separated by more thinly bedded sandstones interbedded with slates. Sandstones in the packages are commonly amalgamated (i.e. layers deposited by successive turbidite events are not separated by slate), and generally show internally scoured, laminated to massive, or massive (Tae) facies. In contrast, the inter-package sandstones more frequently show Bouma sequence structures. The transition matrix (figure 19) reflects this pattern, and is extremely non-random. It shows a strong tendency for like beds to be grouped together in the section, especially the lowest-energy beds (Tc units). Classical turbidites (Tc, Tb and Ta), and massive (Tae) units tend to succeed each other in order of decreasing energy, whereas high concentration turbidites show upward increase in energy. Transitions between high concentration and classical turbidite facies occur with about the same frequencies that would occur in a random sequence. These observations indicate that two facies associations are present. The classical turbitite facies association displays a general thinning-upward cyclicity, whereas the high-concentration facies association shows some tendency toward upward increase in energy. These patterns cannot easily be reconciled with classical fan models in which thickening-upwards sequences are associated with generally thinner bedded sands of depositional lobes, and thinning-upwards cycles are characteristic of thickly bedded channelized turbidites. They suggest that the energy of turbidite flows was controlled by factors external to the depositional system.

Towards the top of the upper sandy unit, slate intervals become thicker and steeply penetrating burrows, especially Teichichnus, become abundant. In the upper slaty unit, sandstones form only a small proportion of the total thickness of strata. Sandstone beds occur grouped in packages. The lowest such package shows medium to thick sand beds that are conspicuously rust-weathered because of their pyrite content. These sandstones vary between massive (Tae) and cross-laminated (Tc) facies. Some are highly bioturbated by Teichichnus spreite burrows. Higher sandstones in the upper slaty unit are predominantly cross-laminated Tc beds, generally somewhat thicker than Tc beds lower in the Member. The slates that form most of the upper slaty unit are poorly laminated at the base, becoming more finely laminated towards the top of the unit. They do not display the abundant well-preserved burrows and mottling structures seen in the lower slaty unit, suggesting that anaerobic or dysaerobic conditions at the sea floor were limiting animal activity (Arthur et al 1984). Thin concretionary beds of manganese-rich carbonate are common. In some cases divergence of laminae around carbonate concretions indicates an early diagenetic (pre- or syn-compaction) origin.

The westward divergence of paleocurrents derived from ripples, when compared to data from flutes and grooves, suggests that a westward paleoscope may have deflected current flow. Possibly the Tancook Island area represents the west flank of a submarine fan centred further east in the Meguma Terrane, where "typical Goldenville" sediments persist to the base of the Halifax Formation, and no complex transition is present (figure 20).

5. Mosher's Island Member

a. Stratigraphy

The Mosher's Island Member is the most distinctive and uniform unit in the Goldenville-Halifax transition, traced by O'Brien (1985, 1986) throughout the area shown in figure 1. Comparable manganiferous greenish slates are present elsewhere in the Meguma Group at the base of the Halifax Formation. O'Brien (1985) initially described the unit as sandstone (Snug Harbour Sandstone) but the sandy appearance of the unit was subsequently shown to be largely due to the presence of metamorphic spessartine.

b. Petrology

Slates from the Mosher's Island Member are predominantly medium dark grey, medium grey and medium bluish grey when fresh but weathered surfaces range from greenish grey and light greenish grey to yellowish grey and light olive grey, and are locally stained brown or brownish grey by manganese oxides. Thin sections of samples from the Mosher's Island Member show mainly fine grained chlorite-sericite slate with scattered secondary opaques. Some samples contain "outsize" coarse silt to very fine sand sized grains of chlorite surrounded by uniform slate with grain size in the range 5 to 20 microns. These large chlorite flakes have anhedral outlines, suggesting that they represent original sedimentary particles rather than metamorphic porphyroblasts; like the chlorite flakes in the upper slaty unit of the Tancook Member, they may be particles of volcanic ash. Cleavage in the fine grained slates is generally a typical domainal slaty cleavage defined by quartz rich lenses about 20 microns thick, surrounded by somewhat thinner anastomosing mica and chlorite rich domains. The mica-chlorite domains are preferentially stained brown in weathered samples, indicating enrichment in iron and manganese relative to the quartz-rich domains.

Siltstone layers varying from less than 1 mm to about 2 cm in thickness are interlaminated with fine-grained uniform and parallel-laminated slates. The silts consist of quartz, alkali feldspar, muscovite, and sometimes include abundant chlorite flakes similar to those found dispersed in the fine-grained slates. The silts generally have a paler appearance in the field. One sample contains a lens of almost pure fine-grained chlorite, within a zone of cross-laminated quartz-chlorite silt. If primary, this concentration of chlorite indicates that silt of a distinctive composition, possibly volcanic, was accumulated by currents at times during deposition of the Member. Both normally and inversely graded profiles are common, and occasional silt layers show sharp contacts at both upper and lower surfaces. In general, inversely graded and sharply bounded silt layers show slightly better sorting than their normally graded counterparts, which generally contain an abundant chlotite-sericite matrix similar in composition to the uniform fine-grained slates. Some silt laminae contain manganiferous carbonate which weathers brownish grey and in thin section is seen altered to fine-grained oxides. The carbonate propably represents cement which has filled pore spaces in the better-sorted silts.

Carbonate laminae are mostly 1-10 mm in thickness and consist of coarse, sometimes poikiloblastic crystals that alter to aggregates of opaque iron and manganese oxides, again indicating a high rhodochrosite content. The carbonate layers behaved extremely competently during regional deformation, showing near-parallel fold geometries and micro-thrust faults in cross-sections cut perpendicular to the bedding-cleavage intersection lineation. Sections parallel to the lineation show boudinage of the carbonate layers. The spaces between boudins are filled by fibrous aggregates of quartz and muscovite.

Carbonate concretions are concentrated in layers. In the lower part of the Member, carbonate concretions occur on-strike with lenticular beds of carbonate. Laminations in adjacent slate diverge around the concretions, suggesting that they formed early in diagenesis, before compaction was complete. At the top of the exposed portion of the Member on the northeast coast of Big Tancook

Island, small button-like concretions, 1-2 cm in diameter and about 5 mm thick, are densely concentrated on certain bedding surfaces. In thin-section, laminations can be traced through these concretions with only slight divergence, indicating that they formed after the majority of compaction. Some such concretions contain irregular intergrowths of megaquartz and opaques at their centres. Others show small garnet crystals at their rims. These minerals are interpreted as products of metamorphism.

The top of the Mosher's Island Member is not exposed on the north coast of Tancook Island, but is well displayed on the south limb of the Indian Path anticline. There, the highest part of the Mosher's Island Member consists of olive grey argillites which are very rich in spessartine. Pseudomorphs of chlorite after garnet occur in one sample; these are quite distinct from the anhedral chlorite flakes seen elsewhere in the Member. "Button" concretions occur at certain horizons; these have a zoned composition of metamorphic spessartine, quartz, and manganese-rich carbonate. Pyrite is increasingly common upwards in the transition to the overlying Cunard Member, and the slates darken from medium to dark grey. This transitional zone is about 3 m thick. At the top of the transition are dark grey slates and siltstones rich in pyrite, typical of the Cunard Member.

c. Sedimentary facies

The Mosher's Island Member is distinctive because of its lack of large-scale current generated structures and trace fossils. Most of the Member consists of alternating laminated and homogeneous slates.

The homogeneous slates occur in beds typically 5 - 30 cm thick and are devoid of visible primary features. Laminated intervals display variations in both colour and texture, and show more sedimentary structures. Occasional dark laminae are more fissile than other lithologies, suggesting that the dark coloration is due to high organic carbon content. Coarser laminae are generally paler on weathered surfaces and show cleavage refracted into an orientation more nearly perpendicular to stratification. A minority of coarser laminated units show small scale current-ripple cross-lamination. No paleocurrent directions have been determined from rippled beds, because tectonic deformation obliterates ripples on the rarely exposed bedding surfaces. Strike-parallel cross-sections indicate both southwestward and northeastward components of paleoflow. Rippled laminae include starved and fading ripples (Stow & Shanmugam 1980).

Occasional laminae and very thin beds of siltstone show soft-sediment deformation features resembling load structures and pseudonodules. These structures are erosionally truncated and clearly synsedimentary. The structures show no clear sense of vergence, suggesting that they formed in response to sediment loading or de-watering, and not as slump structures on slopes.

The slates of the Mosher's Island Member are interpreted as products of sedimentation in relatively deep, generally quiet-water conditions. The lack of bioturbation under such circumstances suggests that bottom waters were low in oxygen. Silt layers were deposited by currents that probably operated episodicaly. These currents were either dilute turbidity currents or continuously operating bottom currents such as contour currents. Stow and Piper (1984) have suggested that muddy turbidites are characterized by a predominance of normal grading whereas contourites show both normal and inversely graded profiles. On this basis, and because of the presence of relatively well sorted, re-worked silt in some layers, the Mosher's Island Member muddy sediments are interpreted at least in part as products of continuously operating bottom currents. However, in the absence of evidence for current direction and paleoslope, they cannot be positively identified as contourites. Normally graded layers, especially those that show load structures suggestive of sudden, rapid deposition, are probably dilute turbidites.

d. Manganese concentration

Manganese must have become concentrated in the Mosher's Island Member at some stage before regional metamorphism, in order to explain the widespread occurrence of garnets within the chlorite zone. Manganese is concentrated in carbonate, much of which is clearly concretionary in origin. Carbonate layers and lenses in the lower part of the Member probably formed early during diagenesis, whereas "button" concretions higher in the sequence formed relatively late. In the absence of any independent evidence for wholesale replacement of calcite, it is here assumed that manganese was present in the sediment or pore waters at the time of concretion formation.

Under normal marine conditions, nodules and crusts of manganese oxy-hydroxides are common at the sediment-water interface in modern ocean basins and on continental margins where sedimentation is slow (e.g. Roy 1981). These concretions have poor preservation potential, dissolving upon burial under reducing conditions, to yield divalent manganese ions in solution. Ions diffuse upwards within the sediment along the concentration gradient thus produced, and are returned to oxidizing conditions near the sediment-water interface. Figure 21 shows that manganese is soluble under the range of reducing diagenetic conditions typical of marine sediments.

In order to preserve manganese rich reduced sediments, a sink for manganese must be provided to break the cycle that continuously returns manganese to the sea floor (Coleman et al 1982). Carbonate ions provide such a sink, enabling manganese carbonate (rhodochrosite or manganoan calcite) to be precipitated (figure 22) in early diagenetic concretions. Two possible sources for carbonate are available in the Mosher's Island Member. Firstly, the limestone bed at the top of the Tancook Member demonstrates that a carbonate producing shelf existed, which may have supplied fine-grained carbonate to the sedimentary basin during deposition of the Mosher's Island Member. Secondly, diagenesis of organic matter in sediments produces CO_2, bicarbonate, or carbonate ions (depending on pH). Carbon isotopes have been used to demonstrate that such carbonate may become incorporated in early diagenetic concretions (e.g. Curtis 1977).

Most described examples of early diagenetic carbonate concretions are calcite, dolomite, or siderite. To produce rhodochrosite or manganoan calcite, the Mn/Fe ratio must be elevated above that existing in normal ocean sediment pore waters. Three mechanisms exist that may have concentrated manganese at the expense of iron. First, manganese may have been initially fixed in the sediments in the form of oxy-hydroxide nodules and crusts at the sea floor, the formation of which is common in areas of slow sedimentation (e.g. Pratt & McFarlin 1966). Secondly, fully anoxic conditions may already have been initiated elsewhere in the basin, resulting in the preferential removal of iron as sulphides. Schlanger and Jenkyns (1976) and Jenkyns (1980) provide a model for the deposition of Mesozoic black shales in which an oxygen minimum zone is established as the result of high organic productivity on continental shelves during marine transgression. This model is applied to Paleozoic examples by Leggett et al (1981). Such a model would imply that black, sulphide rich shales may have been deposited in shallow water for some time prior to the onset of black shale sedimentation within the basin itself (figure 23). Such sedimentation would raise the Mn/Fe ratio in the anoxic water, and lead to increased oxide precipitation close to the boundaries of the anoxic water mass, as occurs at the present day around the margins of the Black Sea (Shimkus & Trimonis 1974). Thirdly, a volcanic source may have been present within the basin, as is suggested by the presence of "oversized" chlorite particles in fine muds of the Tancook and Mosher's Island Member. Hydrothermal sediments associated with ocean floor vulcanism commonly show a zonation in composition, with iron rich muds deposited close to vents and manganese rich muds further away (Bonatti 1975). (An immediate volcanic source is not, however, essential to sedimentary concentration of manganese, as illustrated by the case of the modern Black Sea).

6. Cunard Member

a. Stratigraphy

Black slates of the Cunard Member constitute the bulk of the Halifax formation in the Mahone Bay area (figure 1). The maximum thickness of the member is estimated by O'Brien (1986) at 8 km. Only the basal part of the Member was investigated in this study, to provide a complete picture of the Goldenville-Halifax transition. The base of the Member is exposed on the south coast of Big Tancook Island. The sequence there becomes faulted and poorly exposed about 3.5 m above the base. Slightly higher strata are well exposed on the north coast of the Island; figure 24 shows a detailed measured section at this outcrop (section 13).

b. Petrology

The Cunard Member consists of medium dark grey, dark grey, bluish grey, and dusky blue slates and siltstones which are extremely fissile by comparison with those of the underlying Mosher's Island Member. This fissility is believed to be due to their high graphite content, representing organic matter deposited with the sediments. Pyrite is abundant, and weathered surfaces are typically stained moderate brown to yellowish orange. Rare beds of grey sandstone up to 1 m thick are also present. In thin section the slates appear to consist mainly of quartz, sericite and chlorite with strong cleavage similar to that in the Mosher's Island Member. The siltstones and sandstones contain quartz, alkali feldspar, muscovite and chlorite and are generally poorly sorted and normally graded.

Pyrite is present in both slates and siltstones, comprising more than 50% by volume of some beds. At least two generations of pyrite are present. The first consists of elliptically outlined aggregates of fine crystals clearly pre-dating the cleavage, which diverges around them. Pyrite in these aggregates has been extensively replaced by megaquartz, which sometimes shows a fibrous fabric implying growth in "pressure shadows" during deformation. In sharp contrast to the early pyrite aggregates are cubic euhedral pyrite crystals that overprint the cleavage and are clearly therefore post-tectonic.

Small (0.5 mm) elliptically outlined aggregates of quartz, chlorite, sericite, and opaques are concentrated in a thick slate lamina in one sample. The aggregates show slight concentric zonation of grain size and are finer grained than the quartz-chlorite balls seen in the Tancook Member. They clearly pre-date cleavage, and have pronounced "pressure shadows" of quartz-rich slate. Serial sectioning shows that in three dimensions these aggregates are ellipsoidal, not tubular. Like those in the Tancook Member, they are tentatively interpreted as replacements of early diagenetic concretions.

c. Sedimentary facies

The Cunard Member consists mainly of laminated and finely cross-laminated slates and siltstones that are almost always normally graded. They are interpreted as low-concentration turbidites, showing Tc(d)e and T(d)e Bouma sequences. Occasional beds are grossly lenticular and contain cross-sets with amplitudes of 5 - 10 cm, larger than most cross-laminations in turbidites. These beds may represent re-working of turbidite silt by continuously operating bottom currents similar to those postulated in the Mosher's Island Member. The rarer, thickly bedded blue-grey sandstones show laminated to massive and internally scoured facies similar to those seen in the Tancook Member. These are interpreted as high-concentration turbidites.

The investigated part of the Cunard Member shows no evidence for large scale cycles of sedimentation, or channelization features that might indicate deposition in a submarine fan. Such features were, however, described by Stow et al (1984), working on sections higher in the Member. They interpreted the sediments as products of sedimentation in a muddy submarine fan similar to many which operate at the present day.

The Cunard Member sediments on Tancook Island are not bioturbated. This and their high carbon and pyrite contents suggest that they were deposited under anaerobic sea-floor conditions. Although the slates are darkest, both siltstones and sandstones are notably rich in graphite and pyrite, indicating that both the basin of deposition and the source area of the turbidites were rich in organic matter. The sediments were therefore probably deposited during a period of basin-wide stagnation (figure 23).

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List of Figures

Appendices (separate sheets)

1. Measured sections in top of New Harbour Member and base of Tancook Member.
2. Measured sections in Tancook Member.
3. Measured sections in top of Tancook Member.

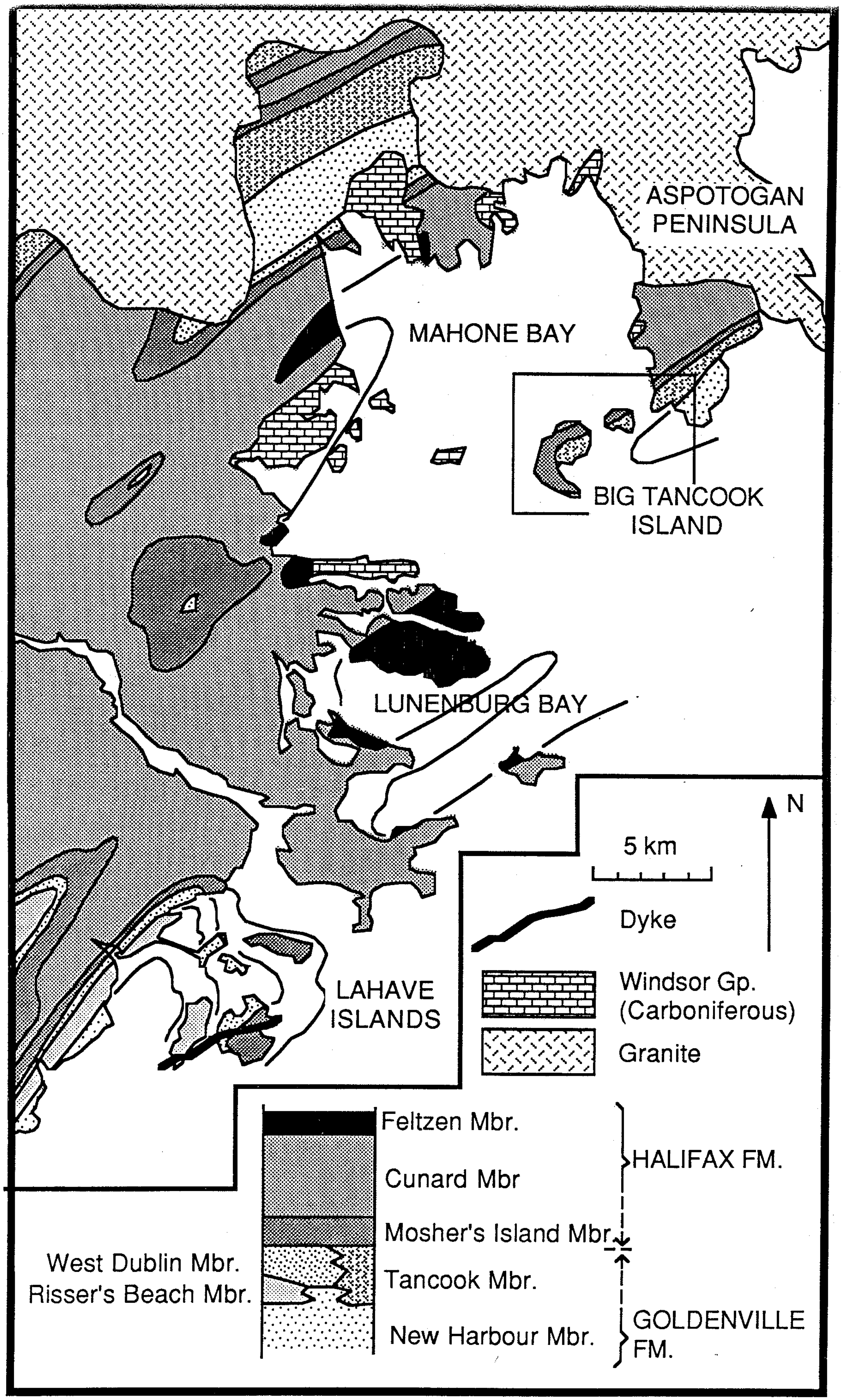


Figure 1. Geological map of Mahone Bay and Lahave areas (after O'Brien 1985, 1986). Lithostratigraphy of Meguma Group in map area is summarized schematically in legend.

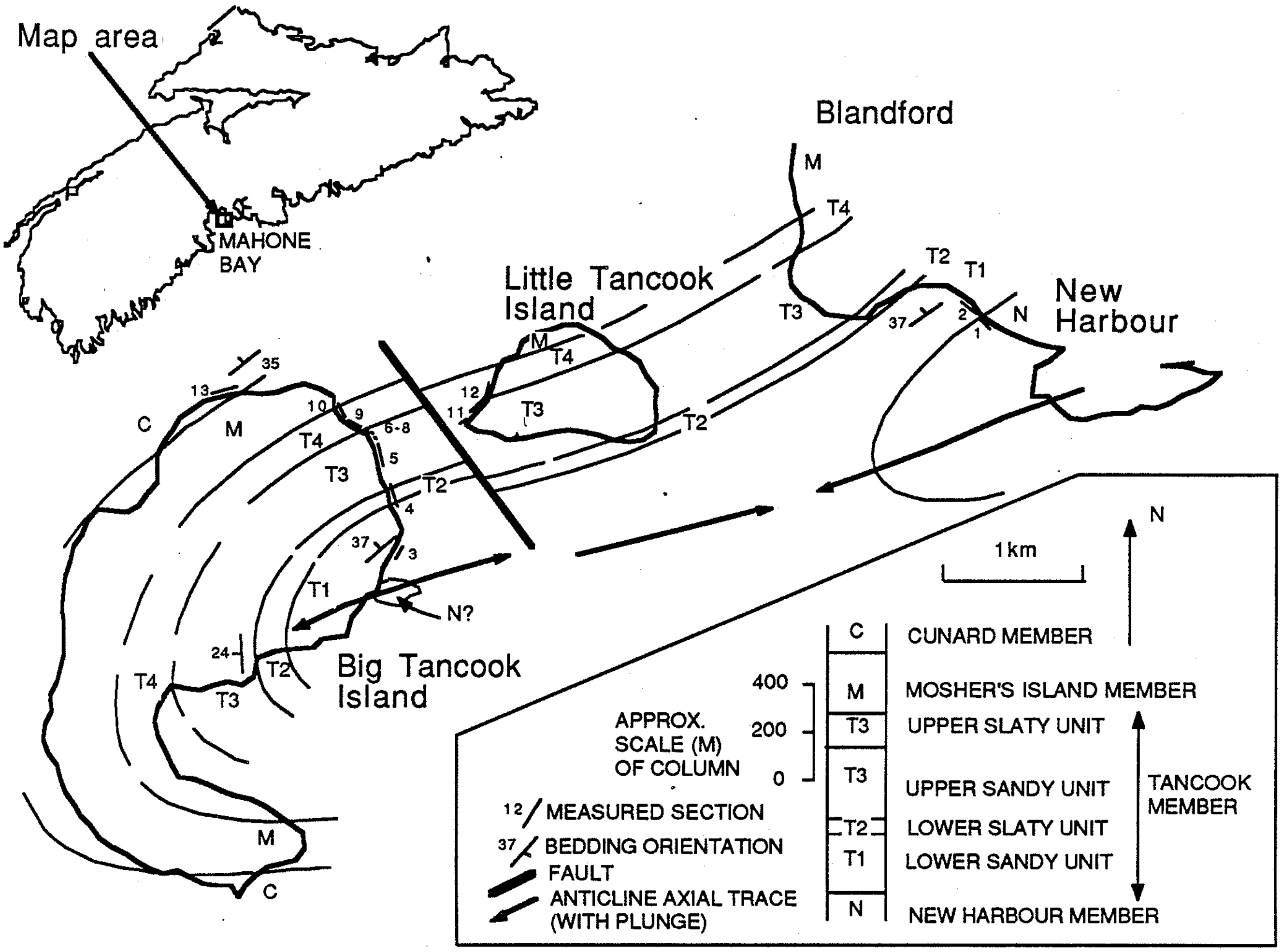


Figure 2. Schematic geological map of Tancook Island area, showing locations of measured sections.

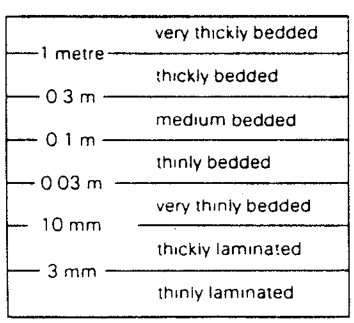


Figure 3. Terminology for bed-thickness description (after Tucker, 1982).

Figure 4 (Separate sheet). Summary of stratigraphy and gross sedimentological characteristics of Goldenville-Halifax transition on Tancook Island and adjoining areas.

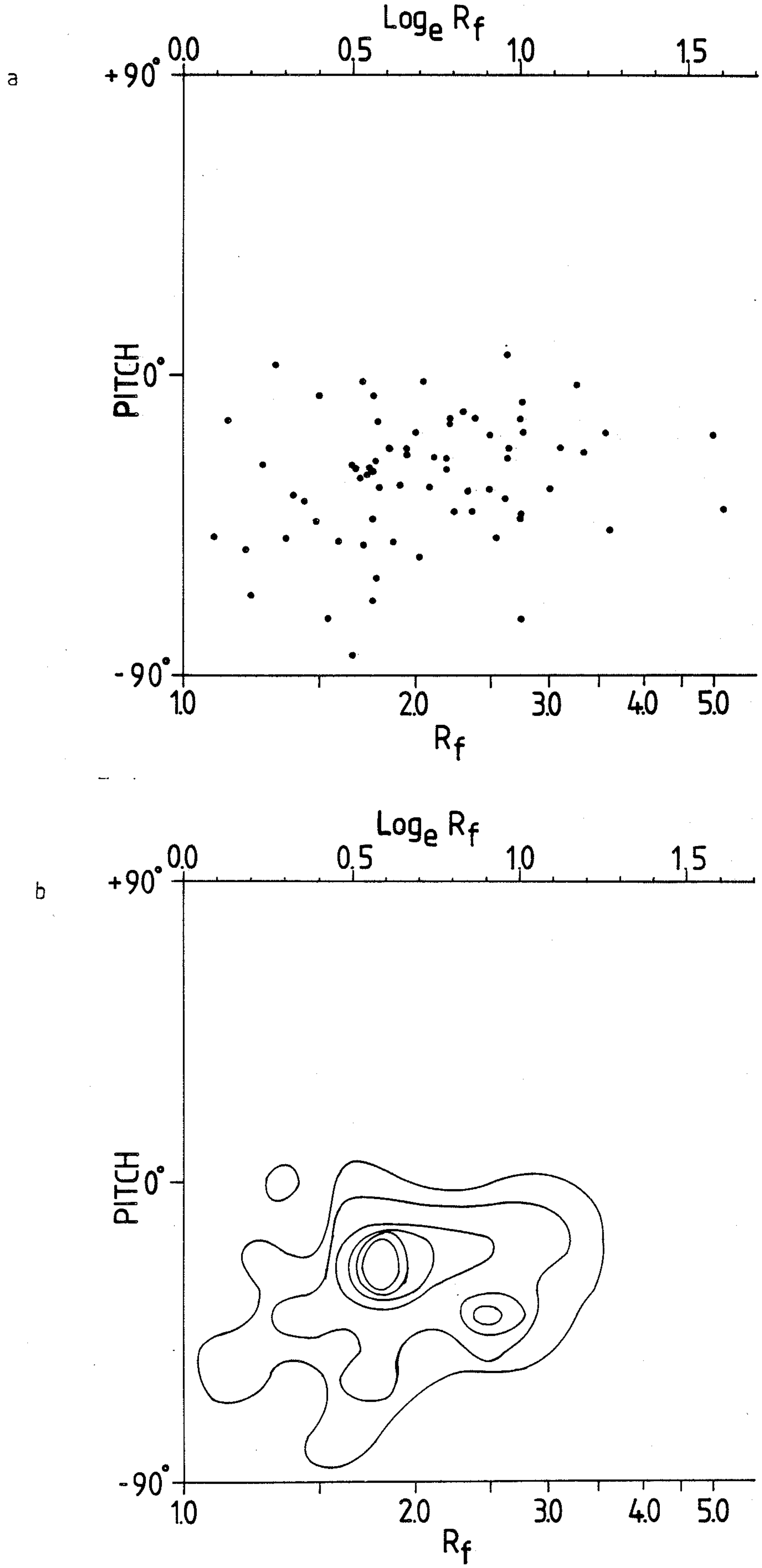


Figure 5. Rf/phi plot of intraclasts from a single bedding surface in upper sandy unit of Tancook Member, Big Tancook Island (measured section 5). Rf is the observed aspect ratio on bedding surface of approximately elliptical slate intraclasts. Phi is pitch of long axis measured clockwise from strike direction. Plot (a) shows raw data; plot (b) is contoured for density at an arbitrary contour interval, to show shape of cluster.

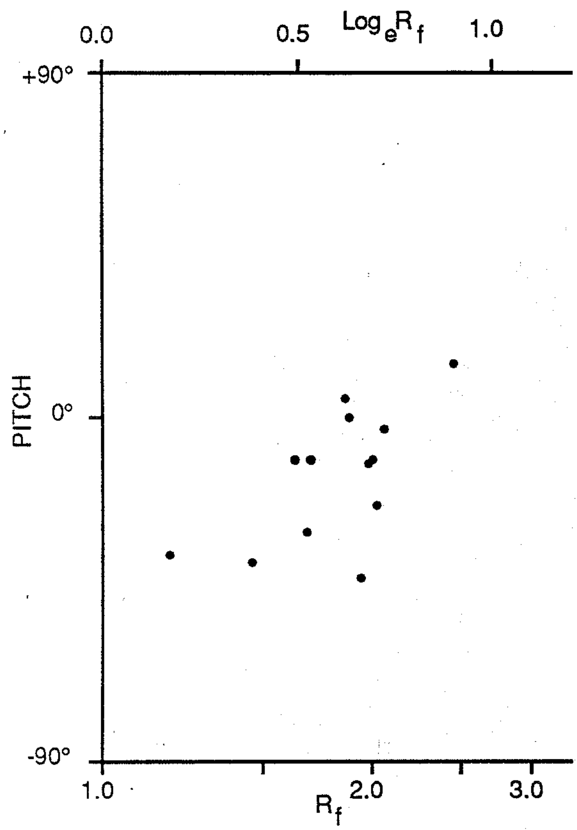
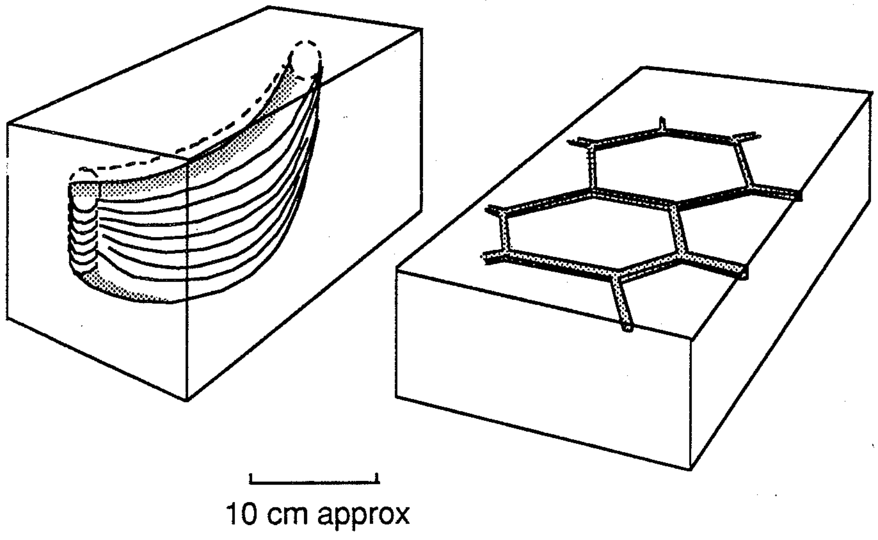


Figure 6. Summary of strain estimates obtained from Paleodictyon hexagonal trace-fossil networks. Rf is estimated strain ratio derived by Mohr circle technique from three-way burrow intersections. Phi is estimated pitch of extension axis measured clockwise from strike direction.

Figure 7. Sketch to show geometry of burrows of Teichichnus (left) and Paleodictyon (right) types.



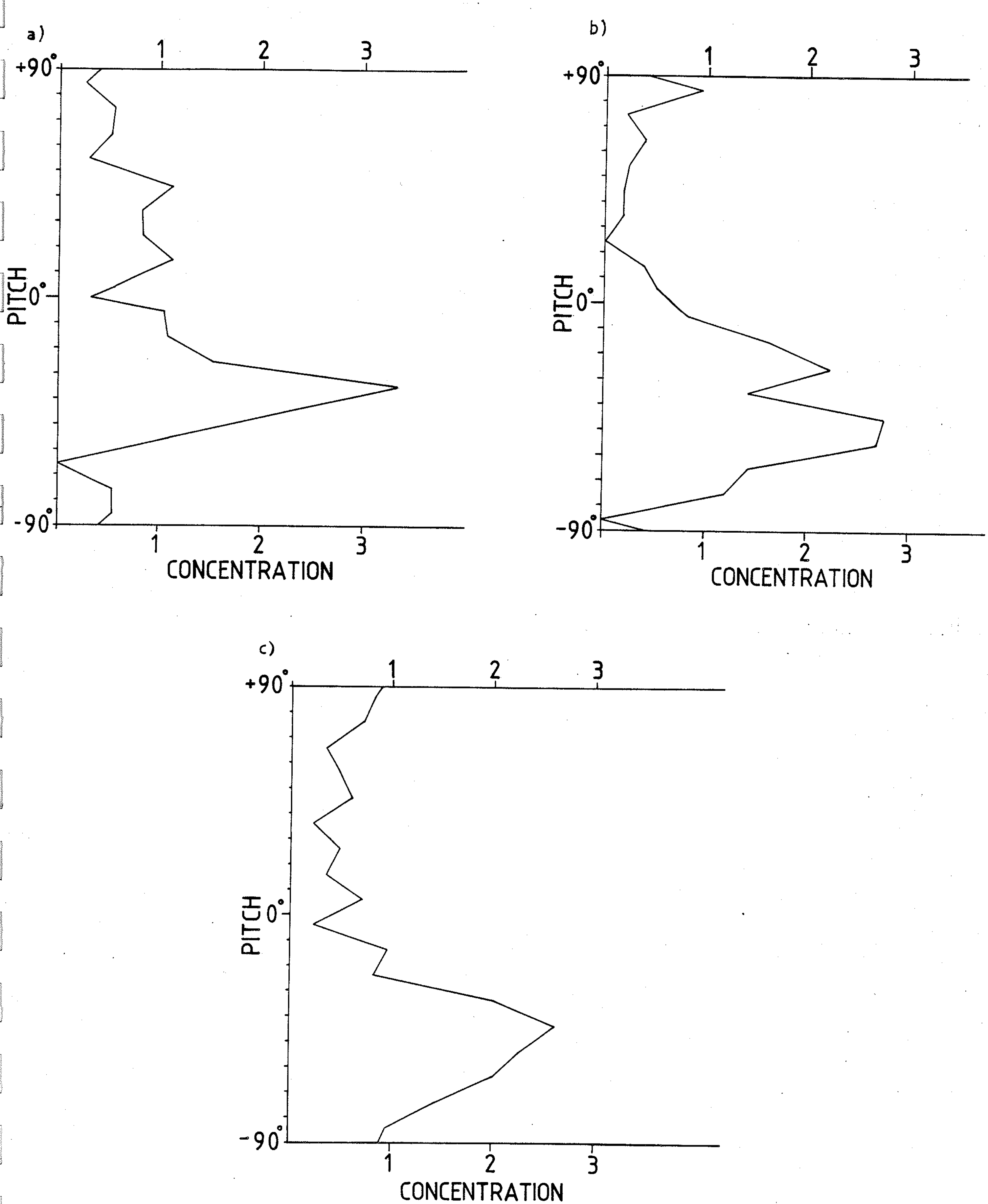


Figure 8. Distribution of Teichichnus spreiten according to direction in a single bedding surface, Little Tancook Island. Concentration is the number of burrows oriented in a 10° interval divided by the number expected from the same interval in a uniform distribution. Diagrams (a) and (b) represent two adjacent areas from same bedding surface. Diagram c represents data from (a) and (b) combined.

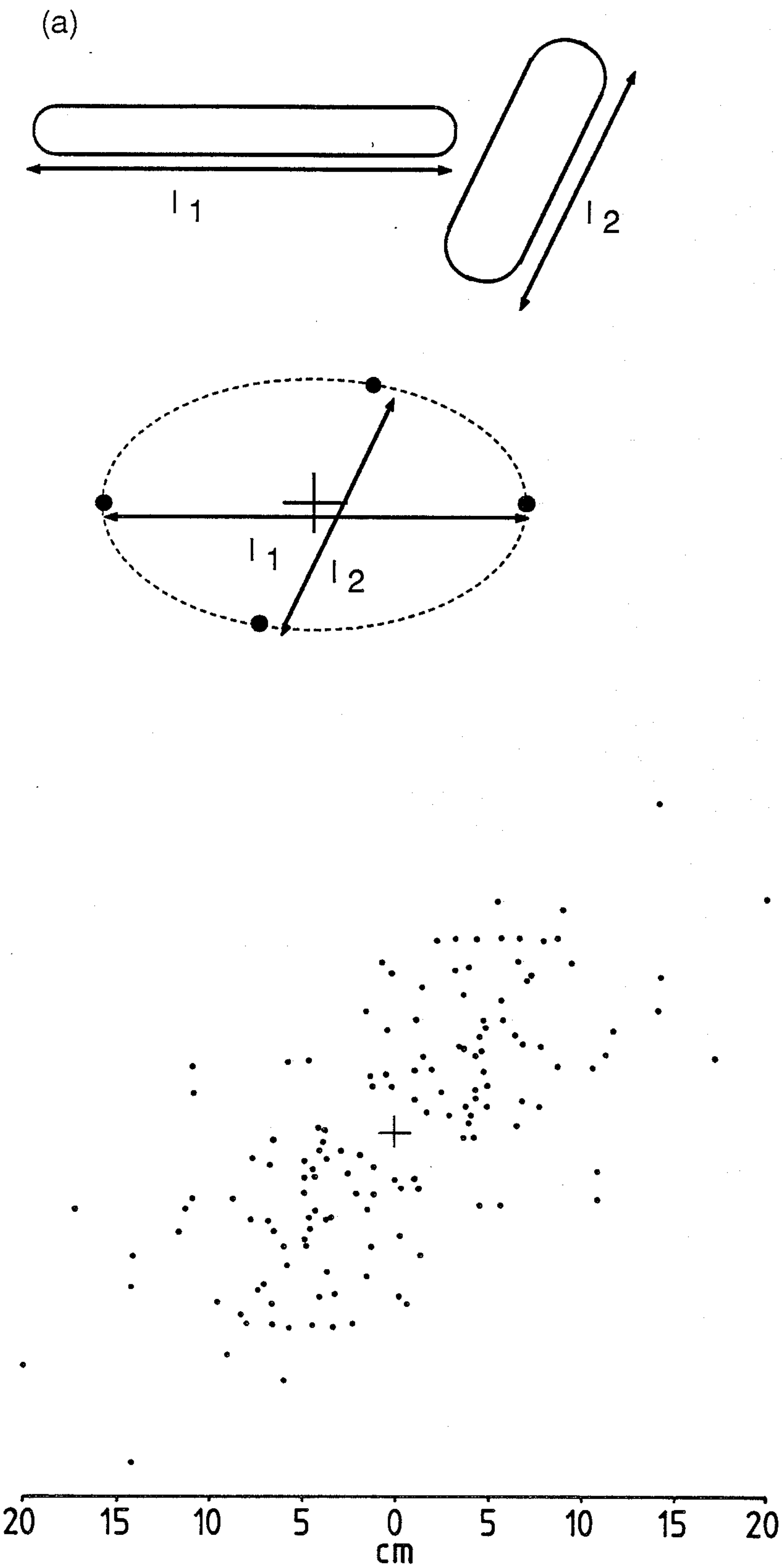


Figure 9. Distribution of Teichichnus burrow lengths with direction in single bedding surface (modified Fry plots). (a) Principle of plot construction. Each burrow is represented by two points symmetrically on opposite sides of the origin (central cross). Distance of points from origin represents length of burrow. Direction of points from origin represents orientation of burrow: horizontal line represents strike direction. (b) and (c): Plots representing burrow lengths from a single bedding surface in upper slaty unit of Tancook Member, Little Tancook Island.

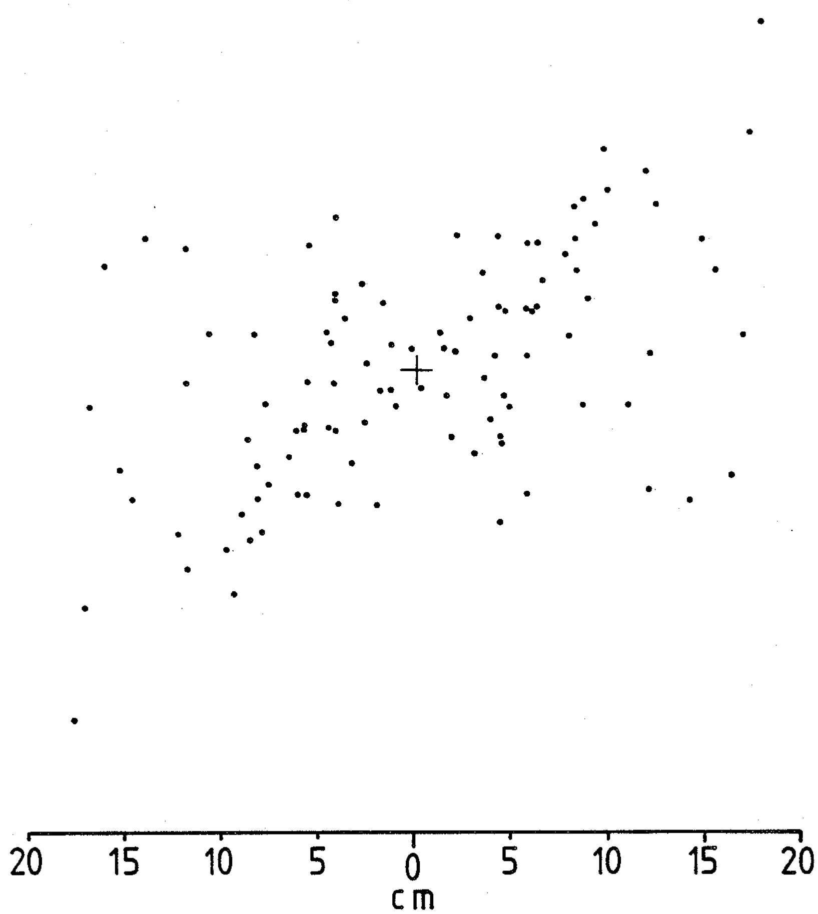


Figure 9(c)

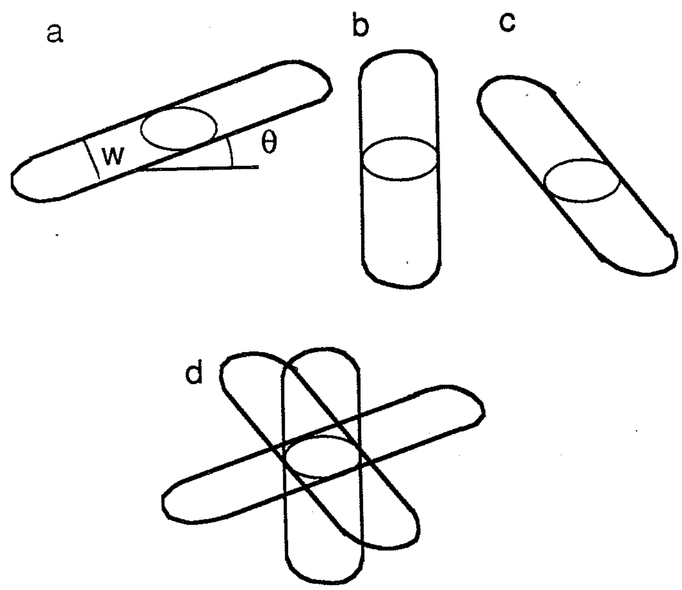


Figure 10. Principle of tangential plot of burrow widths. Diagrams (a), (b) and (c) represent differently orientated burrows of (ideally) identical original width. In each case burrow sides are tangential to an identical inscribed strain ellipse. Diagram (d) is formed by superimposing diagrams a - c, and corresponds to the diagrams used in figure 11 to estimate strain ellipse.

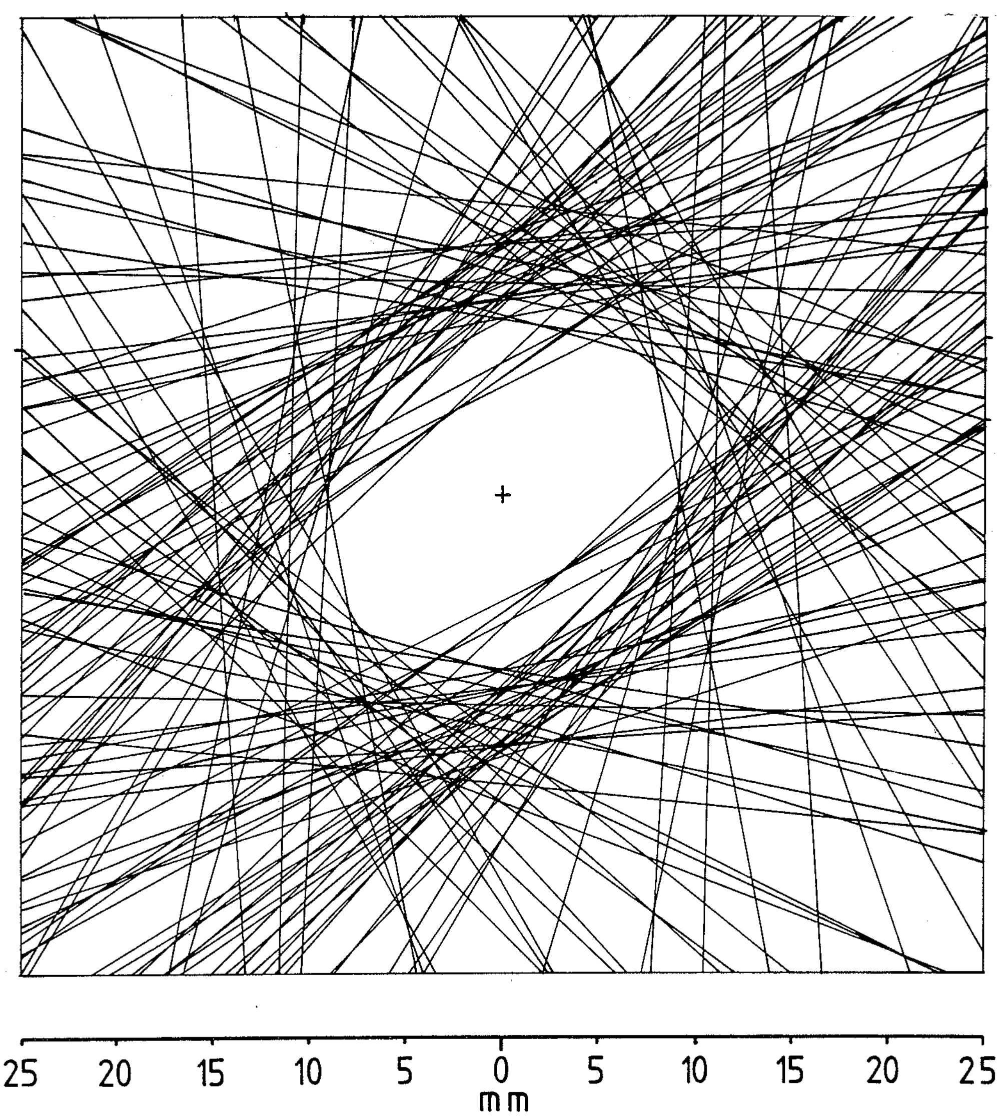


Figure 11. Tangential plots derived from widths of Teichichnus burrows in two adjacent areas of same bedding surface on Little Tancook Island (upper slaty unit of Tancook Member). Principle of plots is shown in figure 10.

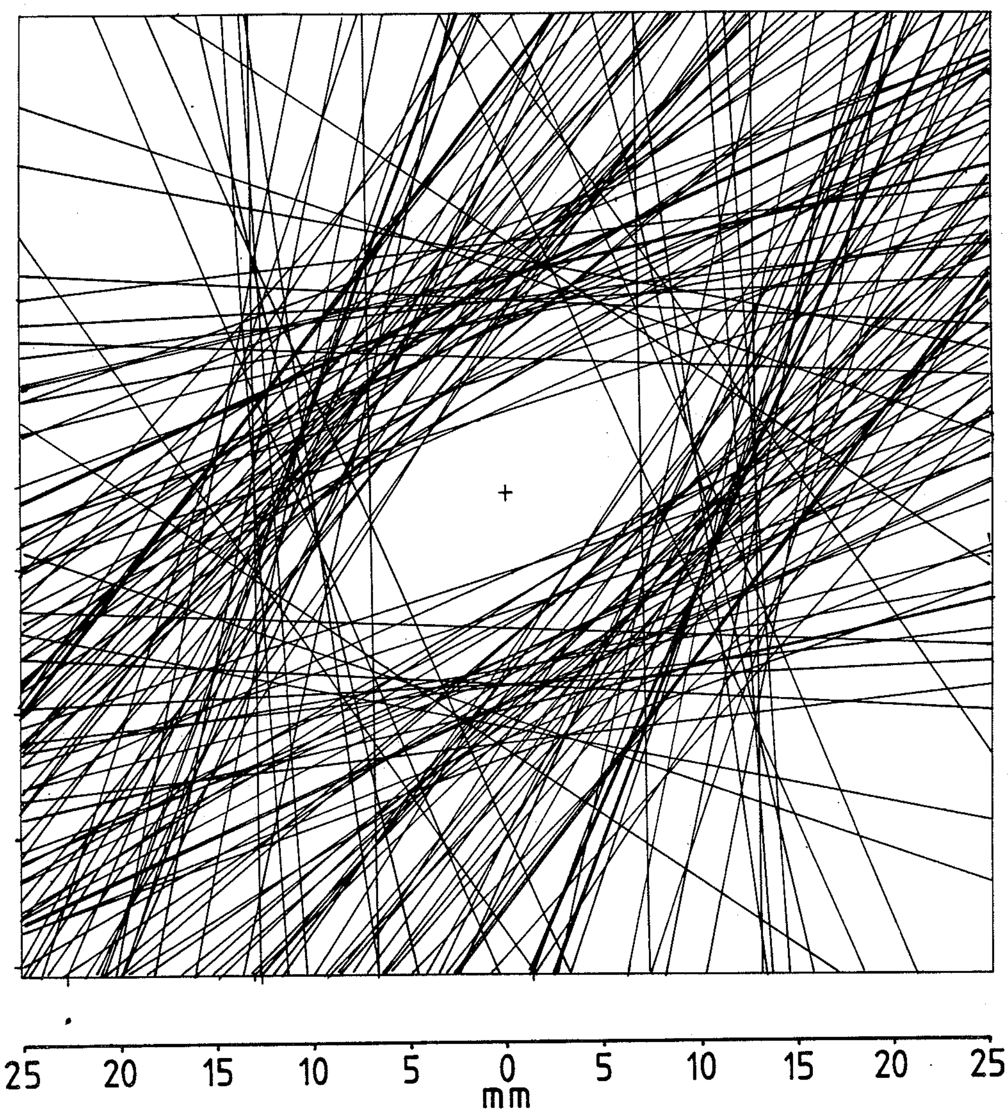


Figure 11 (continued)

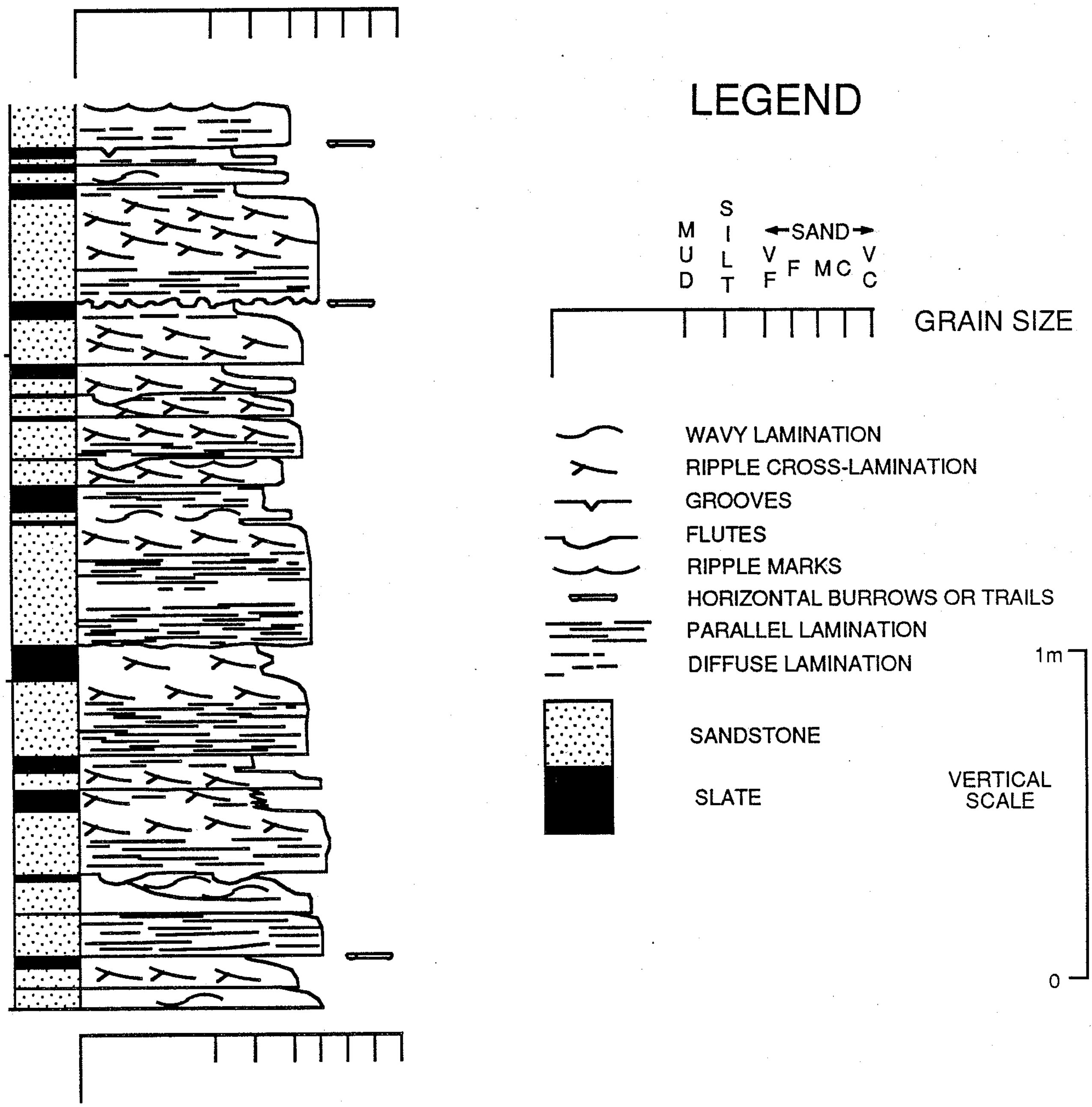


Figure 12. Detailed measured section in lower sandy unit of Tancook Member (part of section 3). Big Tancook Island.

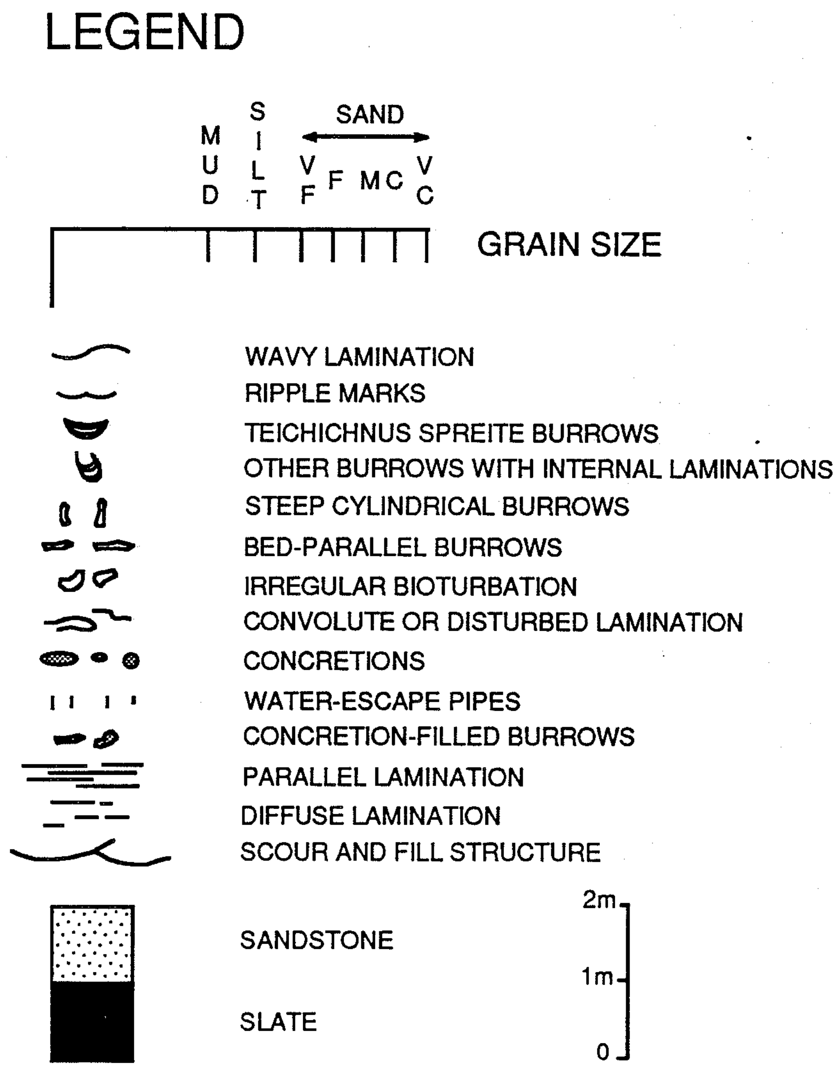


Figure 13. Detailed measured section (section 4) of entire lower slaty unit of Tancook Member, Big Tancook Island (continued overleaf).

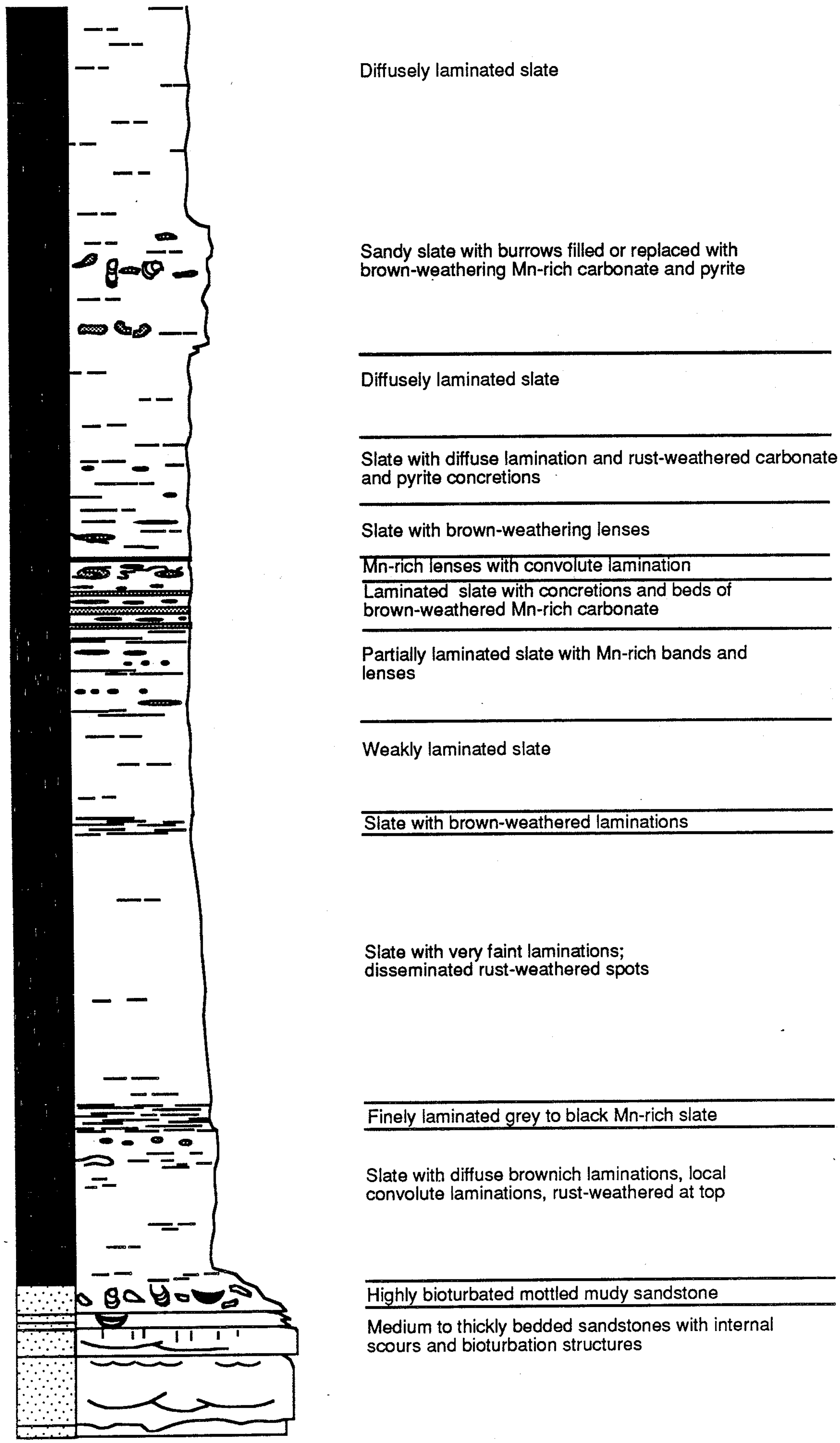


Figure 13 (continued).

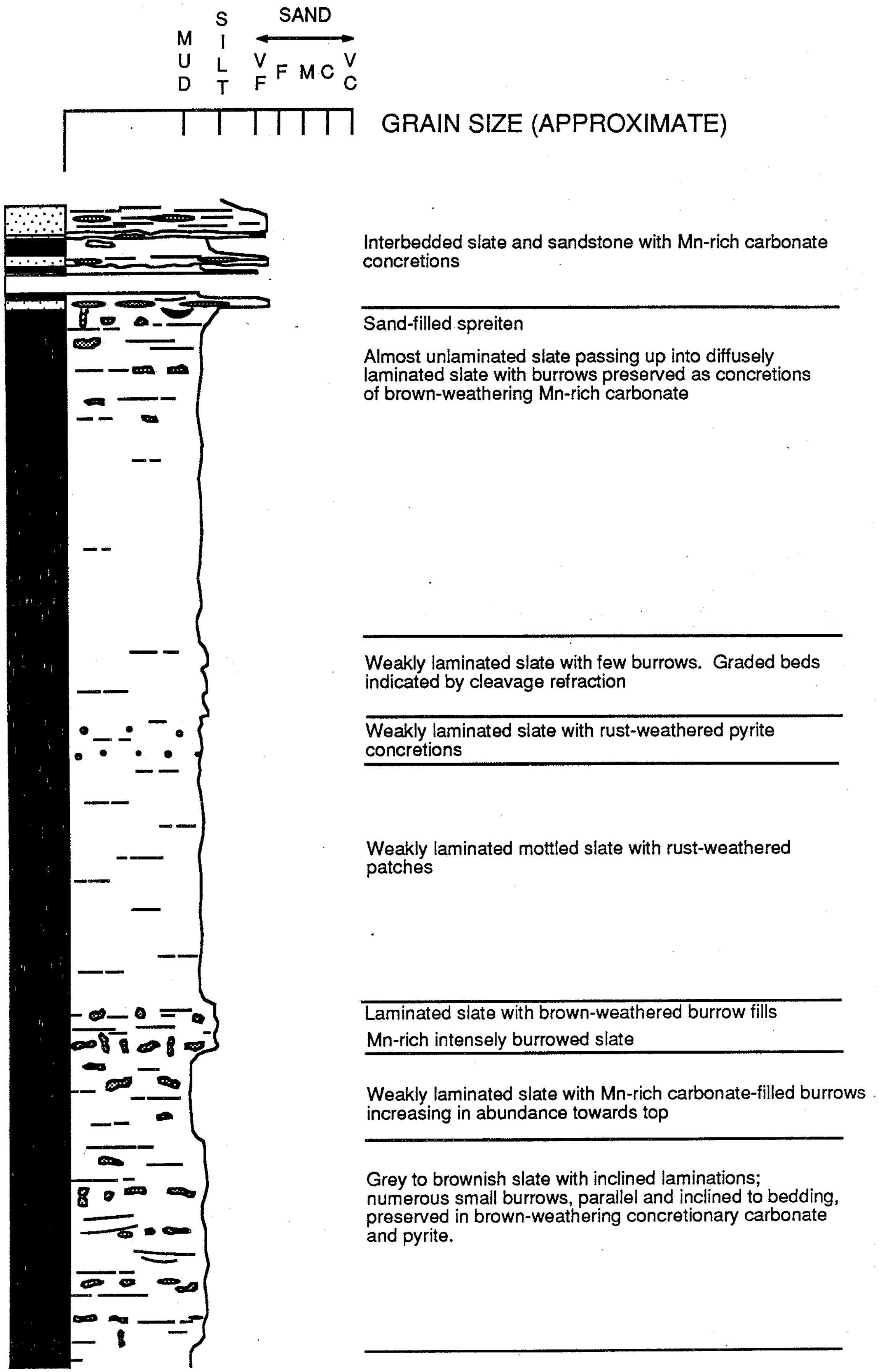


Figure 13 (continued).

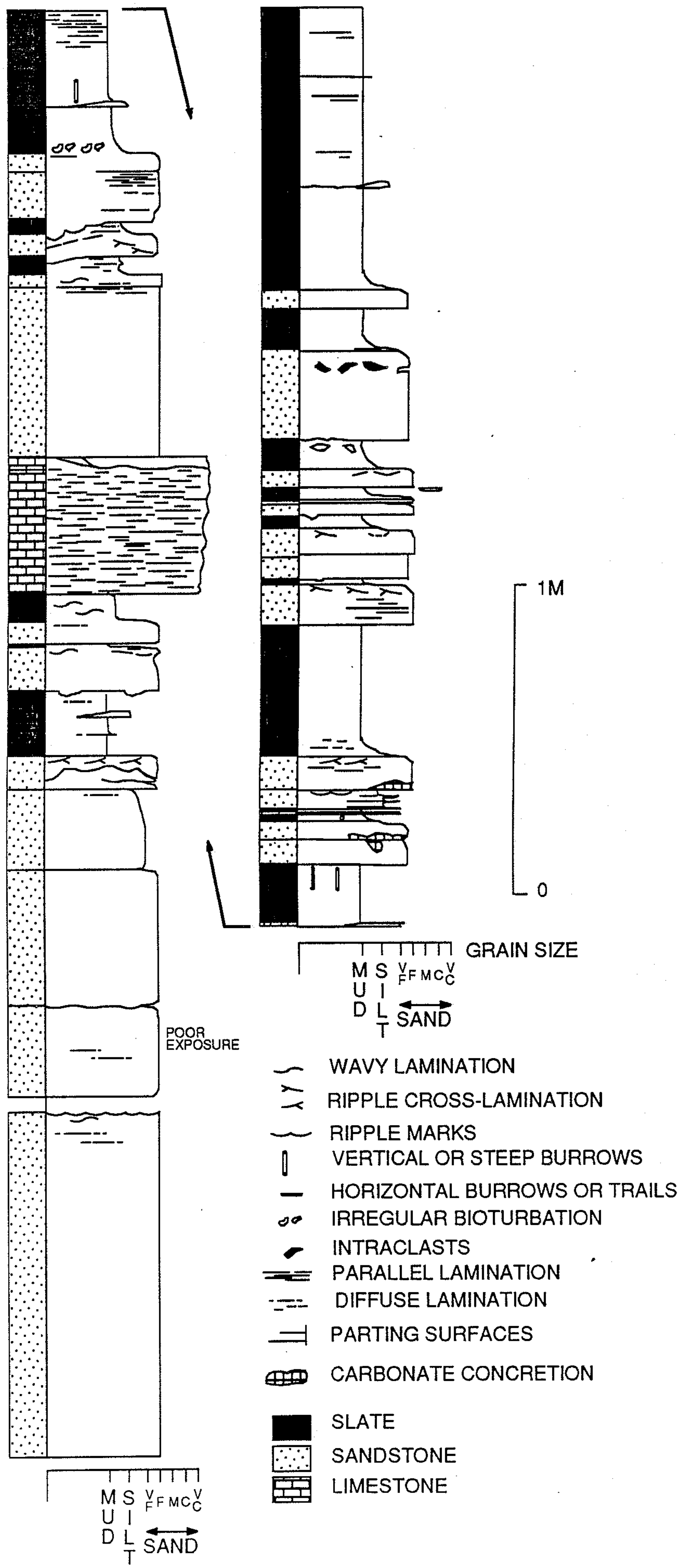


Figure 14. Detailed measured section (section 6) in upper slaty unit of Tancook Member including sandy bioclastic limestone horizon.

Laminated to massive sandstones 49 units

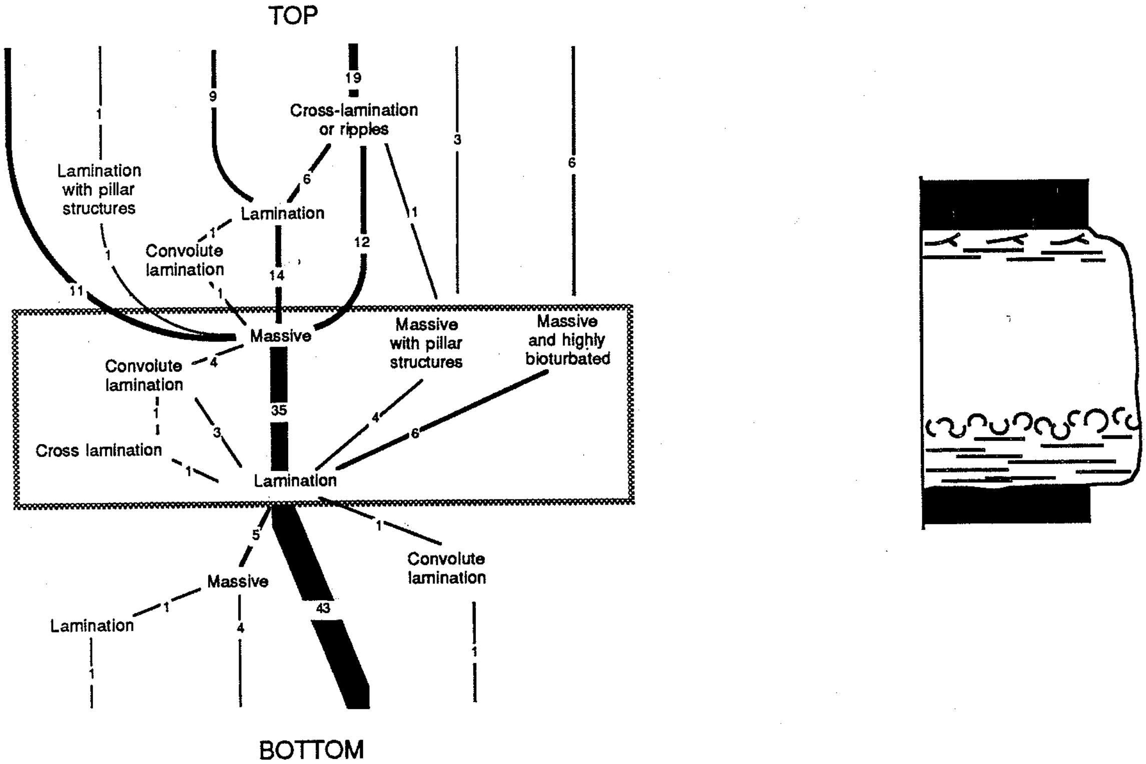


Figure 15. Left: Diagram summarizing sequences of sedimentary structures observed within individual laminated to massive sandstone beds, section 5, Big Tancook Island. Thicknesses of lines are approximately proportional to number of transitions observed. Structure named at upper end of line always overlies structure named at lower end. Right: ideal laminated to massive bed displaying typical sequence of structures.

Internally scoured sandstones 28 units

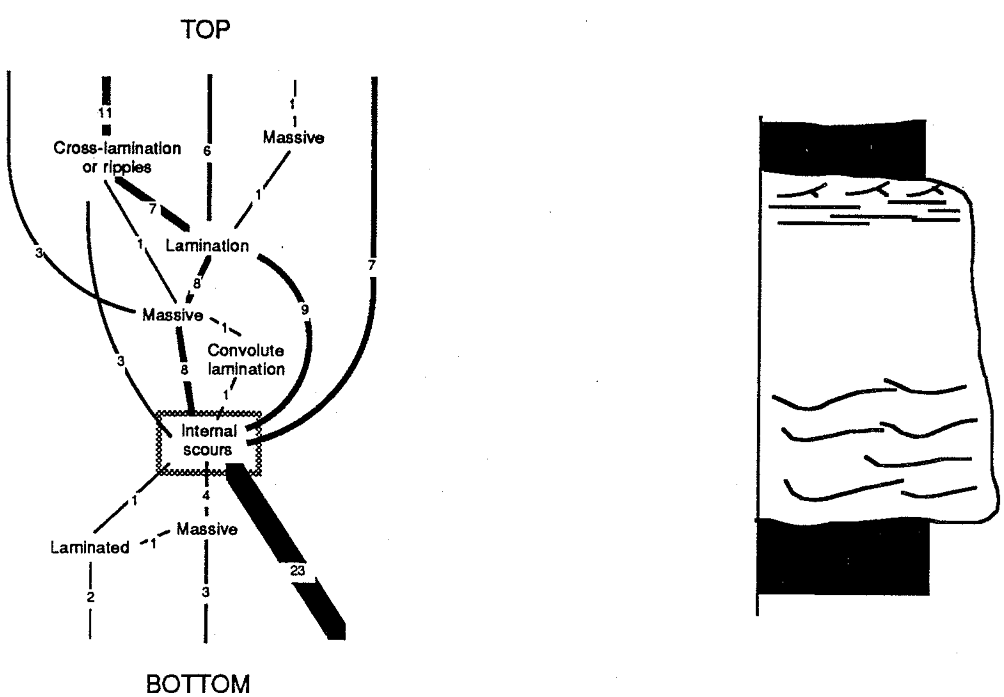


Figure 16. Left: Diagram summarizing sequences of sedimentary structures observed within individual internally scoured sandstone beds, section 5, Big Tancook Island. Thicknesses of lines are approximately proportional to number of transitions observed. Structure named at upper end of line always overlies structure named at lower end. Right: ideal internally scoured bed displaying typical sequence of structures.

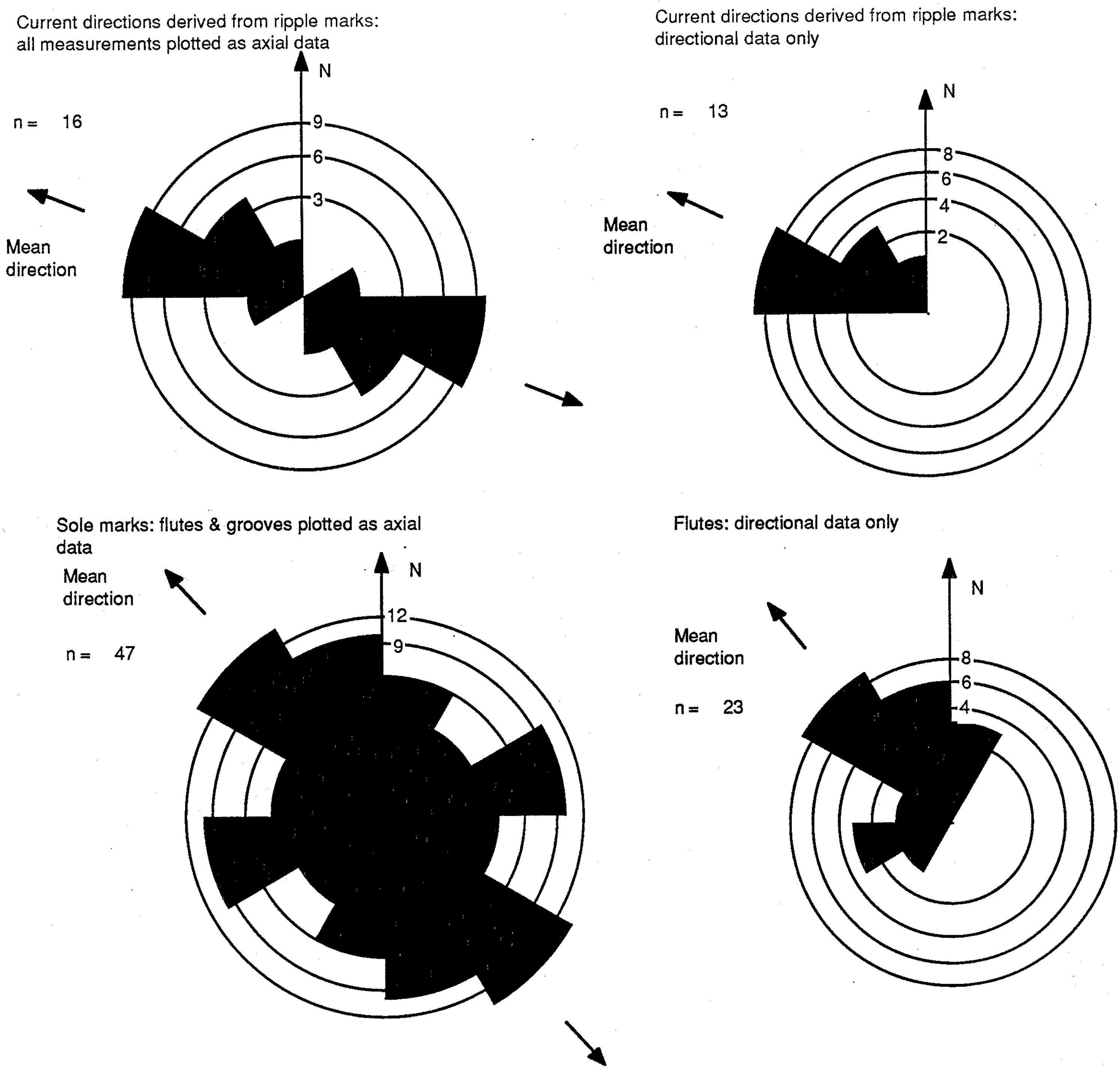


Figure 17. Diagrams showing distribution of paleocurrent directions in Tancook Member. Diagrams are circular histograms: areas of segments are proportional to numbers of readings. All measurements are corrected for strain and rotated to horizontal about strike (see text).

SECTION 3 - TANCOOK MEMBER, LOWER SANDY UNIT

To

From	Tae <3cm	Tc	Tb	Ta	Tae >3cm	Lamin. - massive	Internally scoured	Total
Tae <3cm	0 0.1	1 1.0	0 1.2	2 1.2	1 0.4	0 0.1	0 0.0	4
Tc	1 1.0	<u>19</u> 10.4	12 11.9	5 11.9	4 4.4	0 1.0	0 0.3	41
Tb	1 1.2	13 11.6	13 13.4	15 13.4	3 4.9	1 1.2	0 0.3	46
Ta	1 1.1	5 11.4	13 13.1	16 13.1	6 4.8	3 1.1	1 0.3	45
Tae >3cm	0 0.4	2 4.3	6 4.9	6 4.9	3 1.8	0 0.4	0 0.1	17
Lamin. - massive	1 0.1	0 1.0	1 1.2	2 1.2	0 0.4	0 0.1	0 0.0	4
Internally scoured	0 0.0	0 0.3	1 0.3	0 0.3	0 0.1	0 0.0	0 0.0	1
Total	4	40	46	46	17	4	1	

Upper number in each box shows observed number of transitions; lower number shows mean expected number in a random sequence. Underlined numbers show the most over-represented transitions.

Chi-square test carried out after amalgamating facies Tae<3cm with Tc and facies Tae>3cm with Laminated-massive and internally scoured, to ensure expected totals greater than 5.

$X^2 = 18.4$ 5 degrees of freedom Significant at alpha = .005

Figure 18. Diagram showing transitions between sedimentary facies for section 3, lower sandy unit of Tancook Member

SECTION 5 - TANCOOK MEMBER, UPPER SANDY UNIT

To (columns) / From (rows)

	Tae <3cm	Tc	Tb	Ta	Tae >3cm	Lamin. - massive	Internally scoured	Total
Tae <3cm	1 0.2	2 0.9	1 2.3	2 2.0	3 2.0	0 1.1	0 0.6	9
Tc	4 0.9	14 4.4	7 10.9	9 9.3	7 9.6	2 5.1	0 2.8	43
Tb	3 2.3	16 10.9	35 27.0	18 23.2	18 24.0	12 12.6	5 7.1	107
Ta	0 2.0	7 9.3	28 23.2	22 20.0	17 20.6	11 10.8	7 6.1	92
Tae >3cm	0 2.0	2 9.6	20 24.0	25 20.6	31 21.3	13 11.2	4 6.3	95
Lamin. - massive	1 1.0	2 5.0	7 12.4	10 10.6	13 11.0	8 5.8	8 3.2	49
Internally scoured	0 0.6	0 2.9	9 7.3	6 6.3	6 6.5	4 3.4	4 1.9	29
Total	9	43	107	92	95	50	28	

Upper number in each box shows observed number of transitions; lower number shows mean expected number in a random sequence. Underlined numbers show the most over-represented transitions

Chi-square test carried out after amalgamating facies Tae<3cm with Tc and laminated-massive with internally scoured, to ensure expected totals greater than 5.

$X^2 = 79.2$ 11 degrees of freedom Significant at alpha = .005

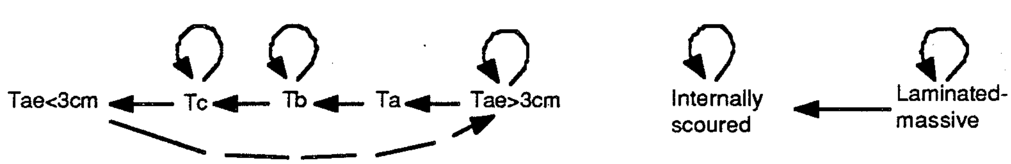


Diagram showing sequences of most common transitions

Figure 19. Diagram showing transitions between sedimentary facies for section 5, upper sandy unit of Tancook Member

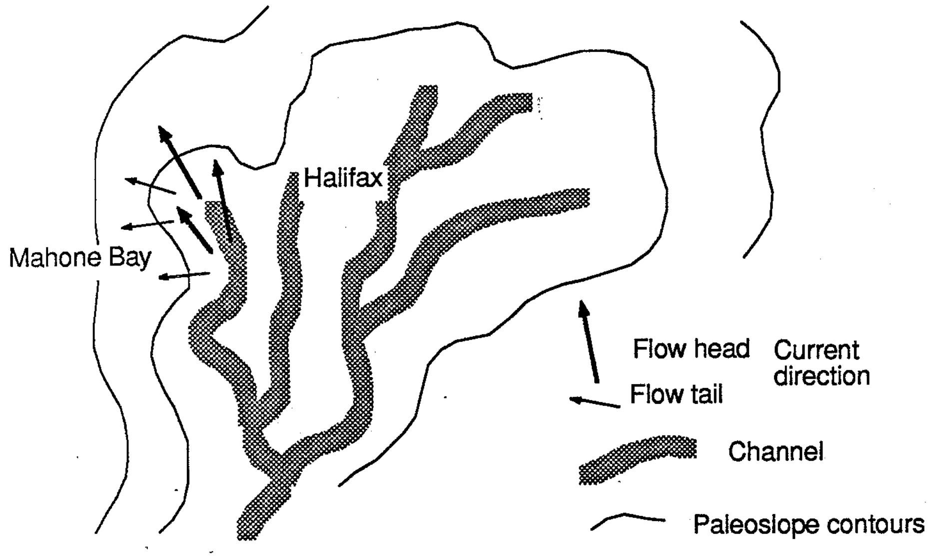
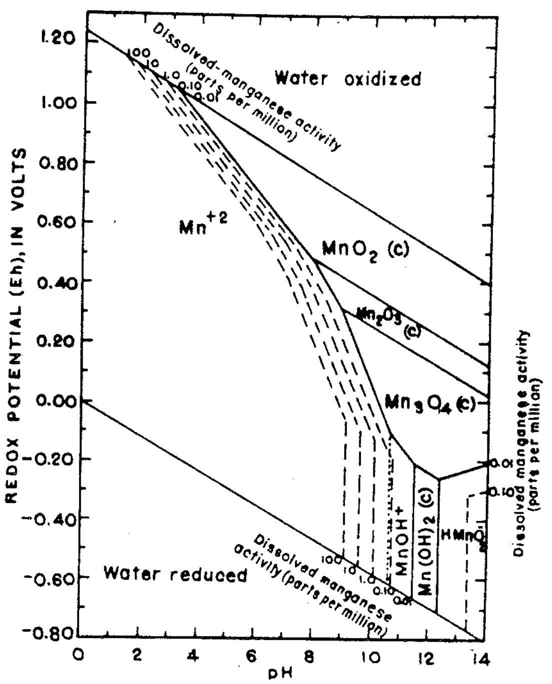


Figure 20. Possible location of Tancook Island area on west flank of submarine fan or fan-lobe. Bold arrows show flow direction of heads of turbidity currents, responsible for sole marks. Thin arrows show flow directions of turbidity current tails, influenced by local slope, and responsible for ripple marks and cross lamination.



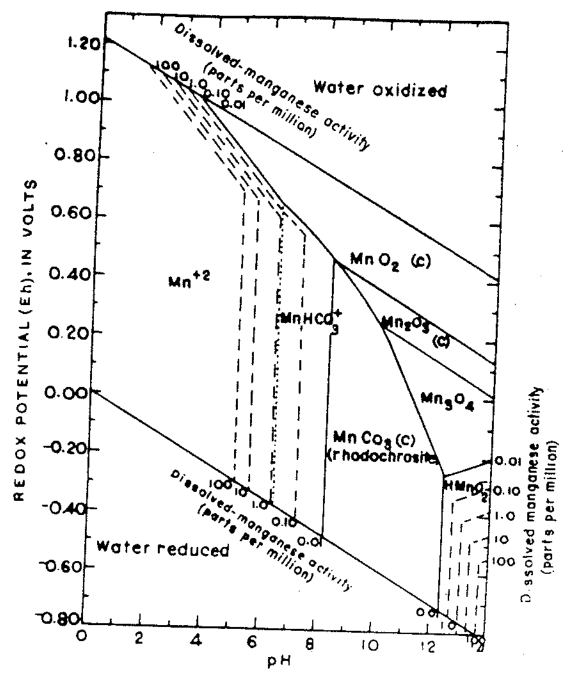


Figure 21. Stability fields of manganese minerals as functions of pH and redox potential at 25°C and atmospheric pressure in the system Mn - H_2O, (After Hem 1972).

Figure 22. Stability fields of manganese minerals as functions of pH and redox potential at 25°C and atmospheric pressure in the system Mn - CO_2 - H_2O. Bicarbonate activity 2000 mg/l as HCO_3^-. (After Hem 1972).

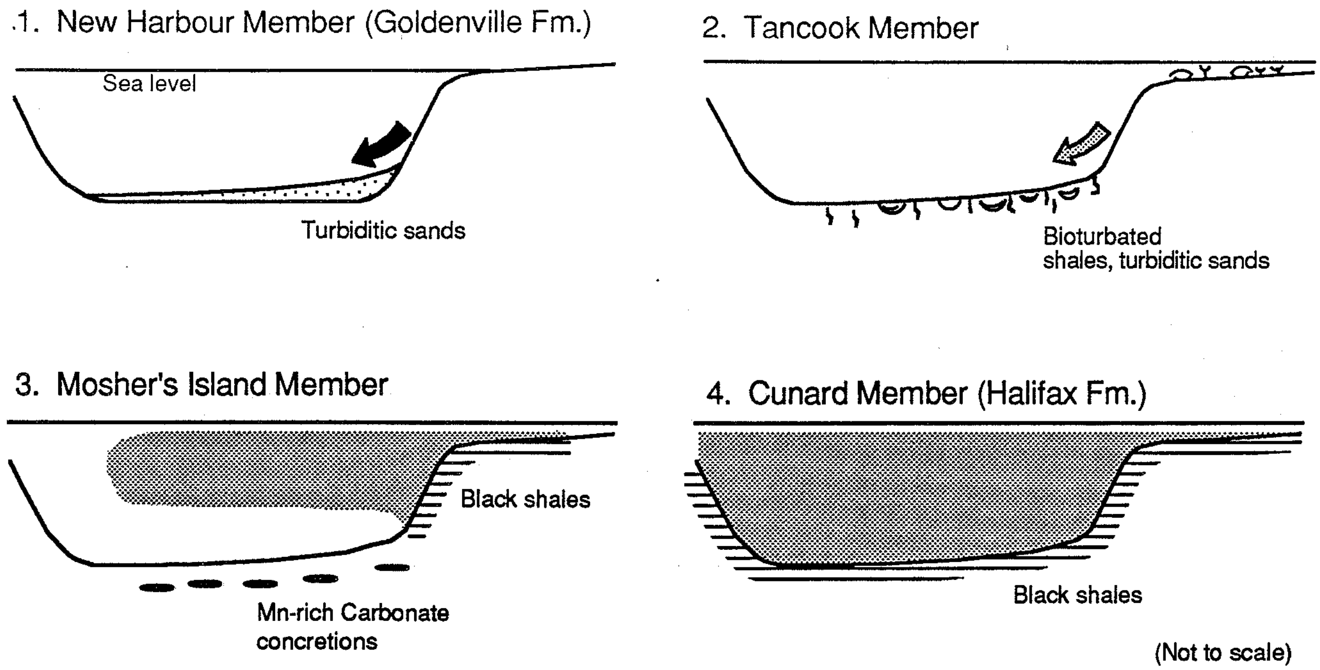


Figure 23. Possible model for the changes in sedimentary environment in Meguma basin during time of Goldenville-Halifax transition.

Diagram (1) represents turbidite deposition in the New Harbour Member and the sandy units of the Tancook Member.

It is speculated that a rise in sea level (2) caused a reduction in sand supply to the basin and permitted temporary establishment of a fauna of carbonate secreting organisms (echinoderms, brachiopods?) on the newly-formed shelf. In the basin, a change from turbidite to predominantly hemipelagic deposition allowed sediment-feeders to become established, producing bioturbated sediments at the top of the upper sandy unit of the Tancook Member.

In (3), representing the upper slaty unit of the Tancook Member and the Mosher's Island Member, organic productivity on the shelf has produced an oxygen minimum zone in the waters of the basin. Conditions at the sea floor are marginally aerobic, producing generally poorly bioturbated and non-bioturbated, laminated muds. Manganese is concentrated relative to iron in the water as a result of precipitation of iron sulphides in the anoxic zone. Manganese(IV) oxides precipitated near the sediment-water interface are dissolved under reducing conditions upon burial, but manganese(II) is fixed within the sediment as carbonate concretions; carbonate ions are supplied either from shelf-derived biogenic carbonate or by in-situ decay of organic matter.

By the time of deposition of the Cunard Member (4), much of the water in the basin is anoxic. The sediments deposited are laminated, black, pyrite-rich muds. As in the modern Black Sea, manganese(IV) oxides precipitate high in the water column but are reduced and re-dissolved upon settling into the anoxic waters.

Although basinal black shales are generally common in Early Paleozoic sequences world-wide, there are no indications of global anoxic events at the probable time of depostion of the sediments of the Goldenville-Halifax transition (Late Cambrian or Earliest Ordovician). The model would therefore suggest that the Meguma Basin was isolated from global ocean circulation during this time.

Appendices (separate sheets)

1. Measured sections in top of New Harbour Member and base of Tancook Member.
2. Measured sections in Tancook Member.
3. Measured sections in top of Tancook Member.

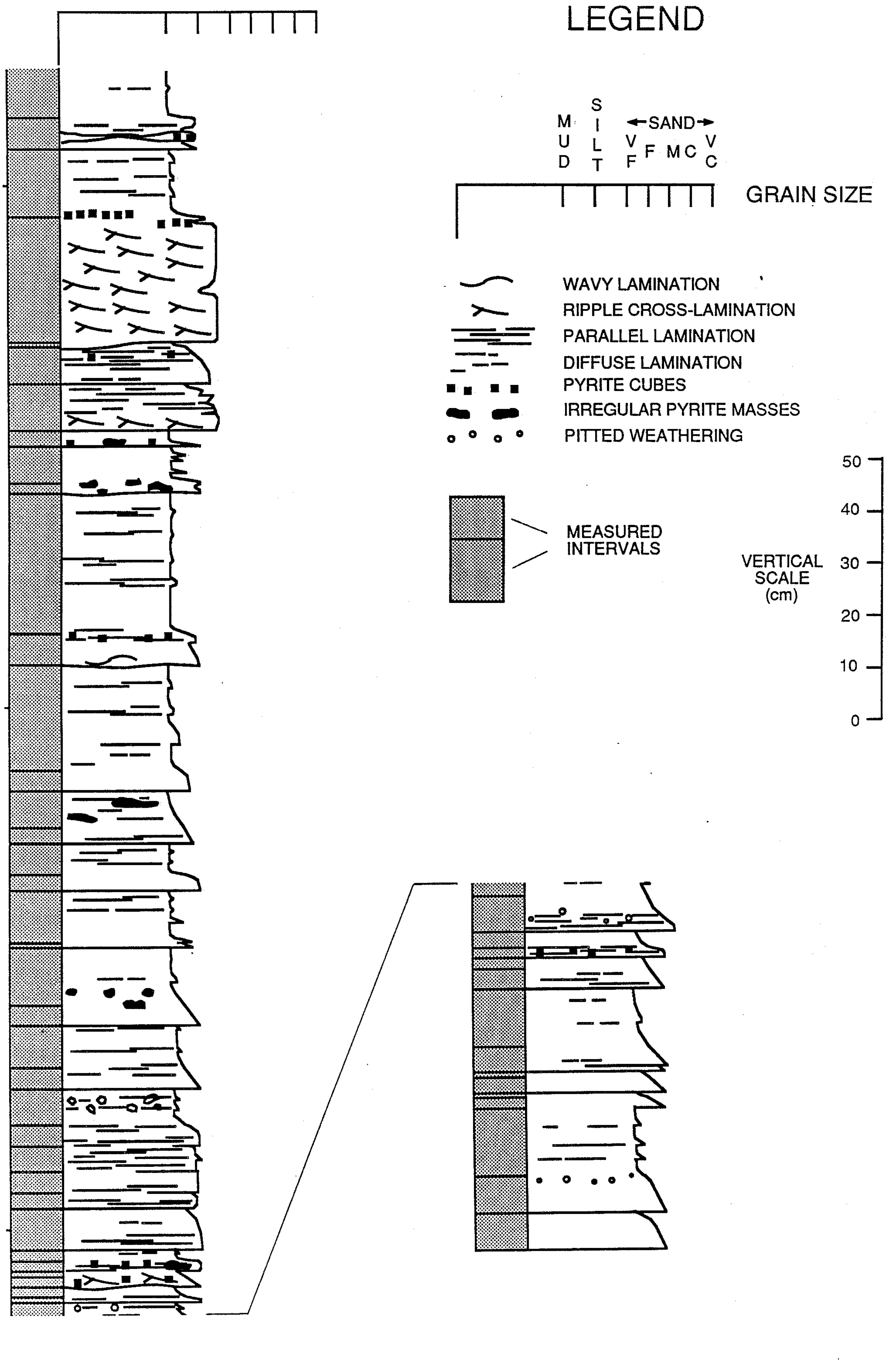


Figure 24. Measured section in Cunard Member (section 13), Big Tancook Island.